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Supply chain design and operational planning models for biomass to drop-in fuel production

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ABSTRACT

Renewable fuel is playing an increasingly important role as a substitute for fossil based energy. The US Department of Energy (DOE) has identified pyrolysis based platforms as promising biofuel production pathways. In this paper, we present a general biofuel supply chain model with a Mixed Integer Linear Programming (MILP) methodology to investigate the biofuel supply chain facility location, facility capacity at strategic levels, and biofuel production decisions at operational levels. In the model, we accommodate different biomass supplies and biofuel demands with biofuel supply shortage penalty and storage cost. The model is then applied to corn stover fast pyrolysis pathway with upgrading to hydrocarbon fuel since corn stover is the main feedstock for second generation biofuel production in the US Midwestern states. Numerical results illustrate unit cost for biofuel production, biomass, and biofuel allocation. The case study demonstrates the economic feasibility of producing biofuel from biomass at a commercial scale in Iowa.

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1. Introduction

Second generation biofuel is attracting increasing attention as a substitute for fossil oil from environmental, economic, and social perspectives. Second generation biofuels are made from nonfood crop or crop residues, such as corn stover, switchgrass, woody biomass, and miscanthus. Thus, the production of biofuel will not be in direct competition with food production. Biomass has different physical properties and component elements, therefore, various products yields can be seen with different thermochemical pathways [1,2]. According to the revised Renewable Fuel Standard (RFS) proposed by US Environmental Protection Agency (EPA), at least 136 Mm^3 of renewable fuels will be produced annually by 2022, and at least 60.6 Mm^3 will be from cellulosic biofuels [3].

Drop-in biofuels are hydrocarbon fuels compared to gasoline and diesel, which can be transported through the existing petroleum pipeline and are ready for vehicles to use without any modification to engines. There are two main processing platforms: thermochemical and biochemical [4]. Thermochemical processes utilize heat to facilitate the depolymerization of biomass compounds which are further processed into biofuel and co-products [5–8]. Biochemical processes involve living organisms to convert organic materials to fuels, chemicals, and other products. Thermochemical pathways are identified as promising pathways

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by the Department of Energy (DOE). This paper focuses on the thermochemical pathways. The biofuel products vary based upon the conversion configuration and reacting conditions.

The general framework for the biofuel supply chain is as follows. Biomass feedstocks are first collected and processed into bale (corn stover) or pellets (woody biomass) for easier storage and transportation [9]. For example, corn stover bales typically have a moisture mass fraction of 30%. The bales are stored on the farm before transported to preprocessing facilities. The physical and chemical properties, information related to corn stover harvesting, storage, and transportation are detailed in Refs. [10,11]. In the preprocessing facility, corn stover is chopped into size (2.5–5.0) cm, then further dried to moisture level of around 7% and grind to (1–2) mm preferably [9]. Preprocessed biomass is then sent to biorefinery facilities to be converted into raw bio-oil and other byproducts. The raw bio-oil is then sent to upgrading facilities to be refined into drop-in biofuels [12–14]. The drop-in biofuels can be transported to Metropolis Statistics Areas (MSAs) for blending or end use.

Supply chain design and operational planning is among the biggest challenges to the cellulosic biofuel industry [15–18]. Feedstock production and logistics constitute 35% or more of the total production costs of advanced biofuel [19,20], and logistics costs can make up (50–75)% of the feedstock costs [21]. To facilitate the commercialization of biofuel production, it is important to investigate the optimal number and locations for biorefinery facilities, and to find the optimal allocation of feedstock and biofuel. There has been an emerging literature in the biofuel supply chain design [15,16,22–25].

Operational planning is also essential for biofuel supply chain and network design. A stochastic multi-period model is proposed in Ref. [18] for hydrocarbon biofuel production from cellulosic biomass, and results for the optimal design of the hydrocarbon biorefinery supply chain are presented under biomass supply and biofuel demand uncertainties. Dal-Mas et al. [17] presented a dynamic multi-echelon Mixed Integer Linear Program (MILP) to assess the economic performance and risk on investment of the biomass-based ethanol plant. Zhu et al. [26] presented a multi-period MILP model to show the feasibility of commercially producing biofuel from switchgrass. Another model also presented by Zhu et al. [27] showed seasonal results for second generation biofuel from a mixture of biomass, and analyzed the effects of biomass yields on biofuel production planning and profit change. In this study, motivated by the real world scenarios, we accommodate the flexibility of fuel demand satisfaction by allowing the shortage of biofuel, which will incur a subjective penalty cost. This is similar to the concept of biofuel importation in Ref. [17].

In addition, this study considers the impact of operational constraints by incorporating the temporal inventory metrics. A multi-period optimization model is also formulated to study the detailed operational planning for biomass collection and drop-in fuel production and distribution. Sensitivity of different biofuel demand patterns is also analyzed.

The rest of the paper is organized as follows. In Section 2, model assumptions and formulation for both annual and operational planning model are presented. In Section 3, we demonstrate a case study in the state of Iowa and numerical results are presented in the same section. Results are summarized in Section 4 along with a discussion of future research directions.

2. Model formulation

This study aims to minimize total biofuel production cost using a Mixed Integer Linear Programming model (MILP). In addition to optimizing the number of biorefinery facilities and locations [23], the proposed model aims to optimize the number of biorefinery facilities, facility capacities, locations, biomass and biofuel allocations considering a variety of biofuel demand scenarios.

As illustrated in Fig. 1, biomass is collected and pretreated at farms into small particles ready for biofuel conversion. Pretreated biomass is transported to biorefinery facilities to go through conversion and upgrading processes to produce advanced biofuel. In this study, it is assumed that biofuel conversion and upgrading are conducted in the same facility, and then transported to the biofuel demand locations, which are Metropolitan Statistical Areas (MSA).

In the following sections, we present an annual based optimization model in Section 2.2 to study the strategic decisions for biofuel supply chain. Analogous to the annual based model, a more detailed operational planning model is presented in Section 2.3 to shed a light on managing the production, allocation and inventory of the biofuel.

Fig. 1 – Biomass supply chain framework for biofuel production and distribution.

2.1. Notations and terminologies

Sets		
I	i,j	Set for biomass supply farms (i) and for biorefinery locations (j)
K	k	Set for MSAs (biofuel demand locations)
L	l	Set for biorefinery capacity levels
T	t	Set of all time periods within a year
Feedstock parameters		
N		Number of counties producing feedstock
A_i	t	Available feedstock at county i in one year
A_{it}	t	Available feedstock at county i in month t
h_i^S	$\$t^{-1}$	Unit feedstock holding cost at county i per month
U_i^S	t	Maximum storage capacity for county i
D_{ij}	km	Great circle distance from county i to county j
S_i		Sustainability factor for county i
ℓ_1		Material loss factor for feedstock over each year
ℓ_2		Material loss factor for feedstock over each month
τ		Tortuosity factor
$C_i^{S,CL}$	$\$t^{-1}$	Feedstock collecting and loading cost at county i
$C_{ij}^{S,T}$	$\$t^{-1}\ km^{-1}$	Feedstock transportation cost from county i to county j
Biorefinery parameters		
$\underline{U}_{lt}^B$	t	Minimum biomass processing quantity in month t for capacity level l
$\overline{U}_{lt}^B$	t	Maximum biomass processing quantity in month t for capacity level l
$h_j^{B,B}$	$\$t^{-1}$	Biomass unit holding cost at biorefinery facility j per month
$h_j^{B,G}$	$\$m^{-3}$	Biofuel unit holding cost at biorefinery facility j per month
$U_j^{B,B}$	t	Maximum biomass storage level at biorefinery facility j
$U_j^{B,G}$	m^3	Maximum biofuel storage level at biorefinery facility j
U_l^B	t	Fixed biorefinery capacity for capacity level l in one year
C_l^B	\$	Fixed biorefinery cost for capacity level l
Y_j		Biomass to biofuel conversion rate at biorefinery facility j
$C_j^{G,C}$	$\$m^{-3}$	Biofuel unit conversion cost at biorefinery facility j
γ	tm^{-3}	Unit conversion coefficient of gallon to ton
Q	\$	Budget for the biorefinery facilities
H	year	Long term planning horizon
r		Annual interest for investment
MSA and biofuel demand parameters		
M		Number of MSAs
G_k	m^3	Total biofuel demand for MSA k
G_{kt}	m^3	Total biofuel demand for MSA k in month t
$C_{jk}^{G,T}$	$\$t^{-1}\ km^{-1}$	Biofuel transportation cost from facility location j to MSA k
h_k^M	$\$m^{-3}$	Unit holding cost for biofuel at MSA k per month
U_k^M	m^3	Biofuel inventory level at MSA k
Continuous variables		
f_{ij}	t	Biomass feedstock flow from county i to county j
f_{ijt}	t	Biomass feedstock flow from county i to county j in month t
q_{jk}	m^3	Biofuel flow from county j to MSA k
q_{jkt}	m^3	Biofuel flow from county j to MSA k in month t
v_{it}	t	Feedstock harvest quantity in county i at time t
q_{jt}^B	t	Biomass process quantity in biorefinery j at time t
I_{it}^S	t	Inventory level of feedstock in county i at time t
$I_{jt}^{B,B}$	t	Inventory level of feedstock in biorefinery facility j at time t
$I_{jt}^{B,G}$	m^3	Inventory level of biofuel in biorefinery facility j at time t
I_{kt}^M	m^3	Inventory level of biofuel in MSA k at time t
Binary variables		
δ_{jl}		Binary variable for biorefinery facility of level l built in county j.

2.2. Annually based model formulation

The annual based model aims to determine the number of facilities, facility sizes, and facility locations for the biofuel supply chain for a long term planning horizon. In this model, we assume that biorefinery facilities will run according to optimal allocation of general biomass and biofuels, constrained by the capacity of storage and refinery facilities, but flexible for storage and production levels. The objective is to minimize total annual cost including biomass transportation, biofuel conversion, biofuel transportation, facility cost, and biofuel shortage penalty. The level of biofuel demand fulfillment also depends on the market price of biofuel, which will be discussed in the case study. The schematic of this model is illustrated in Fig. 2.

The general annual based model formulation is shown in Equations (1a)–(1i).

$$\min \sum_{i=1}^{N}\sum_{j=1}^{N}\left(C_i^{S,CL}+\tau D_{ij}C_{ij}^{S,T}\right)f_{ij}+\sum_{j=1}^{N}\sum_{k=1}^{M}\left(C_j^{G,C}+\tau\gamma D_{jk}C_{jk}^{G,T}\right)q_{jk} + \sum_{k=1}^{M}\lambda_k\left(G_k-\sum_{j=1}^{N}q_{jk}\right)_{+}+\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C_l^B\delta_{jl}}{\frac{(1+r)^H-1}{r(1+r)^H}} \tag{1a}$$

$$\text{s.t.}\quad \sum_{j=1}^{N}f_{ij}\le(1-S_i)A_i,\ \forall i\in I \tag{1b}$$

$$(1-\ell_1)\sum_{i=1}^{N}f_{ij}\le\sum_{l=1}^{L}U_l^B\delta_{jl},\ \ \forall j\in I \tag{1c}$$

$$(1-\ell_1)\sum_{i=1}^{N}f_{ij}Y_j=\gamma\sum_{k=1}^{M}q_{jk},\ \ \forall j\in I \tag{1d}$$

$$\sum_{l=1}^{L}\delta_{jl}\le 1,\ \ \forall j\in I \tag{1e}$$

$$\sum_{j=1}^{N}\sum_{l=1}^{L}C_l^B\delta_{jl}\le Q \tag{1f}$$

$$f_{ij}\ge 0,\ \ \forall i,j\in I \tag{1g}$$

Fig. 2 – Biofuel supply chain framework.

$$q_{jk} \geq 0, \ \forall j \in I, k \in K \tag{1h}$$

$$\delta_{jl} \in \{0, 1\}. \tag{1i}$$

The objective function (1a) is to minimize total system costs including biomass collecting and loading cost $\sum_{i=1}^{N}\sum_{j=1}^{N} C_i^{S,CL} f_{ij}$, biomass transportation cost $\sum_{i=1}^{N}\sum_{j=1}^{N} \tau D_{ij} C_{ij}^{S,T} f_{ij}$, biofuel conversion cost $\sum_{j=1}^{N}\sum_{k=1}^{M} C_j^{G,C} q_{jk}$, biofuel transportation cost $\sum_{j=1}^{N}\sum_{k=1}^{M} \tau\gamma D_{jk} C_{jk}^{G,T} q_{jk}$, penalty cost for biofuel demand shortage $\sum_{k=1}^{M} \lambda_k (G_k - \sum_{j=1}^{N} q_{jk})_+$, and aggregated biorefinery facility building cost $\sum_{j=1}^{N}\sum_{l=1}^{L} \frac{C_l^B \delta_{jl}}{\frac{(1+r)^H - 1}{r(1+r)^H}}$. In the penalty cost for biofuel demand shortage, $(\cdot)_+ = \max\{\cdot, 0\}$. The term λ_k is the penalty for biofuel demand shortage. It is assumed to be the conventional fuel market price, which means if the fuel demand is not satisfied by the biofuel producers, it will be fulfilled with the petroleum based fuel.

Constraint (1b) denotes that for each county i, the shipped-out feedstock $\sum_{j=1}^{N} f_{ij}$ should be no more than available feedstock. Constraint (1c) means that if biorefinery facility j operates ($\sum_{l=1}^{L} \delta_{jl} = 1$), then feedstock shipped to j should be no more than the capacity. Constraint (1d) indicates the mass balance of biomass and biofuel for each biorefinery facility j. Biofuel produced $(1-\ell_1)\sum_{i=1}^{N} f_{ij} Y_j$ should be equal to biofuel shipping quantity $\gamma \sum_{k=1}^{M} q_{jk}$. Constraint (1e) sets that facilities can only built at one levee capacity level. Constraint (1f) included the budget limit for the total investment.

This optimization model includes a nonlinear objective function and linear constraints. Here we propose to linearize the model formulation by adding ancillary continuous variables y_k:

$$\min \sum_{i=1}^{N}\sum_{j=1}^{N}\left(C_i^{S,CL} + \tau D_{ij} C_{ij}^{S,T}\right) f_{ij} + \sum_{j=1}^{N}\sum_{k=1}^{M}\left(C_j^{G,C} + \tau\gamma D_{jk} C_{jk}^{G,T}\right) q_{jk} + \sum_{k=1}^{M} \lambda_k y_k + \sum_{j=1}^{N}\sum_{l=1}^{L} \frac{C_l^B \delta_{jl}}{\frac{(1+r)^H - 1}{r(1+r)^H}} \tag{2a}$$

$$\text{s.t.} \quad \text{Constraints (1b)} - \text{(1f)} \tag{2b}$$

$$y_k \geq G_k - \sum_{j=1}^{N} q_{jk}, \ \forall k \in K \tag{2c}$$

$$\text{Constraints (1g)} - \text{(1i)} \tag{2d}$$

$$y_k \geq 0. \tag{2e}$$

The total annual cost divided by the annual biofuel production would be the average unit cost for biofuel.

2.3. *Model formulation with operational planning*

With the annual based optimization model, the optimal biorefinery location, and biomass and biofuel distribution can be analyzed. In addition to the strategic decision making, the operational planning is also essential for the commercialization of advanced biofuel production. In this section, we present a multi-period MILP model for biomass-based biofuel supply chain. In addition to the strategic decision variables, operational planning design, such as monthly biorefinery production level, biomass and biofuel inventory control and allocation. It should be noted that the multi-period model will increase the computational effort due to the increase in problem size. The modeling schematic is shown in Fig. 3.

$$\min \sum_{t=1}^{T}\Bigg\{\sum_{i=1}^{N}\sum_{j=1}^{N} \tau D_{ij} C_{ij}^{S,T} f_{ijt} + \sum_{j=1}^{N}\sum_{k=1}^{M} \tau\gamma D_{jk} C_{jk}^{G,T} q_{jkt} + \sum_{i=1}^{N} C^{S,CL} v_{it} + \sum_{j=1}^{N} \frac{1}{\gamma} C_j^{G,C} q_{jt}^B + \sum_{k=1}^{M} \lambda_{kt}\left(G_{kt} - \sum_{j=1}^{N} q_{jkt}\right)_+ + \sum_{i=1}^{N} h_i^S I_{it}^S + \sum_{j=1}^{N} h_j^{B,B} I_{jt}^{B,B} + \sum_{j=1}^{N} h_j^{B,G} I_{jt}^{B,G} + \sum_{k=1}^{M} h_k^M I_{kt}^M\Bigg\} + \sum_{j=1}^{N}\sum_{l=1}^{L} \frac{C_l^B \delta_{jl}}{\frac{(1+r)^H - 1}{r(1+r)^H}} \tag{3a}$$

$$v_{it} \leq (1 - S_i) A_{it}, \ \forall i \in I, t \in T \tag{3b}$$

$$\delta_{jl} \underline{U}_{lt}^B \leq q_{jt}^B \leq \delta_{jl} \overline{U}_{lt}^B, \ \forall j \in I, t \in T, l \in L \tag{3c}$$

$$I_{it}^S = (1 - \ell_2) I_{i,t-1}^S + v_{it} - \sum_{j=1}^{N} f_{ijt}, \ \forall i \in I, t \in T \tag{3d}$$

$$I_{jt}^B = (1 - \ell_2) I_{j,t-1}^B + \sum_{i=1}^{N} f_{ijt} - r_{jt}, \ \forall j \in I, t \in T \tag{3e}$$

$$I_{jt}^G = I_{j,t-1}^G + \frac{1}{\gamma} q_{jt}^B Y_j - \sum_{k=1}^{M} q_{jkt}, \ \forall j \in I, t \in T \tag{3f}$$

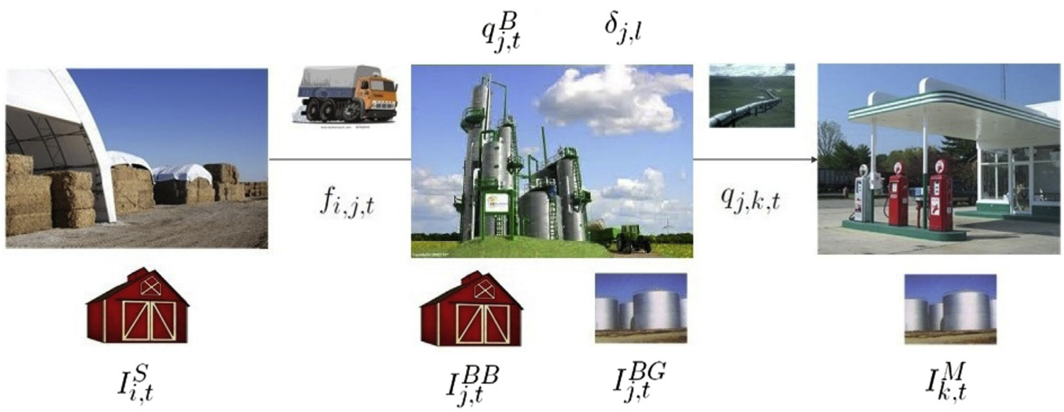

Fig. 3 – Multi-period model framework of biofuel production and distribution.

$$I^M_{kt} \geq I^M_{k,t-1} + \sum_{j=1}^{N} q_{jkt} - G_{kt}, \ \forall k \in K, t \in T \tag{3g}$$

$$\text{Constraints (1e), (1f)} \tag{3h}$$

$$0 \leq I^S_{it} \leq U^S_i, \ \forall i \in I, t \in T \tag{3i}$$

$$0 \leq I^B_{jt} \leq U^{B,B}_j, \ \forall j \in I, t \in T \tag{3j}$$

$$0 \leq I^G_{jt} \leq U^{B,G}_j, \ \forall j \in I, t \in T \tag{3k}$$

$$0 \leq I^M_{kt} \leq U^M_k, \ \forall k \in K, t \in T \tag{3l}$$

$$I^S_{i,0} = I^{B,B}_{j,0} = I^{B,G}_{j,0} = I^M_{k,0} = 0, \ \forall i, j \in I, k \in K \tag{3m}$$

$$f_{ijt} \geq 0, \ \forall i, j \in I, t \in T \tag{3n}$$

$$q_{jkt} \geq 0, \ \forall j \in I, k \in M, t \in T \tag{3o}$$

$$v_{it} \geq 0, \ \forall i \in I, t \in T \tag{3p}$$

$$q^B_{jt} \geq 0, \ \forall j \in I, t \in T \tag{3q}$$

$$\delta_{jl} \in \{0, 1\}, \ \forall j \in I, l \in L \tag{3r}$$

The objective function (3a) is to minimize total system costs over all time periods, including biomass transportation cost $\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j=1}^{N}\tau D_{ij} C^{S,T}_{ij} f_{ijt}$, biofuel transportation cost $\sum_{t=1}^{T}\sum_{j=1}^{N}\sum_{k=1}^{M}\tau\gamma D_{jk} C^{G,T}_{jk} q_{jkt}$, biomass collecting and loading cost $\sum_{t=1}^{T}\sum_{i=1}^{N} C^{S,CL} v_{it}$, biofuel transportation cost $\sum_{t=1}^{T}\sum_{j=1}^{N}\frac{1}{\gamma} C^{G,C}_j q^B_{jt}$, penalty cost for biofuel demand shortage $\sum_{t=1}^{T}\sum_{k=1}^{M}\lambda_{kt}(G_{kt} - \sum_{j=1}^{N} q_{jkt})_+$, and fixed biorefinery facility cost $\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C^B_l \delta_{jl}}{\frac{(1+r)^H-1}{r(1+r)^H}}$. Inventory costs for biomass and biofuel over the time periods are also included in the objective function. The inventory costs include biomass inventory cost $\sum_{t=1}^{T}\sum_{i=1}^{N} h^S_i I^S_{it}$ at farm i, biomass inventory cost $\sum_{t=1}^{T}\sum_{j=1}^{N} h^{B,B}_j I^{B,B}_{jt}$ at biorefinery facility j, biofuel inventory cost $\sum_{t=1}^{T}\sum_{j=1}^{N} h^{B,G}_j I^{B,G}_{jt}$ at biorefinery facility j, biofuel inventory cost $\sum_{t=1}^{T}\sum_{k=1}^{M} h^M_k I^M_{kt}$ at MSA k. Constraint (3b) shows that for each month, biomass harvest cannot exceed available biomass. Constraint (3c) indicates that biorefinery facilities only operate when production reaches a certain level. In this study, both upper and lower bounds for production levels are set for the refinery facilities to operate. Constraints (3d)–(3g) are biomass and biofuel storage balance constraints for facility j at period t. Decision variables in this model include equations (3i)–(3r).

3. Case study

Iowa has been recognized as one of the leading states for biofuel production [28]. Currently, there are several commercial size biorefinery plants under construction in Iowa. In the computation analysis section, we present a case study in the state of Iowa. Results of both the annual based model and the multi-period operational planning model are presented. Parameters and data sources are listed in Table 1.

Corn stover, as the main cellulosic biomass supply in the Midwest, is under consideration in this paper. Corn stover refers to the stalks, leaves, cob, and husk of the maize plants which is harvested together with corn. The moisture content of corn stover is assumed to be 30% in mass, and the ratio of corn stover to corn is assumed to be 1:1 [10] based on the land sustainability and erosion control metrics. The production pathway analyzed in this paper is fast pyrolysis of corn stover with upgrading to drop-in biofuels [29]. The drop-in fuels could be mixture of a range of biofuels including gasoline and diesel range fuel. The percentage varies based on the configuration and conditions [23,29]. Without loss of generality, for the supply chain design model, we assume gasoline to be the main product under consideration. It should be noted that the supply chain design and operational planning model formulated in this study can also be utilized to analyze a variety of pathways. The pathways are chosen based on data availability. Corn stover will be transported through truck or train based on the vehicle and infrastructure availability. In this study, we assume truck is the only transportation mode for corn stover. Bio-gasoline is assumed to be the only

Table 1 – Data source.

Parameters	Data	Notes	References
Feedstock parameters			
N	99	Number of counties in Iowa	
A_t		Available feedstock in one year	[31]
S_t	0.718	Sustainability factor	[10]
$C_t^{S,CL}$	(24–45) $\$t^{-1}$	Feedstock collecting and loading cost	
h_t^S	10% of product value	Unit feedstock holding cost	[32,33]
U_t^S	1 Mt	Maximum storage capacity	Assumed
ℓ_1	5%	Material loss factor for feedstock	Assumed
D_{ij}		Great circle distance	Assumed
T	1.27	Tortuosity factor	[34]
$C_{ij}^{S,T}$	0.11 $\$t^{-1}\ km^{-1}$	Unit feedstock transportation cost	[35]
Biorefinery parameters			
γ	0.72 tm^{-3}	Unit conversion coefficient of biogasoline from liter to tonne	
U_l^B	144, 360, 540, 720 kt	Fixed biorefinery capacity in one year	[36]
C_l^B		Fixed biorefinery cost	[36]
Y_j	0.2180	Biorefinery fuel process yield of feedstock	Assumed
$C_j^{G,C}$	540 $\$m^{-3}$	Unit conversion cost of biofuel	[29]
H	30 years	Long term planning horizon in years	Assumed
r	10%	Annual interest for investment	Assumed
$h_j^{B,B}$	20% of product value	Biomass holding cost at biorefinery facility	Assumed
$h_j^{B,G}$	20% of product value	Biofuel holding cost at biorefinery facility	Assumed
$\overline{U}_{lt}^B$		Fixed biorefinery capacity in each time period	
U_{lt}^B	60% of $\overline{U}_{lt}^B$	Minimum processing quantity per month	
$\overline{U}_j^{B,B}$	0.72 Mt	Biomass storage capacity at biorefinery facility	Assumed
$U_j^{B,G}$	100 dam^3	Biofuel storage capacity at biorefinery facility	Assumed
MSA and biofuel demand parameters			
M	21	Number of MSAs considered	[37]
G_k		Biofuel demand	[37]
G_{kt}		Biofuel demand for month t	
$C_{jk}^{G,T}$	0.01 $\$t^{-1}\ km^{-1}$	Biofuel transportation cost per unit	[38]
h_k^M	30% of product value	Unit holding cost for biofuel	Assumed
U_k^M	50 dam^3	Biofuel storage level	Assumed

transportation fuel in this case study. (In real world scenario, multiple products can be produced through corn stover fast pyrolysis. Since bio-gasoline is the major product we are considering here. The profit for other byproducts can be treated to offset the production cost.) Bio-gasoline is assumed to be transported through existing petroleum pipelines. An ideal assumption to assume that pipelines are accessible anywhere within Iowa. In real world problem, it has to be sent to intermediate hubs to be access to the pipelines. Therefore, one more layer of stakeholders will be added to the biofuel supply chain. In this paper, the authors decide to simplify this without comprimising the quality of the solution. Since the simplification is applied to all the biorefinery facilities in the supply chain. Biofuel demand is based on the population in the MSA areas as shown in Fig. 4 [30].

In the following sections, an example for the state of Iowa (which has 99 counties and 21 MSAs) is presented. The computational results are obtained with CPLEX and ARCGIS.

3.1. Annual model results and analysis

The annual model has around 12 000 continuous variables, 400 binary variable, and 400 constraints. This problem can be solved within a few seconds.

In this scenario, gasoline shortage penalty λ is set at 1060 $\$m^{-3}$, the average market price of gasoline. This means that we need to purchase gasoline at 1060 $\$m^{-3}$ at market to fulfill biofuel demand in all MSAs if there is any gasoline shortage.

- If there is no budget limit for biorefinery facility investment, the optimal number of facilities is 23. All gasoline demands are satisfied with the average unit cost for producing gasoline to be 730 $\$m^{-3}$. The biomass and biofuel allocation as shown in Fig. 5. The cost components are shown in Fig. 7.

From the Fig. 5, we see that there are 4 biorefinery facilities built in the same location with MSAs, and they are all running 2000 td^{-1}. Among all 23 facilities built 10 are running 1500 td^{-1} and 13 are running 2000 td^{-1}. This allocation of facilities is optimal in minimizing biomass and biofuel transportation distance. Gasoline demand in all MSAs is satisfied.

- If the budget is limited, then the minimum budget to satisfy all gasoline demand is 4200 M \$. The optimal number of facilities we is 21. The average unit cost of gasoline is 740 $\$m^{-3}$. Biomass and biofuel allocations are shown in Fig. 6. Cost allocation is shown in Fig. 7.

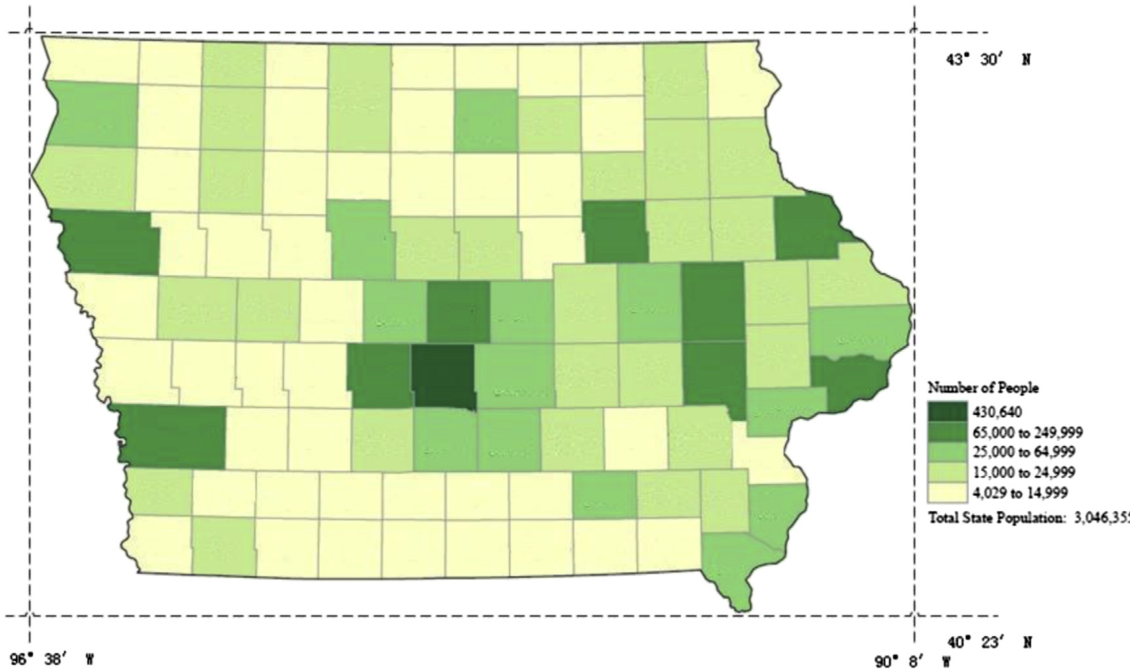

Fig. 4 – Iowa population estimation for 2010 [30].

If only 21 biorefinery facilities are built, only two facilities will run 1500 td^{-1}, and all the others will run 2000 td^{-1}. In this scenario, all gasoline demand can still be satisfied. From Fig. 7, it is observed that gasoline conversion cost, biomass collection cost, and facility building cost are three major cost components for gasoline production. The increase in the unit production cost is mainly due to feedstock transportation.

- If the budget is further reduced thus not enough facilities built to satisfy all demand, then either nearby MSAs or MSAs with higher biofuel shortage penalty λ will receive higher priority to consume the biofuel. For example, if there is only enough budget to build one facility, and penalties for all MSAs are the same, then the optimal location to build this facility is Webster County (see Fig. 8) which would supply biofuel to three nearby MSAs. If priority is provided to MSA

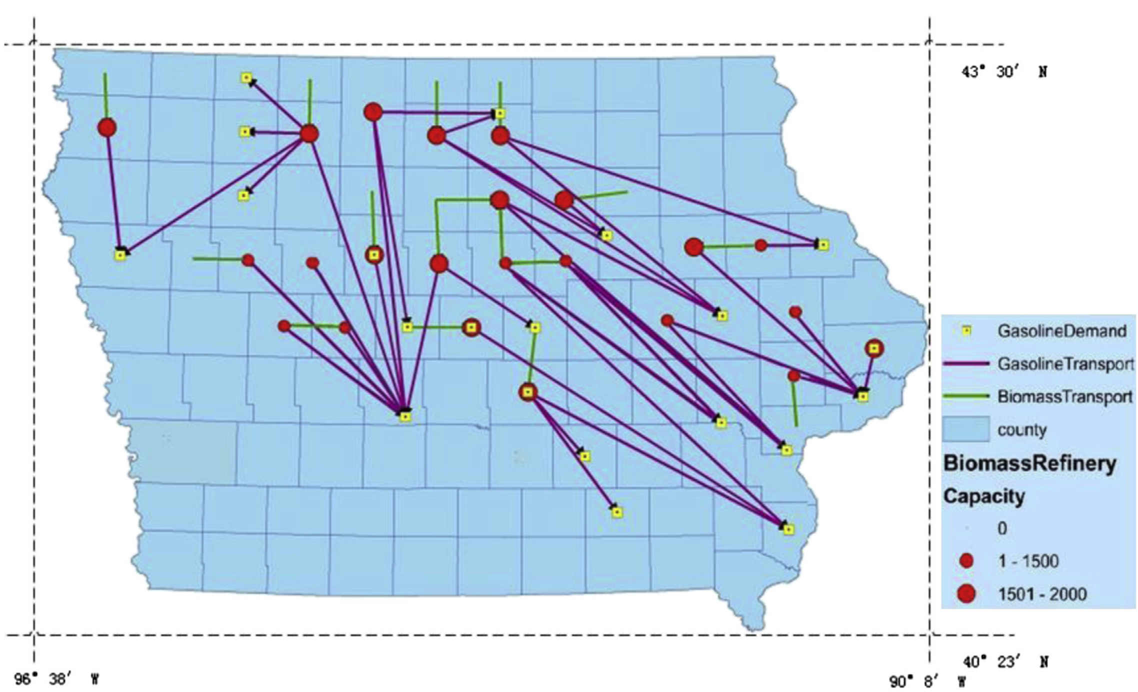

Fig. 5 – Annual model result with no capital budget limit.

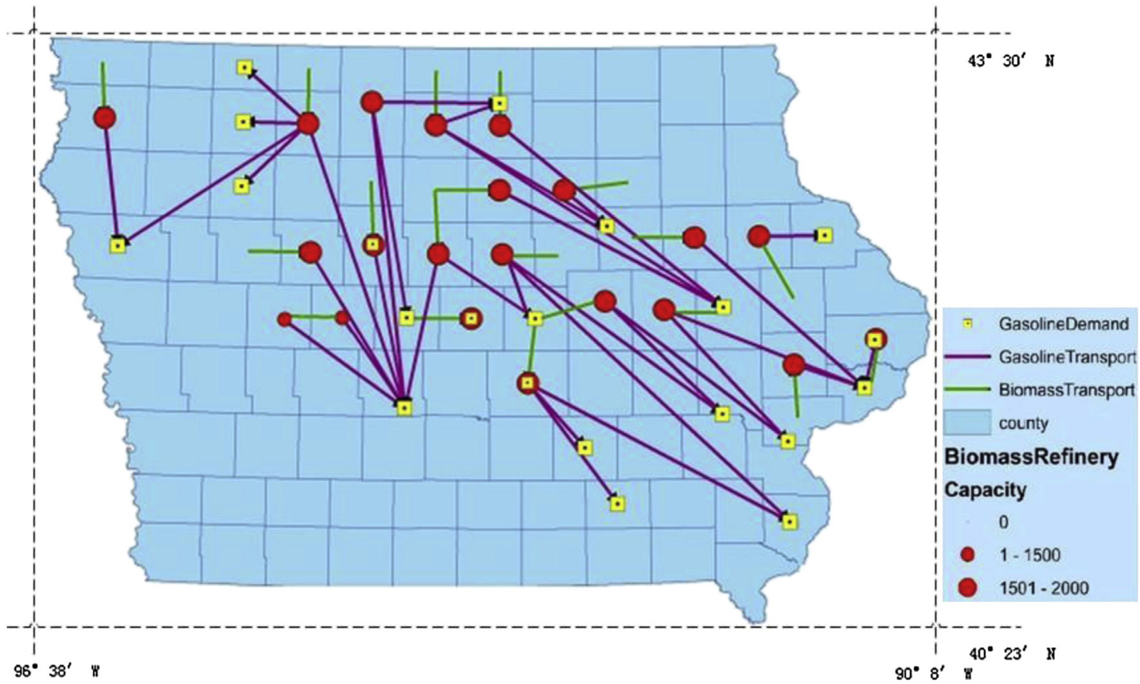

Fig. 6 – Annual model result with capital budget limit.

Burlington (the biofuel shortage penalty in Burlington as $\lambda = 10\,000$ and other MSAs as $\lambda = 1060$), then the optimal location to build a facility is Franklin County (see Fig. 9), and we can see that gasoline demand in Burlington can still be satisfied even though transportation distance is longer.

3.2. *Monthly model results and analysis*

To better present the detailed allocation, feedstock, and biofuel storage over multiple operational periods, a multi-period model is analyzed and the optimal number of facilities, facility

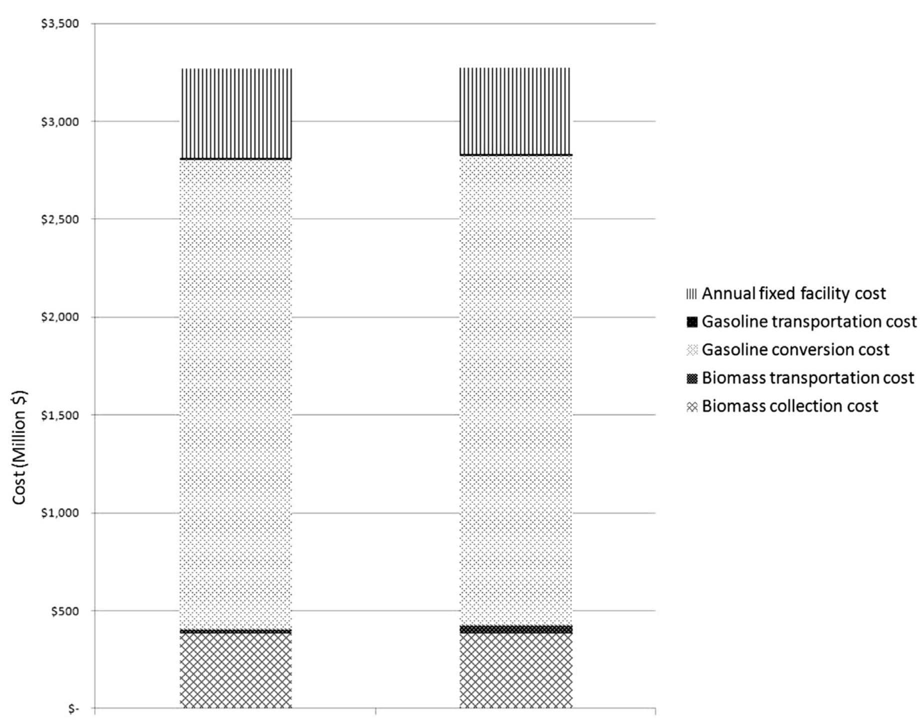

Fig. 7 – Comparison of total annual biogasoline production costs.

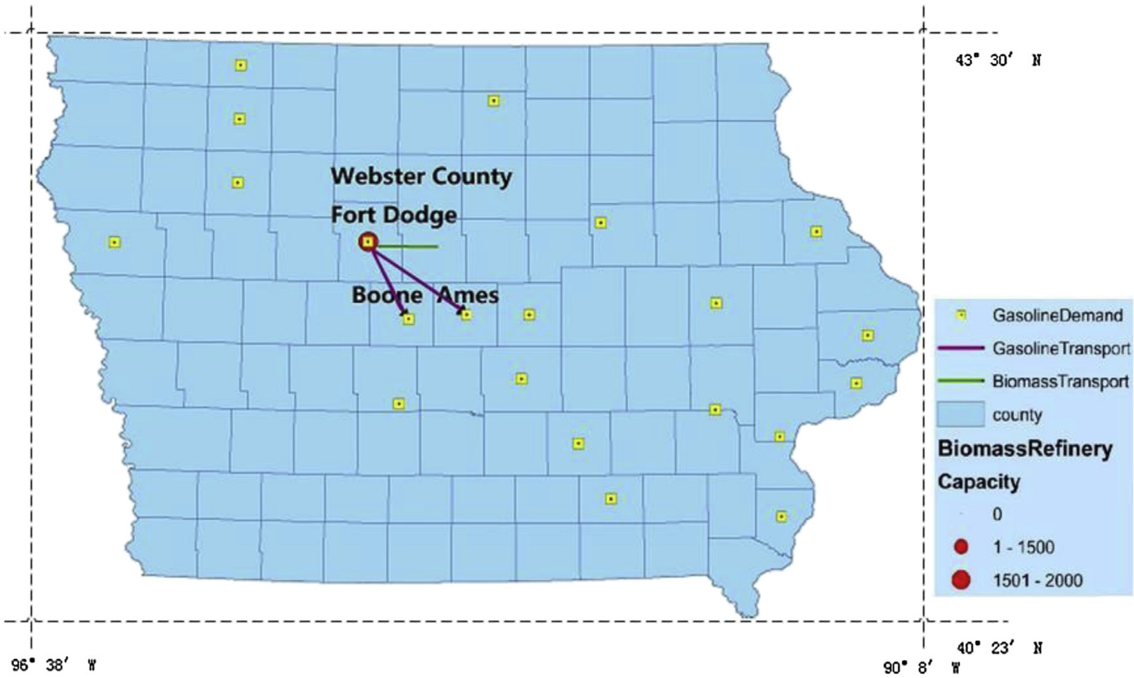

Fig. 8 – Biomass and biofuel distribution under uniform penalty.

locations, biomass and biofuel allocation, storage levels at each storage facility, and unit production costs for biofuel are investigated.

In this example, we consider scenarios for which there is no budget limit, since cases with a budget limit will get similar results with more facilities built at 2000 td^{-1}. For different demand patterns over twelve months, different biorefinery facility numbers, sizes and production level results are shown. The operational planning problem includes around 145 000 continuous variables, 400 binary variables, and 219 000 constraints. The solving time varies for different demand patterns and the average solving time is 30 min.

- If the biofuel demand pattern is uniform, then optimal allocation is shown in Fig. 10, with the optimal number of facilities being 23, including 10 facilities built for 1500 td^{-1}.

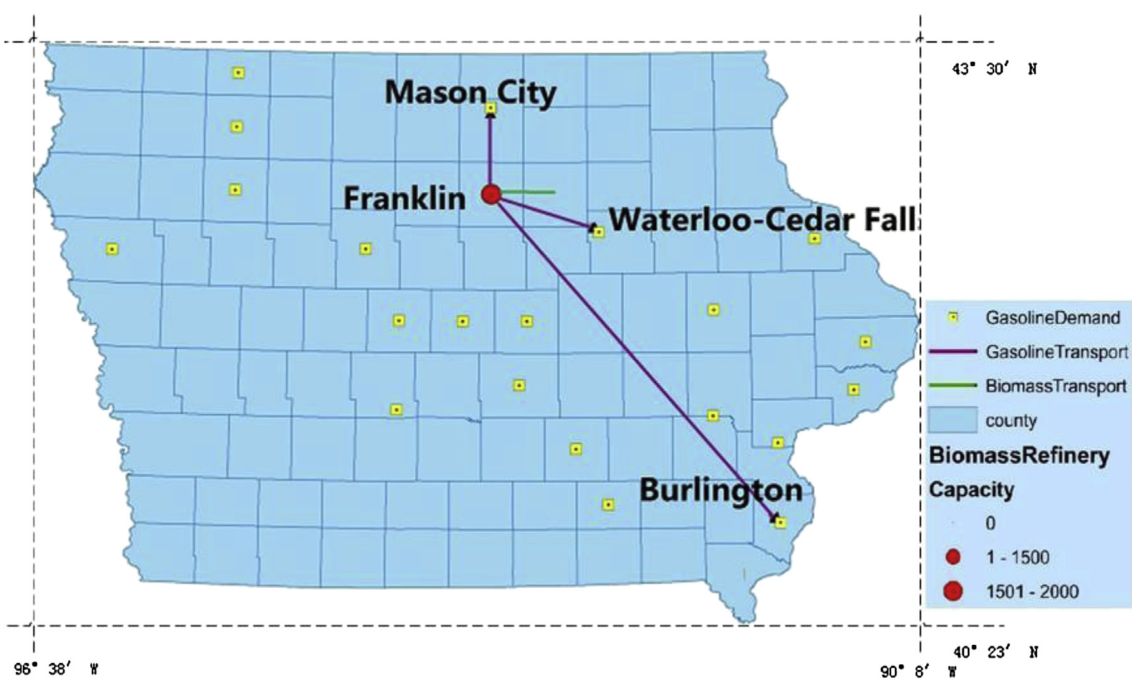

Fig. 9 – Biomass and biofuel distribution under uneven penalty.

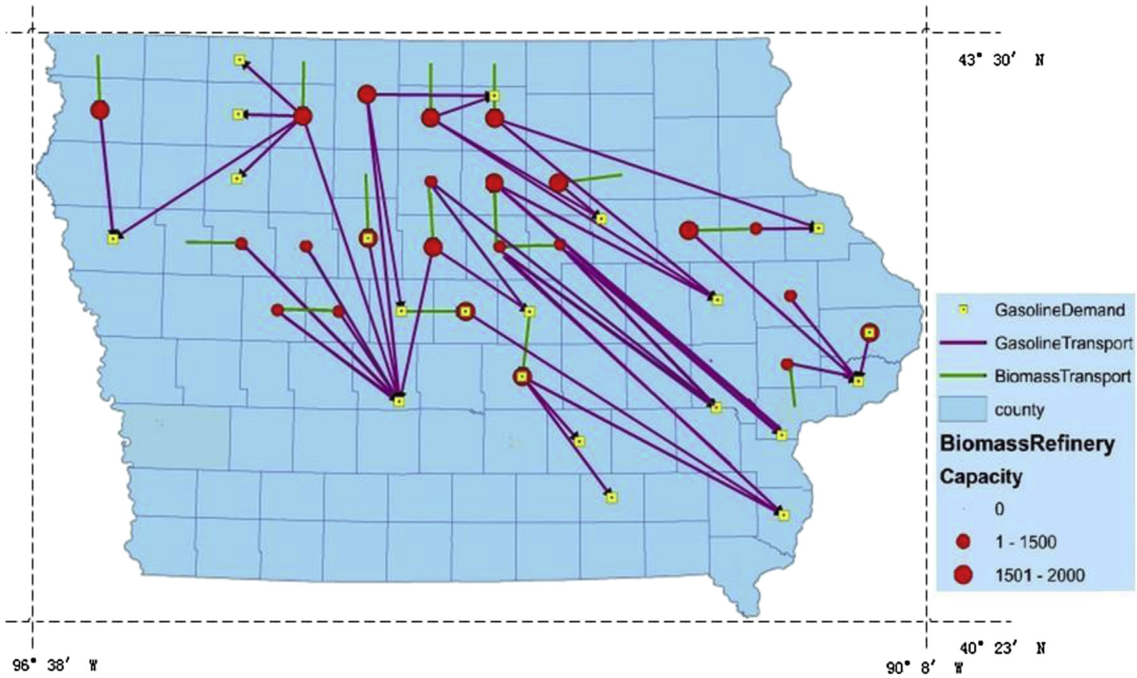

Fig. 10 – Monthly based model results under uniform gasoline demand.

The average unit cost of gasoline is 730 $m^{-3}, and biofuel demands in all MSAs are satisfied. The cost components are presented in Fig. 12. We see that biofuel conversion cost, fixed facility building cost, and biomass harvesting cost are three major costs in the supply chain of biofuel production. There is no storage cost in this case. Biofuel production distribution over all months is also uniform Fig. 11

- For the increasing biofuel demand pattern in Fig. 11, the optimal number of facilities is 24, with 2 facilities built at 1500 td^{-1} and all others built at 2000 td^{-1}. The average unit cost of gasoline is 790 $m^{-3}, and all biofuel demands are satisfied. The cost components are shown in Fig. 12. Biofuel production in all biorefinery facilities follows an nondecreasing distribution, and facilities produce extra biofuel in previous months to satisfy higher biofuel demand in later months.
- For the decreasing pattern in Fig. 11, if the biofuel shortage penalty is 1060 $m^{-3}, then the optimal number of facilities built is 20, with all 20 facilities built at the 2000 td^{-1} level. The average unit cost of gasoline is 880 $m^{-3} including biofuel shortage cost, and 820 $m^{-3} without considering a biofuel shortage cost. In this case, not all biofuel demands are satisfied, and 10 of 21 MSAs' biofuel demands are not satisfied in the first month. Biofuel production in each month follows a non-increasing distribution. Cost components in this scenario are seen in Fig. 12. In this scenario, the biofuel shortage cost is an additional significant component for total cost.

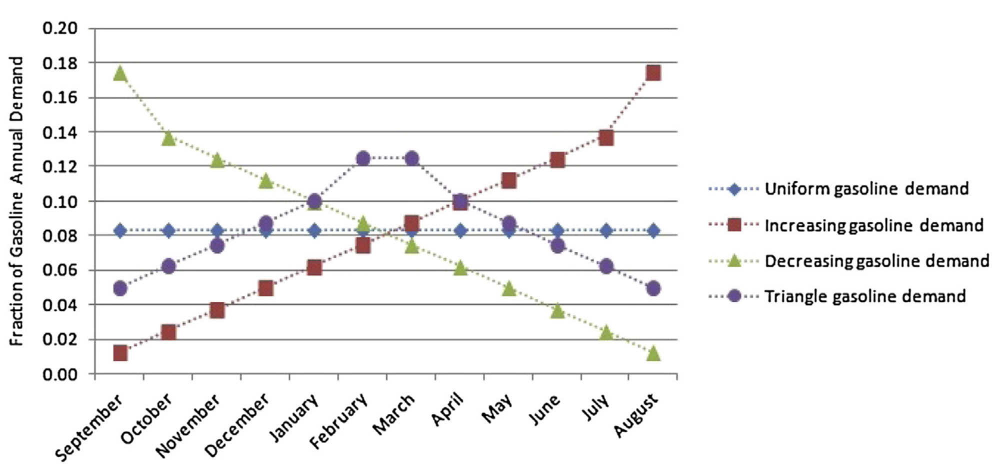

Fig. 11 – The fraction of gasoline annual demand per month.

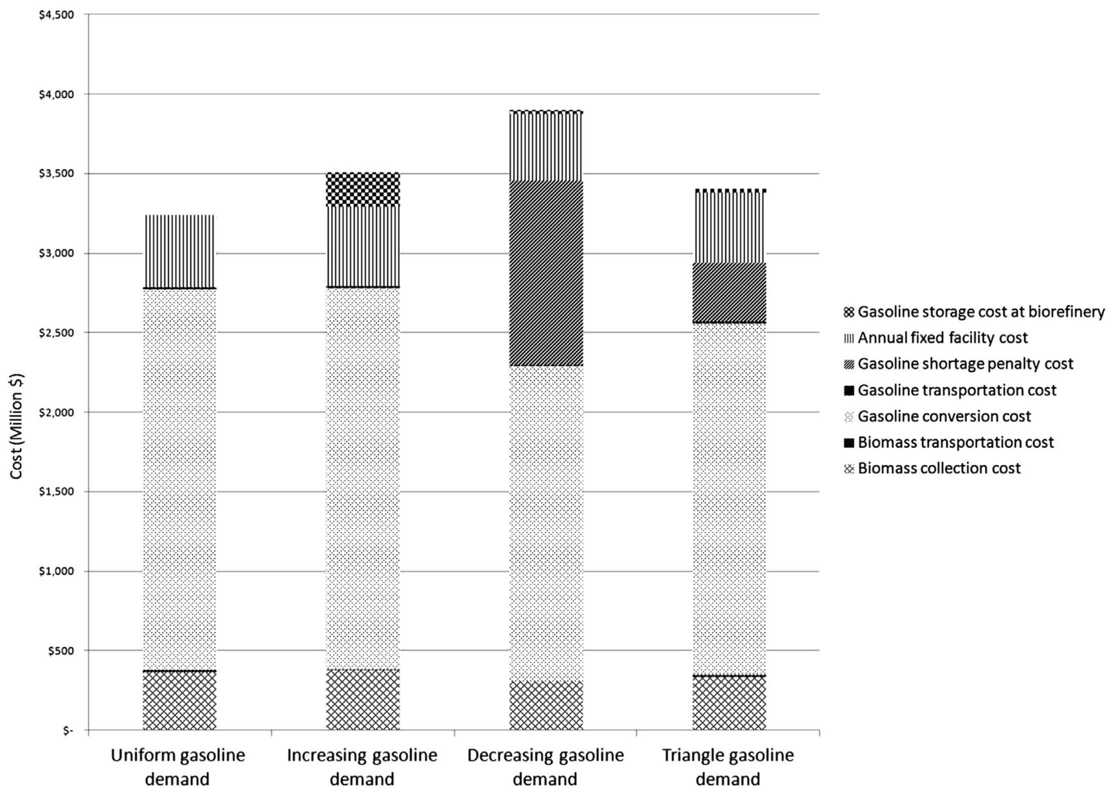

Fig. 12 – Comparison of total annual biogasoline production costs under different biofuel demand patterns.

- For the triangle demand pattern illustrated in Fig. 11, the optimal number of facilities is 21, with 2 facilities built at 1500 td^{-1} and all others built at 2000 td^{-1}. 8 out of 21 MSAs' biofuel demands are not satisfied. The average unit cost of gasoline is 770 $\$m^{-3}$ including biofuel shortage cost, and 740 $\$m^{-3}$ without biofuel shortage cost. Biofuel demands in eight counties are not satisfied during February and March. The cost components are shown in Fig. 12. Biofuel production in all biorefinery facilities follows a non-increasing distribution, and facilities produce extra biofuel in the first two months to satisfy higher biofuel demand in February and March.

4. Conclusion

Technology innovation and improvement in advanced biofuel production has made it possible for commercial production of the second generation biofuel. Supply chain design and operational planning represents one of the major challenges to cellulosic biofuel commercialization. The strategic and operational planning decisions for the biorefinery facilities are essential for the successful deployment of the advanced biofuel industry due to the special properties of biomass handling, transportation, biofuel conversion, distribution and consumption. Quantitative models are necessary to assist the decision making for investors, facility manager as well as government agencies to understand the impact of biofuel supply chain design and operational planning.

In this paper, we formulated two models to optimize the number, capacities and locations of biorefinery facilities. Biomass feedstock collection, transportation and biofuel distribution decisions are also investigated. The first model is an annual model for long term strategic planning. It illustrates the feasibility of biofuel production by presenting the facility locations and biofuel unit production cost. Biomass collection cost, biofuel conversion cost, and facility capital investment cost are the three major components in the cost model. From the case study in Iowa, it is optimal to build 23 facilities and fulfill the demand from all of the MSAs with flexible budget. If budget is limited, then the number of facilities will be constrained by the available capital budget, with more facilities built at the largest size due to the economies of scale. The effect of a biofuel shortage penalty is analyzed. For MSAs with a higher penalty cost, the demand satisfaction represents the trade-off between biofuel shortage penalties and biofuel transportation costs. Therefore, higher shortage penalty and shorter distance from the facility receive higher priority to satisfy the demand.

The second model analyzes detailed operational planning on feedstock and biofuel allocation, and sensitivity of biofuel demand pattern is also investigated. It is observed that the satisfaction of biofuel depends on the demand patterns over the planning horizon. For uniform and increasing demand patterns, all biofuel demand can be satisfied. However, for decreasing and triangle demand patterns, biofuel demands at the highest demand months will not be fulfilled even with increasing number of facilities. Based on this sensitivity analysis, it can be concluded that the commercialization of advanced biofuel is advantageous if the biofuel demand pattern is steady or increasing over the operational horizon.

Assumptions have been made in this study, which suggest the future research directions. One major assumption is that all facilities can be built simultaneously. For future work, a sequential facility sitting problem should be considered in the long term planning model. Parameters are assumed to be deterministic in this study. In the future, uncertainty can be incorporated into the modeling framework. For example, biomass feedstock supply could be uncertain, considering weather conditions, seed quality, soil fertilization, etc. The biofuel demand is estimated based on the population in MSAs. Demand uncertainty could be incorporated to make the model more realistic. The case study in this paper only considered one type of biomass, one pretreatment technology, and one final product category. To better represent the biofuel supply chain, a more comprehensive model with multiple types of biomass, multiple processing technologies and a variety of final products can be analyzed.

REFERENCES

[1] Barton GM. Definition of biomass samples involving wood, bark and foliage. Biomass 1984;4(4):311–4.

[2] Brewer CE, Unger R, Schmidt-Rohr K, Brown RC. Criteria to select biochars for field studies based on biochar chemical properties. Bioenergy Res 2011;4(4):312–23.

[3] Schnepf R, Yacobucci BD. Renewable Fuel Standard (RFS): overview and issues. CRS report for congress; January 2012. p. 31. Report No: R40155.

[4] Wright M, Brown RC. Comparative economics of biorefineries based on the biochemical and thermochemical platforms. Biofuel Bioprod Bioresour 2007;1(1):49–56.

[5] Babu BV. Biomass pyrolysis: a state-of-the-art review. Biofuel Bioprod Bioresour 2008;2(5):393–414.

[6] Fahmi R, Bridgwater AV, Donnison I, Yates N, Jones JM. The effect of lignin and inorganic species in biomass on pyrolysis oil yields, quality and stability. Fuel June 2008;87(7):1230–40.

[7] Balat M, Balat M, Kirtay E, Balat H. Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 1: pyrolysis systems. Energy Convers Manage 2009;50(12):3147–57.

[8] Brown RC, Stevens C. Thermochemical processing of biomass: conversion into fuels, chemicals and power. John Wiley and Sons Ltd: Wiley Series In Renewable Resource; 2011. p. 124–231. Ch. 5–7.

[9] Ileleji KE, Sokhansanj S, Cundiff JS. In: Blaschek HP, Ezeji TC, Scheffran J, editors. Farm-gate to plant-gate delivery of lignocellulosic feedstocks from plant biomass for biofuel production. Wiley-Blackwell; 2010. p. 117–59. Ch. 7.

[10] Sokhansanj S, Turhollow A, Cushman J, Cundiff J. Engineering aspects of collecting corn stover for bioenergy. Biomass Bioenergy 2002;23(5):347–55.

[11] Milhollin R, Hoehne J, Horner J, Weber S. Feasbility of corn stover in Missouri. University of Missouri: Missouri Stover Products Commercial Agriculture Program; January 2011. p. 86 [Technical Report].

[12] Ravula PP, Grisso RD, Cundiff JS. Comparison between two policy strategies for scheduling trucks in a biomass logistic system. Bioresour Technol 2008;99(13):5710–21.

[13] Demirbas MF. Biorefineries for biofuel upgrading: a critical review. Appl Energy 2009;86(Issue Suppl. 1):S151–61.

[14] Wang C. Economic analysis of delivering switchgrass to a biorefinery from both the farmers' and processor's perspectives [Graduate thesis and dissertation (M.S.)]. Knoxville: University of Tennessee; 2009 [cited Oct. 2012] Available from:, http://etd.utk.edu/2009/May2009Theses/WangChenguang.pdf.

[15] Tsiakis P, Papageorgiou LG. Optimal production allocation and distribution supply chain networks. Int J Prod Econ 2008;111(2):468–83.

[16] Bai Y, Hwang T, Kang S, Ouyang Y. Biofuel refinery location and supply chain planning under traffic congestion. Transport Res B: Meth 2011;45(1):162–75.

[17] Dal-Mas M, Giarola S, Zamboni A, Bezzo F. Strategic design and investment capacity planning of the ethanol supply chain under price uncertainty. Biomass Bioenergy 2011;35(5):2059–71.

[18] Gebreslassie BH, Yao Y, You F. Design under uncertainty of hydrocarbon biorefinery supply chains: multiobjective stochastic Programming models, decomposition algorithm, and a comparison between CVaR and downside risk. AIChE J 2012;58(7):2155–79.

[19] Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al. Lignocellulosic biomass to ethanol process design and economic utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Golden (CO): National Renewable Energy Laboratory; June 2002. p. 154. Report No: TP-510-32438.

[20] Phillips S, Eggeman TJ. Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. Golden (CO): National Renewable Energy Laboratory; 2007. Report No: TP-510–41168.

[21] Hess JR, Kenney K, Laney P, Muth D, Prygofle P, Radtke C, et al. Feasibility of a producer owned ground-straw feedstock supply system for bioethanol and other products, grant 4-D farms duane grant. Straw Value Add Committee and Idaho National Laboratory; 2006. Report No: INL/EXT-06–12000.

[22] Eksioglu SD, Li S, Zhang S, Sokhansanj S, Petrolia D. Analyzing impact of intermodal facilities on design and management of biofuel supply chain. Transport Res Rec: J Transport Res Board 2010;2191(1):144–51.

[23] Wright M. Techno-economic, location, and carbon emission analysis of thermochemical biomass to transportation fuels [Graduate thesis and dissertations]. Iowa State University; 2010 [cited Oct. 2012] Available from:, http://lib.dr.iastate.edu/etd/11727.

[24] Bowling IM, Ponce-Ortega JM, El-Halwagi MM. Facility location and supply chain optimization for a biorefinery. Ind Eng Chem Res 2011;50(10):6276–86.

[25] Horner J, Milhollin R. Marketing study for corn stover in Missouri. Missouri Stover Products Commercial Agriculture Program. University of Missouri; August 2011. p. 39 [Technical Report].

[26] Zhu X, Li X, Yao Q, Chen Y. Challenges and models in supporting logistics system design for dedicated-biomass-based bioenergy industry. Bioresour Technol 2010;102(2):1344–51.

[27] Zhu X, Yao Q. Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. Bioresour Technol 2011;102(23):10936–45.

[28] USDA, U.S. Department of Agriculture. Iowa agricultural statistics bulletin. National Agricultural Statistics Service; 2012 [cited Oct. 2012] Crops and Plants, Crops, Field Crops, Corn. Available from: http://www.nass.usda.gov/ [Files updated Annually].

[29] Jones SB, Holladay JE, Valkenburg C, Stevens DJ, Walton CW, Kinchin C, et al. Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case. Pacific Northwestern National Laboratory: U.S.

Department of Energy (DOE); February 2009. p. 76. Report No: PNNL-18284.

[30] US Census. US census bureau delivers Iowa's 2010 census population totals, including first look at race and hispanic origin data for legislative redistricting. U.S. Census; Febuary 2011. Report No: CB11–CN24.

[31] USDA, United States Department of Agriculture. Crop production 2011 summary. USDA, National Agriculture Statistics Service; January 2012. p. 95. ISSN: 1057-7823.

[32] Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL. Current and potential US corn stover supplies. Agron J 2007;99(1):1–11.

[33] Petrolia D. The economics of harvesting and transporting corn stover for conversion to fuel ethanol: a case study for Minnesota. Biomass Bioenergy 2008;32(7):603–12.

[34] Rogers JG, Brammer JG. Analysis of transport costs for energy crops for use in biomass pyrolysis plant networks. Biomass Bioenergy 2009;33(10):1367–75.

[35] Searcy E, Flynn P, Ghafoori E, Kumar A. The relative cost of biomass energy transport. Appl Biochem Biotech April 2007;137–140(1–12):639–52.

[36] Wright M, Brown RC. Establishing the optimal sizes of different kinds of biorefineries. Biofuel Bioprod Bior 2007;1(3):191–207.

[37] EIA, U.S. Energy Information Administration. Annual energy review 2011. Washington DC: United States: Energy Information Administration, Department of Energy; September 2012. p. 390. Report No: DOE/EIA-0384(2011).

[38] RITA, Research and Innovative Technology Administration. National transportation statistics [database on the Internet]. Washington DC: United States: Department of Transportation, Research and Innovative Technology Administration; 2012 [cited 2013 Jul 23] Publications, RITA, Bureau of Transportation Statistics, National Transportation Statistics. Table 3-21-Average Freight revenue per Ton-Mile (updated April 2012). Available from: http://www.rita.dot.gov/bts/ [Files updated Annually].