A Sequential Fast Pyrolysis Facility Location-Allocation Model

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Abstract. The revised Renewable Fuel Standard (RFS2) mandates the U.S. consume16 billion gallons per year (BGY) of biofuels from cellulosic sources by the year 2022. Fast Pyrolysis of biomass is a renewable conversion process developed for producing liquid transportation fuels, such as gasoline and diesel. The pathway investigated in this study is fast pyrolysis and hydroprocessing to produce transportation fuels from corn stover. A mathematical model is formulated to study the supply chain design problem. The objective is to optimize an orderly fast pyrolysis facility locations and capacities that maximize the net present value (NPV) of the total profit for the next 10 years (2013-2022). Numerical examples for Iowa are also presented.

Keywords: cellulosic biofuels, fast pyrolysis, sequential location

1 Introduction

Biofuels has been recognized as important sources of renewable energy for their potential benefit on the environment, rural development, and reducing dependency on petroleum import. With the stimulation of enactment of Renewable Fuel Standard (RFS2) (1) in 2007, cellulosic based biofuels are gaining more attention. Biofuel industry can help improve the rural economics and job creation. Cellulosic biofuel production technologies are still mainly on the experimenting stage (2, 3). Studies on biomass logistics and biofuel supply chain management are also emerging. Stephen et al. show technology selection strategy based on biomass moisture content, energy density and load capacity of different transportation mode (4). Kocoloski et al. develop a mathematical model to optimize facility placement, and examine the impact of location and sizing selection (5). Ekşioğlu et al. propose a mixed integer programming model to design supply chain and manage logistics con-

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sidering biomass transportation, inventory and process ability (6). And intermodal transportation is taken into consideration in the following work (7). In this paper, a sequential location allocation model for the fast pyrolysis facilities is investigated. Formulations are presented in Section 2, and case study based on Iowa is included in Section 3. Paper concludes in Section 4 with major findings and future research directions.

2 Methodology

2.1 Problem description

This study considers lignocellulosic biomass as the feedstock for fast pyrolysis facility to produce bio-oil, and the bio-oil will be used as feedstock of biorefinery, where it is converted to liquid transportation fuels. **Fig. 1** illustrates the supply network setting.

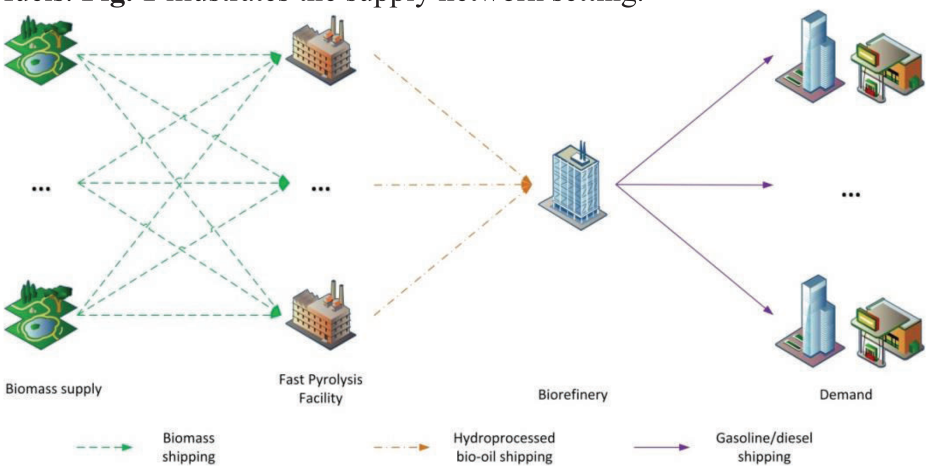

Fig. 1. Supply chain structure for cellulosic biomass pyrolysis – hydroprocessing –refining process

Major assumptions used in modeling are listed as follows:

1. Facility construction time is one-year and the facility life is 20-year.
2. A biorefinery with enough capacity exists in Iowa, and the location of the biorefinery is the county centroid that minimizes the total annual cost if all facilities are at optimal locations and capacities.

3. The facility location and material (feed and products) allocation decisions are made to maximize total profit of all facilities as a system.
4. The requirement for Iowa biofuel consumption in transportation increase linearly from 2013 to 2022, with demand in 2013 set at 0, and in 2022 set as the total gasoline demand within Iowa.
5. Fast pyrolysis and hydroprocessing for the cellulosic biomass are performed at distributed fast pyrolysis facility, while the hydroprocessed bio-oil are refining to gasoline/diesel range fuels in a centralized biorefinery.
6. Annual budget is set for construction of the distributed fast pyrolysis facilities.

2.2 Model formulation

Notations:

i	Index for biomass supply locations
j	Index for candidate fast pyrolysis facility locations
k	Index for gasoline demand locations
l	Index for fast pyrolysis facility capacity level
t	Index for time period (decision making time)
GP_t	Projected gasoline price (8)
BCC_i	Unit biomass collecting cost (9)
BSC_{ij}	Unit biomass shipping cost (10, 11), $BSC_{ij} = FSC + VSC \times D_{ij}$, which is a combination of fixed shipping cost and variable shipping cost (related to shipping distance)
HSC_j	Unit hydroprocessed bio-oil shipping cost (11, 12)
GSC_k	Unit gasoline shipping cost (12)
FOC_l	Fixed facility operating cost (3)
GCC	Gasoline conversion cost, derived from variable facility operating cost, related to facility operating level (proportional to gasoline production amount) (3)
FFC_l	Fast pyrolysis facility capital cost, using scaling factor of 0.6 (3)
AFC_l	Amortized fast pyrolysis facility capital cost, derived from facility capital cost, with facility life of 20-year (3)
SPP_{it}	Maximum biomass supply amount, total corn stover available amount (13, 14) times maximum removal proportion (15)
$loss$	Biomass loss during transportation, assumed to be 5 wt%
θ_1	Conversion ratio from cellulosic biomass to hydroprocessed bio-oil (3)

θ_2	Conversion ratio from hydroprocessed bio-oil to gasoline diesel fuel (3)
$\overline{Dmn_k}$	Total gasoline demand level (16)
Dmn_t	Gasoline demand, $Dmn_{kt} = \sum_k \overline{Dmn_k} \times pr_t$, pr_t is the mandate proportion of total demand to be satisfied during the t^{th} year
F_t	Fund raised from government or company
r	Annual interest rate, assumed to be 10%
x_{ijt}	Cellulosic biomass shipping amount (decision variable)
y_{jt}	Hydroprocessed bio-oil shipping amount (decision variable)
z_{kt}	Gasoline shipping amount (decision variable)
A_t	Total available fund (decision variable)
δ_{jlt}	Indicator of fast pyrolysis facility construction state (decision variable)

Mixed integer linear programming method is used to formulate the sequential location and allocation problem. The objective is to maximize the net present value (NPV) of the total profit of the next 10 years (2013-2022). Total profit calculation considers revenue from selling products, feedstock costs (collecting and shipping costs), intermediate product (hydroprocessed bio-oil) shipping costs, final products shipping costs, facility capital cost, and operating costs (reflected by fixed operating costs and conversion cost).
Objective function is presented below:

$$\max \sum_{t=1}^{T} (1+r)^{-t} \Big(\sum_{k=1}^{K} z_{kt} (GP_t - GCC) - \sum_{i=1}^{N} \sum_{j=1}^{M} \big(BSC_{ij} + BCC_i\big) x_{ijt} - \sum_{j=1}^{M} HSC_j y_{jt} - \sum_{k=1}^{K} GSC_k z_{kt} - \sum_{j=1}^{M} \sum_{l=1}^{L} FOC_l \delta_{jlt} \Big) - \sum_{t=1}^{T} (1+r)^{-t} \sum_{j=1}^{M} \sum_{l=1}^{L} AFC_l \delta_{jlt} \quad (1)$$

Major constraints include: biomass supply availability due to total grown amount and sustainability factor (2), biofuel conversion balance with conversion ratios from pathway techno-economic analysis (3,6), fast pyrolysis facility existence and capacity limit (4), a maximum of one facility per candidate facility construction location (5), no destruction of facility (9), minimum demand requirement and demand upper bound with linearly increase demand each year (7,8), limited available construction budget (10-12), and initialization of current situation of fast pyrolysis facility, which is none of such facilities exist at current stage (13).

$$\sum_{j=1}^{M} x_{ijt} \leq Spp_{it}, \ \forall i, t \tag{2}$$

$$y_{jt} = (1 - loss)\theta_1 \sum_{i=1}^{N} x_{ijt}\ , \ \forall j, t \tag{3}$$

$$(1 - loss) \sum_{i=1}^{N} x_{ijt} \leq \sum_{l=1}^{L} \delta_{jlt} C_l\ , \ \forall j, t \tag{4}$$

$$\sum_{l=1}^{L} \delta_{jlt} \leq 1, \ \forall j, t \tag{5}$$

$$\theta_2 \sum_{j=1}^{M} y_{jt} = \sum_{k=1}^{K} z_{kt}, \quad \forall t \tag{6}$$

$$\sum_{k=1}^{K} z_{kt} \geq \sum_{k=1}^{K} Dmn_{kt}, \quad \forall t \tag{7}$$

$$\overline{Dmn_{kt}} \geq z_{kt}, \quad \forall k, t \tag{8}$$

$$\delta_{j,l,t} \geq \delta_{j,l,t-1}, \qquad \forall j, l, t \geq 2 \tag{9}$$

$$\sum_{j=1}^{M} \sum_{l=1}^{L} FFC_l \delta_{j,l,2} \leq F_1 \tag{10}$$

$$\sum_{j=1}^{M} \sum_{l=1}^{L} FFC_l \left(\delta_{j,l,t+1} - \delta_{j,l,t}\right) \leq A_{t-1}(1 + r) + F_t, \tag{11}$$

$$\forall T - 1 \geq t \geq 2$$

$$A_t = A_{t-1}(1 + r) + F_t - \sum_{j=1}^{M} \sum_{l=1}^{L} FFC_l \left(\delta_{j,l,t+1} - \delta_{j,l,t}\right), \tag{12}$$

$$\forall T - 1 \geq t \geq 2$$

$$\delta_{j,l,1} = 0, \qquad \forall j, l \tag{13}$$

$$x_{ijt}, y_{jt}, z_{kt} \geq 0, \delta_{jlt} \in \{0,1\}, \ \forall i, j, k, l, t \tag{14}$$

3 Results and discussion

In this section, the results of a case study in Iowa are illustrated. Candidate fast pyrolysis facility locations are the county centroids in Iowa, and four facility capacities are allowed: 400, 1000, 1500, and 2000 metric ton of dry basis biomass per day, respectively.

To satisfy the minimum demand requirement, available fund per year needs to be at least enough to construct two 2000 metric ton/day facilities. The results under this minimum budget scenario are shown in **Fig. 2**. The county that is assumed to locate the existing biorefinery is represented using cross-shaded lines. Stars represent the fuel demand locations (centroids of MSAs), and star sizes illustrate the magnitude of fuel demand from the MSAs. From the results, all facilities built are of the highest allowed capacity, and in the figure, different color circles are used to represent the difference in construction order. The labeled year is the first year the corresponding facility starts to operate (construction finished). Facility locations are listed in legend, using FIPS codes of facility-located counties. The optimal NPV in the scenario is $5.28 billion.

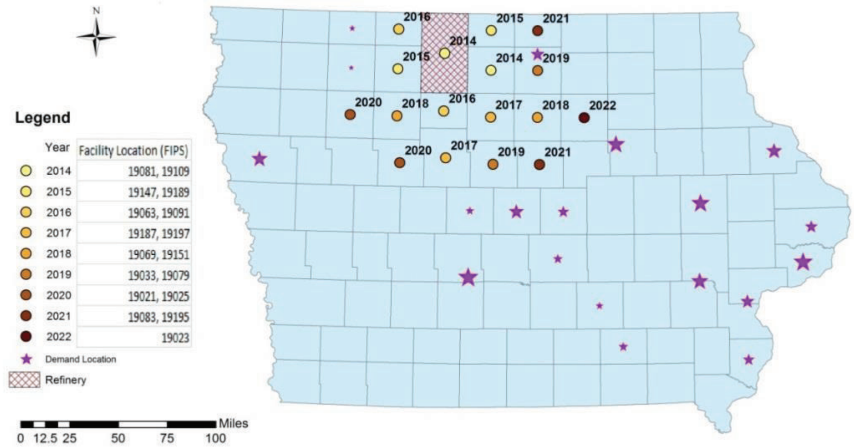

Fig. 2. Sequential facility construction under annual fund of twice the capital cost of 2000 metric ton/day facility

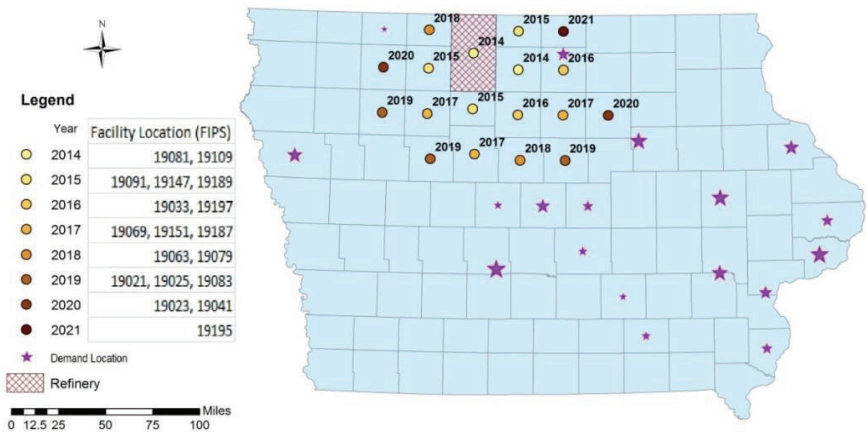

Fig. 3. Sequential facility construction under annual fund of 2.5 times capital cost of 2000 metric ton/day facility

If annual available fund increases to 2.5 times capital cost of 2000 metric ton/day facility, the results are shown in **Fig. 3**. It could be seen in the figure, that with more available fund, it takes fewer years to finish constructing all facilities needed for the demand goal in 2022. The optimal NPV in the scenario is $6.03 billion.

Comparing the results under different budget limitations, several observations are summarized as follows:

- All facilities are built with the highest allowed capacity level. This is due to the scaling factor in capital cost estimation, which makes larger capacity facilities more cost-effective.
- Facility locations are very much affected by the centralized biorefinery location. From the yearly allocation results, most biomass supply could be satisfied within the facility-located county; therefore, hydroprocessed bio-oil shipping costs become a major concern in facility location decisions. To minimize the transportation costs, locating fast pyrolysis facilities close to biorefinery is the optimal option.
- With the increase in annual available fund, the overall sequence of fast pyrolysis facility construction does not change much. It's noticed that with higher available fund, facilities tend to build earlier to achieve a higher NPV.

4 Conclusion

Biofuels have become increasingly attractive to replace petroleum fuels. In this study, the pathway of fast pyrolysis, hydroprocessing and refining is considered to produce gasoline-diesel ranged fuels from cellulosic biomass. Mixed integer linear programming models are formulated to investigate the supply network design and the sequence of the facility construction. The objective is to maximize the NPV of the total profit till 2022, which is the target year of RFS2. A case study in Iowa is conducted to illustrate the modeling approach. Numerical results show the preference for high capacity facilities, facility locations that are close to existing biorefinery, and earlier construction time as long as the budget allows. It is also concluded that the increase in annual available fund level does not have much impact on the construction sequence.

It should be noted that this sequential facility location problem is an ongoing research work that can be further investigated. Better data or modeling information, including the annual requirement of bio-based fuels, annual budget, and uncertainties in the feedstock availability and logistic cost, are to be investigated for more realistic decision making. In addition, facility capacity expansion could also be taken into consideration in the modeling framework.

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