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Production cost and supply chain design for advanced biofuels

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Production cost and supply chain design for advanced biofuels

by

Yihua Li

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MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
Guiping Hu, Major Professor
Sarah M. Ryan
Mark Mba-Wright

Iowa State University
Ames, Iowa
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DEDICATION

I would love to dedicate this thesis to my beloved mom and dad.

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ACKNOWLEDGEMENTS

I would like to take this opportunity to express my thanks to many people who made this thesis possible.

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ABSTRACT

The U.S. government encourages the development of biofuel industry through policy and financial support since 1978. Though first generation biofuels (mainly bio-based ethanol) expand rapidly between the early 1980s and late 2000s, more attention has turned to second generation biofuels, such as cellulosic biofuels, due to the ‘food-versus-fuel’ debate, and potential impact on land use and climate change caused by the development of first generation biofuel production.

Over the last few years, a rich literature has arisen on lignocellulosic crops or crop residues being used as biomass feedstock for second generation biorefineries. In this thesis, two types of assessments on cellulosic biofuel production have been conducted: techno-economic analysis of the fast pyrolysis fractionation pathway and supply chain design for the advanced biofuel production.

Firstly, the economic feasibility of a fast pyrolysis fractionation facility is examined. The facility takes lignocellulosic biomass feedstock, goes through the pyrolysis process, recovers pyrolysis oil into different fractions, and upgrades the fractions into two main products: commodity chemicals and liquid transportation fuels. The Internal Rate of Return (IRR) of this production pathway is evaluated to be 8.78%.

Secondly, mixed integer linear programming models are used to optimize locations and capacities of distributed fast pyrolysis facilities. The supply chain optimization framework is implemented in a case study of Iowa with the goal of minimizing total annual production cost. Comparisons are carried out to investigate the two choices for the centralized refining facility: outsourced to Louisiana or build a refining facility in Iowa. An extension of the supply chain design model to sequential facility location-allocation analysis is also performed for Iowa, taking budget availability and revised Renewable Fuel Standard (RFS2) goal into consideration. The objective is to maximize the net present value (NPV) of the profits over the next 10 years.

CHAPTER 1 GENERAL INTRODUCTION

Petroleum is the primary source for a wide range of products, such as gasoline, diesel fuel, commodity chemicals, etc. Petroleum products are important primary energy sources, mainly due to their high energy density and easy transportability[1]. In the U.S., the majority of petroleum is used for transportation, and the rest for industry, residential and commercial uses [2]. However, the International Energy Agency (IEA) estimated that conventional crude oil production has peaked and will decline continuously over the next quarter century [3]. Non-renewable petroleum resources decrease, while the demands of transportation fuels increase due to growing economies. Besides the energy security issue, there are environmental consequences with prevailing usage of the petroleum energy, including air pollution, global warming, and impacts from oil spills [4].

The Renewable Fuel Standard (RFS) program was created under the Energy Policy Act of 2005, and established the first renewable fuel volume mandate in the U.S. In 2007, the U.S. government enacted the revised version of RFS (RFS2) [5], in which a target of 36 billion gallons per year (BGY) of biofuels in domestic transportation fuel consumption is set up. Of this volume, 16 BGY must come from cellulosic biofuels. The mandates in RFS2 lead to the emergence of biofuel economy, and prompt consideration from a variety of societal sectors.

A biofuel is any type of liquid or gaseous fuel that can be produced from biomass substrates and that can be used as a (partial) substitute for fossil fuels [6]. Different types of biofuels are used in the U.S., including E10, E85, biodiesel, biobutanol, etc. Biofuels are often viewed as renewable, cleaner fuels with societal benefits on rural development and job creation. While biofuels have been recognized as potential sustainable fuel sources, a number of issues have arisen and would impact the assessment of the production pathways: (a) Substitutability issues: biodiesel and ethanol have inherent limitations due to their reliance on fossil fuel blending, while biobutanol is a liquid alcohol fuel that can be used in today's gasoline-powered internal combustion engines [7], and bio-based hydrocarbon fuels can also be used in existing engines [8]. (b) Infrastructure issues: Yacobucci et al. [9] concluded that investment in new infrastructure would be necessary for ethanol-blended gasoline beyond certain levels. Drop-in biofuels show the benefits of utilizing existing infrastructure for petroleum fuels, such as pumps and pipelines [8]. (c) Emission issues: analysis of carbon requirements [10] and total fuel-cycle emissions [11] show that most biofuels are more environmental friendly than conventional fossil fuels. However, detailed lifecycle assessment has to been conducted on individual production pathway to ensure the environmental impact. (d) Land issues: land availability, indirect land use changes, fertility of land resources, and deforestation issues have significant impact on the outlook of biofuels in global fuel supplies [12]. Previous studies [6, 13] have shown that not enough arable land is available for biomass feedstock supply, which leads to land conversion and deforestation, which might cause elimination in some environmental benefits.

With the development of biofuels industry, rich literature has dealt with biomass logistics analysis, supply chain design and operational planning for biofuel production. Sokhansanj et al. [14] provided an integrated biomass supply analysis and logistics (IBSAL) model for simulating collection, storage and transport operations of biomass supply, and a numerical example of corn stover collection and transportation in bales was analyzed. Kumar et al. [15] employed IBSAL model to switchgrass delivery analysis. Ekşioğlu et al. [16] proposed a multi-period MIP to design the network and material flows of biomass-to-biorefinery supply chain and later extended the model with consideration of different transportation modes [17]. Cundiff et al. [18] analyzed harvest, storage and transportation of herbaceous biomass to conversion plants, and developed a stochastic linear programming approach for modeling under production uncertainty due to weather conditions.

Despite of the increasing interests in research institutes, national labs and start-up companies, cellulosic biomass to liquid fuel technologies are yet to be commercialized at larger scale. To investigate the production cost of cellulosic based drop-in fuels, the economic feasibility of a biofuel facility with multiple products is conducted in the thesis. Logistic decisions are essential in supply chain network design. Mathematical models to assist decision making of facility locations and capacities are discussed considering the spatially distributed feedstock supplies and customers’ demands. The rest of the thesis is organized as follows:

In Chapter 2, we present the techno-economic analysis of fast pyrolysis fractionation pathway, with woody biomass as feedstock, liquid fuels and chemicals as the final products. The techno-economic analysis utilizes the experiment design for the chemical processes, simulates the production process at commercial scale, estimates the capital investment and annual operating costs, and finally evaluates the economic profitability of the production at commercial scale. The results and process design information derived from the techno-economic analysis are important data sources in the biofuel supply chain design and operational planning analysis.

In Chapter 3, facility location and capacity decision models are formulated to study the optimal siting and sizing of the distributed fast pyrolysis facilities. Two scenarios are considered for the centralized upgrading refinery, one using existing petroleum refinery and the other using newly constructed biorefinery at the optimal location provided by the model. The comparison of the two scenarios shows the economic feasibility for a new centralized biorefinery construction.

An extension of facility decision making is to investigate the optimal sequence of facility construction with the consideration of budget limitation and demand pattern. In Chapter 4, a preliminary sequential location and allocation model is proposed, and case study results are also illustrated.

Chapter 5 concludes the thesis with the summary and conclusions. Future research directions are also discussed in the Chapter 5.

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CHAPTER 2 TECHNO-ECONOMIC ANALYSIS OF BIOCHEMICAL AND LIQUID FUELS PRODUCTION VIA FAST PYROLYSIS FRACTIONATION

Modified from a paper to be submitted to *Bioresource Technology*

Yihua Li[1], Chamila Thilakaratne[2], Tristan Brown[3], Guiping Hu[4], Robert Brown[5]

Abstract

This techno-economic study evaluates the economic feasibility of producing commodity chemicals and liquid fuels with a fast pyrolysis fractionation facility. In the process, conventional pyrolysis oil converting from woody biomass is recovered into a series of stage fractions (SFs) with distinctive physical and chemical properties. The SFs are then assigned to different upgrading processes with different products: catalytic hydroprocessing of heavy ends to produce gasoline and diesel range fuels, while two stage hydrotreating combined with fluid catalytic cracking (FCC) of aqueous phase to produce commodity chemicals.

Internal rate of return (IRR) is calculated for the pathway, considering the capital investment, annual operational costs and projected revenues for the facility. Under a baseline condition, the facility IRR is estimated to be 8.78%, which is influenced mainly by changes in major products prices and yields, total capital cost and feedstock cost.

1. Introduction

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Biofuels are clean and renewable, and they are receiving much attention all over the world for the increasing energy demand and environmental concerns. The Renewable Fuel Standard (RFS) [1] is brought out by the U.S. federal to require a minimum volume of renewable fuels contained in transportation fuel consumed in the U.S. The revised RFS (RFS2) [1, 2] in 2007 requires the renewable fuels to be blended into transportation fuel reach 36 billion gallons per year (BGY) by 2022. Of the 36 BGY, conventional biofuel is restricted to 15 BGY, while cellulosic biofuel has the minimum requirement of 16 BGY. Under RFS2, cellulosic biofuel technologies have gained increasing attention. Hydrocarbon biorefinery converts cellulosic biomass (including crop residues, woody biomass, dedicated energy crops etc.) to liquid drop-in fuels. Compare to conventional ethanol, drop-in fuels have better engine and infrastructure compatibility. Drop-in fuels could be used directly in gasoline- or diesel-powered vehicles, and do not require substantial changes in refining or distribution infrastructure of traditional fossil fuels [3]. And drop-in fuels also have the following advantages comparing to petroleum based transportation fuels [4]:

- Increased Energy Security: drop-in fuels can be produced domestically from a variety of feedstock and contribute to the rural economic development and additional job opportunities.
- Fewer Emissions: carbon dioxide captured by growing biomass reduces overall greenhouse gas emissions by balancing carbon dioxide released from burning drop-in fuels.

- More flexibility: drop-in fuels are replacements for diesel, jet fuel and gasoline allowing for multiple products from various types of feedstock and production technologies.

Despite of the advantages of cellulosic based drop-in fuels, the production pathways are not commercialized at significant scale yet. The main obstacle for commercialization is the high production cost, especially the capital investment, which is the motivation for this study.

Pyrolysis oil can be used for a range of applications [5], including combustion of pyrolysis oil in boilers for heat [6], the use of pyrolysis oil in diesel engines and gas turbines for power production [7-10], upgrading of pyrolysis oil to automotive fuels [11-13] or hydrogen [14], processes to extract high-value chemicals from pyrolysis oil [15-17], etc. In this study, fast pyrolysis is performed on pre-processed biomass. The pyrolysis oils are then recovered into different fractions and produce commodity chemicals and transportation fuels.

Elliott et al. [12] proposed that catalytic hydroprocessing could be applied to fast pyrolysis liquid product (bio-oil), and the processed bio-oil could be used as feedstock of a petroleum refinery. Low temperature hydrotreating and high temperature hydrocracking were investigated on different kinds of biomass (mixed wood, mixed wood heavy phase, corn stover, oak, poplar, etc.). Brief process results of different biomass are provided, while more detailed component group percentage data are also given for mixed wood bio-oil hydroprocessing.

Vispute et al. [16] explored process for bio-oil deoxygenation into high-yield commodity chemicals using a combined approach of hydrotreating and fluid catalytic cracking (FCC). Five scenarios are analyzed in this paper, a) FCC of crude bio-oil (BO); b) one stage hydrotreating and FCC of BO; c) FCC of water soluble fraction of a pinewood bio-oil (WSBO); d) one stage hydrotreating and FCC of WSBO; e) two stage hydrotreating and FCC of WSBO. It is concluded that an integrated approach of hydrotreating and FCC could finally convert the feedstock into aromatics and olefins, and is more economically attractive.

Pollard et al. [18] pointed out that bio-oil contains compounds that have wide range of boiling points, including volatile organic compounds, water, and non-volatile compounds (i.e. sugars and lignin oligomers). And in Pollard's paper, they developed a recovery system into distinctive stage fractions. Fractionation is achieved with coolants operate at carefully controlled temperature and capture compounds in each stage fraction (SF) selectively. The first and second fractions were collected with similar properties and composition. These fractions were high in levoglucosan and water insoluble content, and low in water and acid. The third and fourth fractions were high in phenolic compounds and acetic acid, and relatively low moisture. The final fraction contained large amounts of water and acetic acid. Fractionated bio-oil is improved in heating value for low water and acid content.

In this study, we use a series of condensers and electrostatic precipitators (ESPs) to recover fast pyrolysis bio-oil into six stage fractions. The temperatures of all equipment in fractionation section are carefully controlled to capture compounds with distinct physical and chemical properties. SF1-4 are treated as the heavy ends, treated with catalytic hydroprocessing to produce feedstock for refinery. SF5-6 are treated as the aqueous phase, treated with two-stage hydrotreating and FCC to produce commodity chemicals. Process design and economic analysis, including capital costs and operating costs estimation, are discussed in the paper.

2. Process Design

2.1 Process description

The fast pyrolysis converts woody biomass to pyrolysis bio-oil. Fractionation section recover bio-oil into 6 different stage fractions using physical and chemical properties difference of various compounds. In this study, we assume sugar mainly exists in the first 2 stage fractions. Extract sugar from the first 2 stage fractions, mix up the remainders with SF3-4, this part is treated as the heavy phase. Catalytic hydroprocessing is utilized to convert the heavy ends to upgraded bio-oil that could be used for refinery feedstock. Phase separations are performed after low temperature hydrotreating and high temperature hydrocracking. The aqueous yield produced during catalytic hydroprocessing of the first 4 stages is mixed with the SF5-6, which are treated as the aqueous phase. The aqueous phase is processed using one stage of low temperature hydrotreating, one stage of high temperature hydrotreating, and FCC with zeolite as catalyst. Main products of the aqueous phase are olefins and aromatics. The process flow diagram is shown in Figure 2.1.

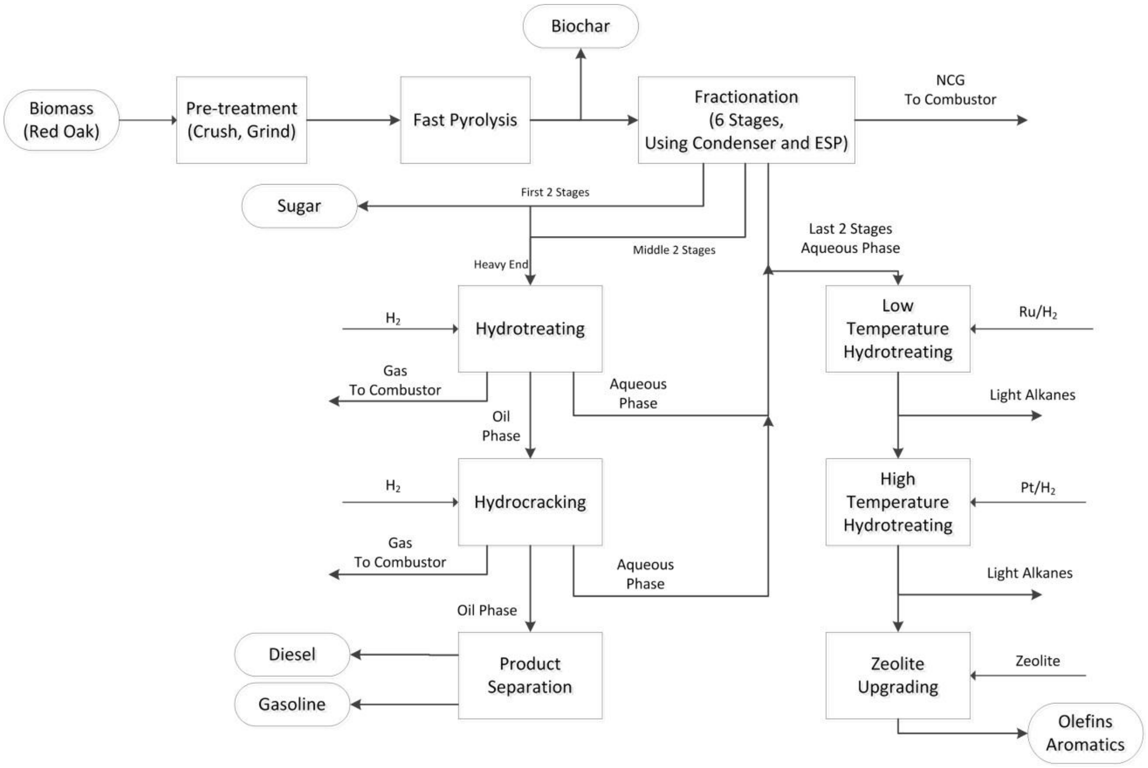

Figure 2.1 *Process flow diagram for fast pyrolysis fractionation*

2.2 Data sources and major assumptions

Figure 2.2 includes detailed schematic of the fast pyrolysis fractionation process. In this section, process description, main data sources, and major assumptions used in data processing of different areas of the conversion process are introduced, including.

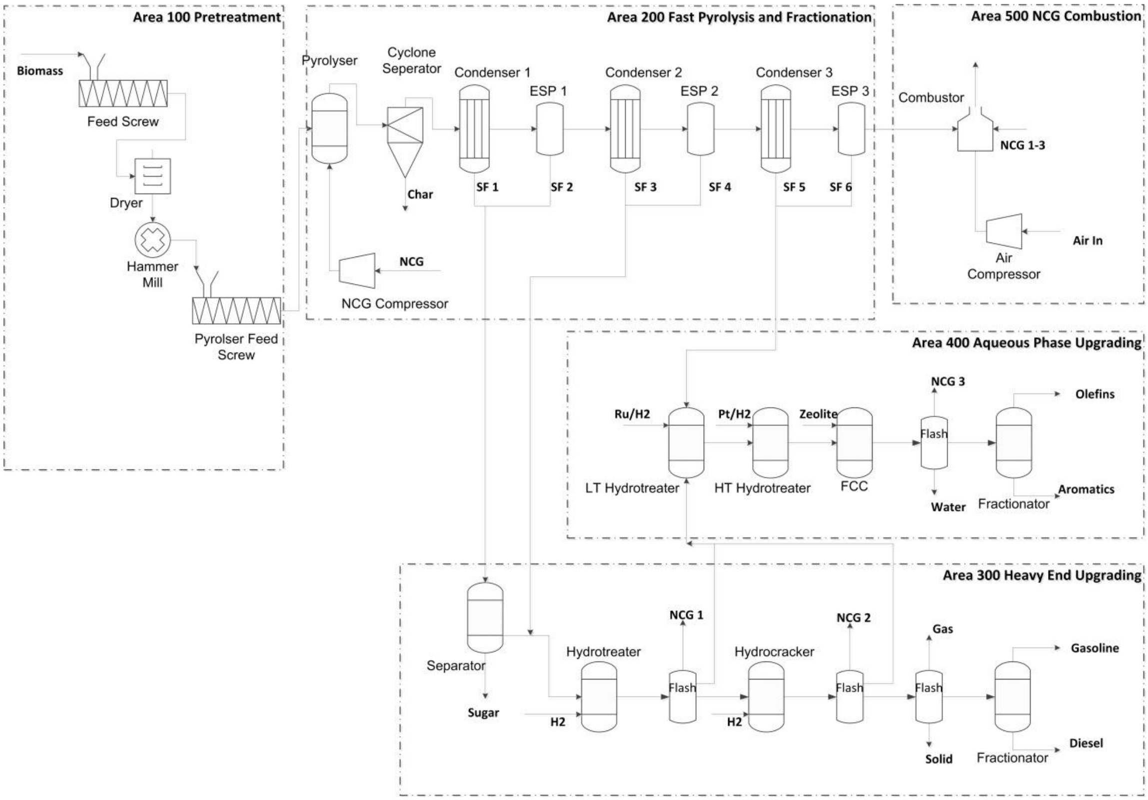

Figure 2.2 *Schematics of fast pyrolysis with upgrading*

a) Pretreatment

Woody biomass (red oak) is used as feedstock in the process. During preprocessing, woody biomass is first dried to less than 10% moisture content, and then grinded to particles of 3mm in diameter. The pyrolysis reactor is a fluidized bed reactor operating at approximately 500 ℃. The solid particles such as ash and char are removed using high efficiency cyclone separators, which collect 95% of solid particles from the stream.

b) Fast pyrolysis and fractionation

In the pyrolysis oil recovery part, the temperatures are based on the design report for the fast pyrolysis fractionation process [19], shown in Figure 2.3. Different compounds are captured as follows: **SF1**, levoglucosan and other compounds with high dew points; **SF2**, aerosols produced in the pyrolysis reactor or stage 1; **SF3**, compounds with dew points close to that of phenol; **SF4**, aerosols left from stage 2 or produced in stage 3; **SF5**, water and light oxygenated compounds such as acetic acid. Here it is assumed that the commercial scale industrial plant could perform the separation similarly as in the experiment setting. The non-condensable gas produced during fast pyrolysis will be separated out of SF6, and get combusted for heat.

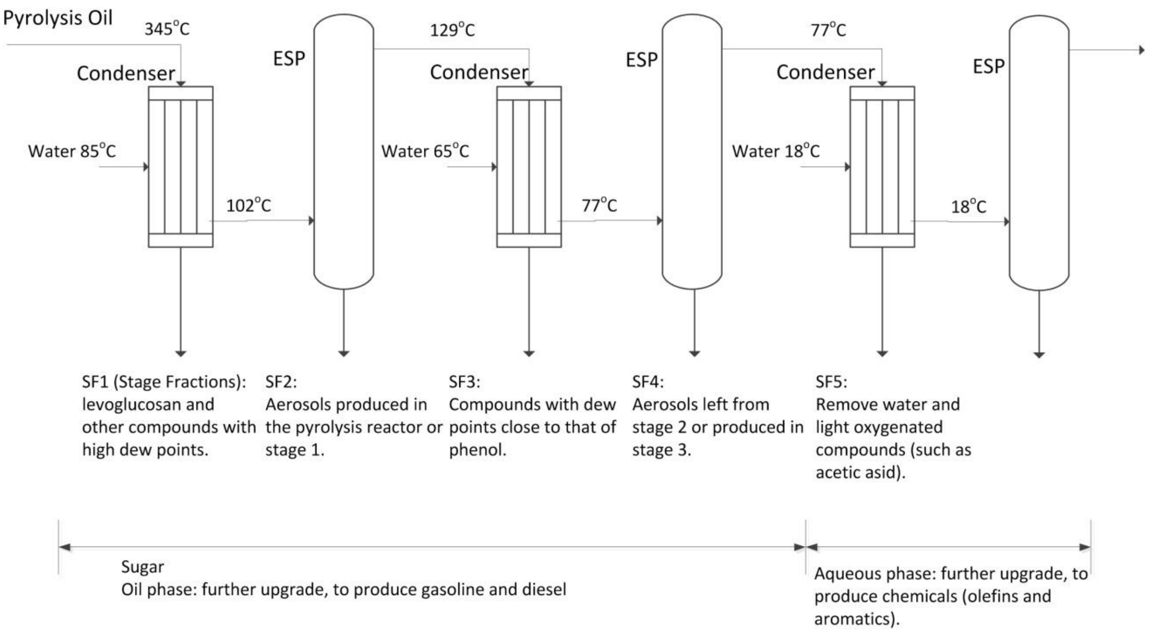

Figure 2.3 *Pyrolysis oil recovery process*

Compositions of SF1-6 utilize the experiment data from the design report with red oak as the feedstock [19]. Composition of the NCG is also obtained from experiment data at Iowa State University under same condition. Table 2.1 listed data used.

Table 2.1 *Composition for the pyrolysis oil stage fractions (source: A.J. Pollard's thesis 2011)*

	Char	SF1	SF2	SF3	SF4	SF5	SF6	NCG
Mass Balance	21.7%	11.7%	13.2%	3.2%	6.2%	19.3%	1.1%	23.6%

Stage Fractions Compounds Analysis (wt% bio-oil)

	SF1	SF2	SF3	SF4	SF5	SF6	Total
Water	7.8%	7.7%	9.5%	12.9%	62.1%	62.1%	35.6%
Char & Ash	24.0%	4.7%	0.7%	1.4%	0.5%	0.5%	2.2%
Water Insoluble	40.0%	46.4%	6.9%	12.9%	0.8%	0.8%	25.7%
Water Soluble	49.8%	41.2%	82.9%	72.8%	36.7%	36.7%	36.5%
Levoglucosan	6.3%	3.6%	1.6%	1.6%	0.0%	0.0%	1.5%
Acetic Acid	2.1%	2.0%	9.2%	9.2%	0.4%	0.4%	5.1%
Furans	2.6%	1.3%	1.7%	1.7%	0.5%	0.5%	2.7%
Phenols	1.6%	0.7%	1.2%	1.2%	0.3%	0.3%	2.3%
Guaiacols	3.8%	1.7%	2.4%	2.4%	0.4%	0.4%	2.9%
Syringols	6.6%	3.1%	2.5%	2.5%	0.3%	0.3%	2.0%
Benzenediol	0.6%	0.3%	0.1%	0.1%	0.0%	0.0%	0.7%
Other detected	7.9%	2.9%	8.3%	10.1%	5.7%	5.7%	14.8%
Other WS	18.3%	25.6%	55.9%	44.0%	29.1%	29.1%	4.5%

c) Heavy ends upgrading

In the heavy ends upgrading, we assume that SF1-2 contain most sugar products, and get extracted first. After sugar is removed, SF1-2 are combined with SF3-4 to form the heavy ends. The following hydrotreating process is operated at 340℃, 2000 psig with excess hydrogen flow. A three-way flash separates gas, aqueous and oil yield after hydrotreating. Hydrocracking is performed with the oil phase products from upstream hydrotreating, at 405℃, 1500 psig, also with large excess hydrogen flow. Another three-way flash operates after hydrocracker to separate products of hydrocracking into gas, aqueous and oil yield. The oil yield from hydrocracking can be used as feedstock for the refinery. The aqueous yields from both hydrotreating and hydrocracking are used for the aqueous phase upgrading, and gas yields will be combusted and provide heat for fast pyrolysis reaction.

The composition for catalytic hydrotreating and hydrocracking outputs and hydrogen consumption data are from Elliott et al. [12], with mixed wood as feedstock. Table 2.2 includes the data used for heavy phase hydroprocessing.

Table 2.2 *Catalytic hydroprocessing of fast pyrolysis bio-oil (source: Elliott et al. 2009)*

Hydroprocessing yields

Mixed wood	Oil yield g/g dry feed	Aqueous yield g/g wet feed	Gas yield g/g carbon feed	H2 consumption liter/liter feed
Hydrotreating (340C, 2000psig)	0.62	0.48	0.062	205
Hydrocracking (405C, 1500 psig)	0.61	0.24	0.087	290

Chemical components in hydroprocessing feed and product oil (average if multi-trials in source file)

Hydrotreating Components	Feed	Oil	Hydrocracking Components	Feed	Oil
Unsaturated ketones/aldehydes	3.92	0.46	Unsaturated ketones	0.00	0.00
Carbonyls (hydrooxyketones, aldehydes)	9.32	1.09	Carbonyls (hydrooxyketones)	0.00	0.00
Total alkanes	0.00	5.83	Naphthenes	4.22	69.99
Saturated guaiacols (diol, ones)	0.00	0.38	Saturated guaiacols (diol, ones)	0.00	0.00
Phenol and alkyl phenols	8.55	19.69	Phenol and alkyl phenols	15.68	0.00
Alcohols and diols	6.41	3.95	Alcohols and diols	22.67	0.00
HDO aromatics	0.00	0.65	HDO aromatics	10.51	12.61
Total saturated ketones	1.05	21.25	Total saturated ketones	12.84	0.00
Total acids and esters	30.80	24.77	Total acids and esters	11.89	0.00
Total furans and furanones	5.76	1.60	Total furans and furanones	0.00	0.00
Total tetrahydrofurans	3.03	3.42	Total tetrahydrofurans	3.28	0.00
Complex guaiacols	17.37	7.25	Complex guaiacols	0.00	0.00
Guaiacol and alkyl guaiacols	7.24	5.70	Guaiacol/syringols	18.91	0.00
Unknowns	6.58	3.94	Straight-chain/branched alkanes	0.00	12.21
			Unknowns	*0.00*	5.20

In this study, the heavy phase (with more hydrophobic compounds) of the pyrolysis oil is used for hydroprocessing, thus, a higher oil yield from both hydrotreating and hydrocracking are expected. Because of the water content percentage difference, the yield amount does not completely match with data provided in Elliott's paper. It is assumed that oil and gas yields are consistent with the paper, and the remaining compositions are treated as the aqueous yield. We use typical NCG compositions for NCG and guarantee carbon balance, water percentages are assumed to be proportional to gas yield.

d) Aqueous phase upgrading

The aqueous yield from the heavy ends catalytic hydroprocessing is combined with SF5-6 from pyrolysis oil recovery form the aqueous phase. The aqueous phase upgrading employs an integrated process of two-stage hydrotreating and FCC. The low temperature hydrotreating uses Ru-based catalyst and operates at 200 ℃, 100 bar, while high temperature hydrotreating step uses Pt-based catalyst and operates at 260 ℃, 100 bar, both steps consume hydrogen to complete the hydrogenation. The FCC step operates at 467 ℃, 100 bar, and uses zeolite to convert products from two-step hydrotreating into aromatics and olefins. The gas yield from aqueous phase will also be combusted and provide heat for pyrolysis reaction.

The compositions of the outputs from low temperature hydrotreating, high temperature hydrotreating and FCC are based on Vispute et al. [16] (article and supporting material). Table 2.3 includes the data used for aqueous phase upgrading.

Table 2.3 *Two-step hydrotreating and FCC process*

Two-step hydrotreating output composition (show in wt% of yield)

LT: Low temperature hydrotreating; HT: High temperature hydrotreating.

Compounds	LT output	HT output	Compounds	LT output	HT output
pentane	0.00	0.38	2,3-butanediol	0.00	1.43
hexane	0.00	3.02	Cyclohexanol	3.34	1.56
Acetic acid	9.79	5.74	1,2-butanediol	1.16	5.64
levoglucosan	14.82	0.00	tetrahydrofurfuryl alcohol	0.03	2.71
sugars	2.08	0.36	1,4-butanediol	1.96	2.82
methanol	2.52	3.32	γ-Butyrolactone	3.56	4.34
ethanol	0.73	2.01	γ-Valerolactone	0.31	0.46
1-propanol	0.31	1.55	Glycerol	0.00	2.73

tetrahydrofuran	0.00	0.20	1,2-Cyclohexanediol	3.32	3.80
2-butanol	0.00	0.51	4-Hydroxymethyl-γ-butyrolactone	2.42	1.84
2-methyltetrahydrofuran	0.00	0.67	Sorbitol	18.85	1.21
2,5-DimethylTetrahydrofuran	0.00	0.60	3-Methylcyclopentanol	0.00	1.03
1-butanol	0.13	0.39	1,2,3-Butanetriol	0.00	1.41
2-pentanol	0.00	0.14	1,4-Pentanediol	0.00	0.88
1-pentanol	0.00	0.27	3-methylcyclohexanol	0.00	1.02
ethylene glycol	24.80	26.30	4-methylcyclohexanol	0.00	0.61
cyclopentanol	0.26	0.72	1,2-Hexanediol	0.00	0.99
2-hexanol	0.00	0.24	1,2,6-Hexanetriol	0.00	0.58
propylene glycol	9.61	18.52			

FCC output composition (show in wt% of yield)

Compounds	FCC output	Compounds	FCC output
Benzene	3.99	Ethylene	12.00
Toluene	7.37	Propylene	20.17
Xylenes	2.86	Butylene	5.33
Ethyl benzene	0.35	**Olefins**	**37.50**
Styrene	0.21	Coke	4.31
Indene	0.07	CO	8.44
Naphthalene	0.07	CO2	34.41
Aromatics	**14.93**	Undefined	0.41

e) NCG treatment

The non-condensable gases from fractionation process, the heavy ends hydrotreating and hydrocracking, and the aqueous phase upgrading are mixed together and burn in a combustor to provide heat for other reactions.

3. Results and discussion

3.1 Economic Analysis

This project employs ChemCAD for the main process modeling, and Aspen Energy Analyzer for heat exchanging network modeling (based on ChemCAD energy balances). A summary of material flow for this process is included in Table 2.4.

Table 2.4 *Major material flows in fast pyrolysis fractionation process*

Input (dry basis)	Fast Pyrolysis Fractionation

Woody biomass (metric ton/day)	2,000
Hydrogen (kg/day)	2,000
Output	
Liquid Fuels (mmgal/y)	19.3
Aromatics (kg/day)	3,400
Olefins (kg/day)	10,200
Char (metric ton/day)	20
Sugar (kg/day)	22,500
NCG	Consumed to provide heat

Installed equipment costs for a 2,000 metric ton per day (MTPD) fast pyrolysis fractionation facility are summarized in Figure 2.4. The costs of equipment involved in heat exchanging network are estimated separately using Aspen Energy Analyzer, which are included in “Heat Balance and Steam Generating”. Total installed equipment cost for the project is $158.6 million. Some equipment costs are from ChemCAD process model and Aspen Energy Analyzer, others are from existing literatures [11, 20-23]. Capital investment of the project is estimated based on assumptions shown in Table 2.5 [24].

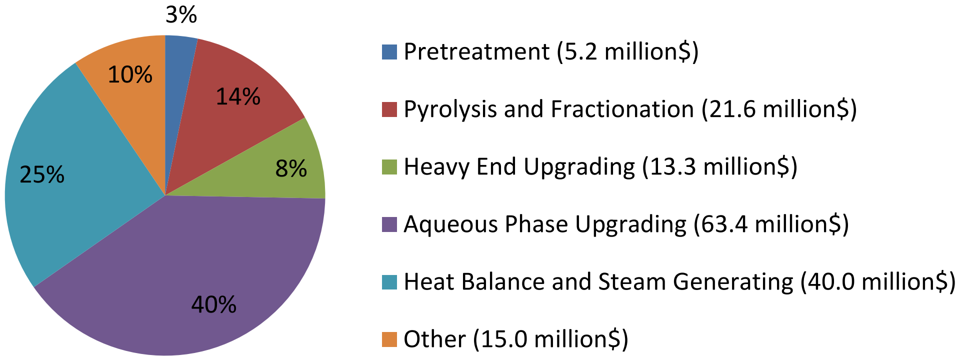

Figure 2.4 *Installed equipment costs*

Table 2.5 *Capital investment estimation*

Total Purchased Equipment Cost (TPEC)	100%
Purchased Equipment Installation	39%
Instrumentation and Controls	26%

Piping	31%
Electrical Systems	10%
Buildings (including services)	29%
Yard Improvements	12%
Service Facilities	55%
Total Installed Cost (TIC)	3.02 * TPEC
Indirect Costs (% TPEC)	
Engineering	32%
Construction	34%
Legal and Contractors Fees	23%
Total Indirect Costs (IC)	89%
Project Contingency (% TPEC)	78%
Fixed Capital Investment (FCI)	TIC+IC+Project contingency
Working Capital (WC, % TPEC)	15.00%
Land (% TPEC)	6.00%
Total Project Investment (TPI)	FCI+WC+Land
Installation Factor	TIC/TPEC=3.02
Lang Factor	TPI/TPEC=5.46

Operating costs in this process include fixed operating costs and variable operating costs. The former costs include fixed labor, facility maintenance, insurance and taxes etc. while the latter contains raw materials (biomass, hydrogen, and catalysts), waste disposal, utilities (cooling water, and electricity), and by-product (biochar) credits. The costs of biomass, hydrogen, and catalysts are listed in Table 2.6. A summary of operating costs is in Table 2.7, and an annual operating cost of $101.8 million is incurred.

Table 2.6 *Cost of raw materials used in the conversion process*

Biomass [25]	81.45	$/dry metric ton
Hydrogen	2	$/kg
Pt [23]	56.29	$/kg
Ru [23]	5.6	$/kg
Zeolite [23]	1.6	$/kg
Hydroprocessing catalyst [26]	15.5	$/lb

Table 2.7 *Annual operating costs for the conversion process*

	$ million
Fixed operating costs	15.7
Variable operating costs	86.1
Biomass	69.4
Hydrogen	1.7

Catalysts	8.2
Waste Disposal	1.7
Utilities	9.2
By-product credits	-4.1

The selling prices for the final products are assumed to be $3.00 per gallon for liquid fuels, and weighted average of various commodity chemical prices [23], $1.43 per kilogram for olefins, and $0.78 per kilogram for aromatics. Under these conditions, the project IRR is evaluated to be 8.78%.

3.2 Sensitivity Analysis

Sensitivity analysis of the fast pyrolysis fractionation facility is conducted to investigate the impacts of the uncertain factors on facility IRR. The parameters of interests include the selling prices of final products (chemical products and liquid fuels), product yield (liquid fuel, olefins and aromatics), major feedstock costs (biomass and hydrogen), and total capital investment. A 20% fluctuation is considered for optimistic and pessimistic cases.

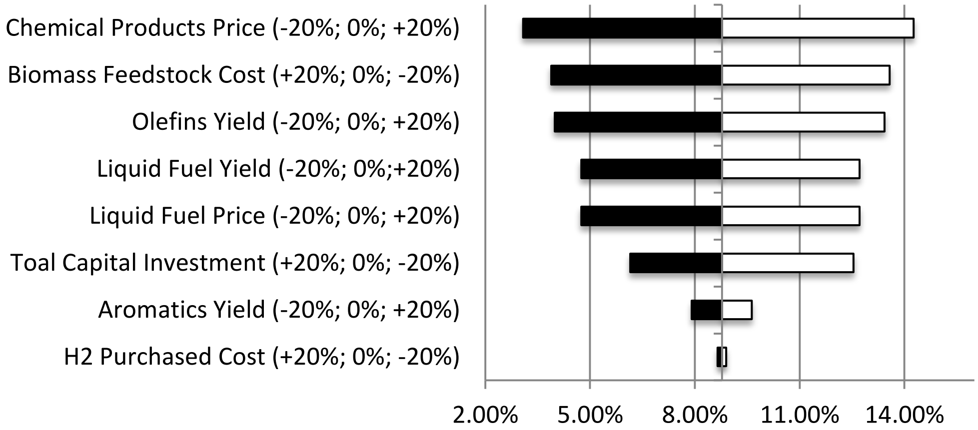

Figure 2.5 *Sensitivity analysis*

Figure 2.5 shows that main product yields and prices, total capital investment and biomass feedstock costs have major impact on the IRR. Take chemical products price as an example, a 20% increase in selling price increase IRR to 14.3%, while a 20% decrease in celling price change IRR to as low as 3.09%.

4. Conclusions

In this paper, the economic feasibility, of a fast pyrolysis fractionation facility producing both liquid fuels and commodity chemicals, is analyzed. Instead of single major product, two different upgrading methods are performed to different stage fractions of pyrolysis oil, and two major final products (liquid fuels and chemical products) are produced from heavy ends and aqueous phase oil. An 8.78% IRR is evaluated for the facility in a base condition, and sensitivity analysis shows that main products yields and selling prices, total capital investment and biomass feedstock costs have large influences on project IRR.

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CHAPTER 3 AN OPTIMIZATION MODEL TO DETERMINE THE CAPACITIES AND LOCATIONS FOR A THERMOCHEMICAL BIOREFINERY SUPPLY NETWORK

Modified from a paper submitted to *Journal of Energy Engineering*

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Abstract

This work studies supply chain network design for the fast pyrolysis and hydroprocessing 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 production cost. The economic feasibility of building a new refinery in Iowa is analyzed based on the supply chain configuration and the cost of transporting hydrotreated bio-oil to an existing petroleum refinery in Louisiana for refining to gasoline and diesel.

1. 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 [1]. Cellulosic biofuel production pathways, such as fast pyrolysis with hydroprocessing, are expected to play an essential role in fossil fuel displacement, national energy security, greenhouse gas reduction, and rural economic development [2].

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In 2007, the U.S. government 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 [3]. The cellulosic biofuel volume standard for 2012 is 10.45 million gallons per year (MGY) [4], 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. Feedstock production and logistics constitute 35% or more of the total production costs of advanced biofuel [5, 6], and logistics associated with moving biomass from land to biorefinery can make up 50–75% of the feedstock costs [7]. Total logistic cost along the supply chain constitutes 25% of the total fuel cost [8]. Collectively, the supply system activities of harvest, collection, storage, preprocessing, handling, and transportation, represent one of the largest challenges to the cellulosic biofuels industry. It becomes very important to investigate the supply chain of biofuel production system [9].

Thermochemical biofuel production pathways offer opportunities for rapid and efficient processing of diverse feedstock into fuel and chemicals [10-12]. 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) [13]. Bio-oil is a viscous and corrosive liquid that must be upgraded prior to refining, which can occur either onsite (at a decentralized fast pyrolysis facility) or at a conventional petroleum refinery with some adjustments. Upgrading can be accomplished either catalytically via fluid catalytic cracking or by reaction with hydrogen via hydroprocessing. Hydroprocessing is generally performed in two steps: hydrotreating occurs under low-severity conditions and deoxygenates and desulfurizes the raw bio-oil, while hydrocracking occurs under high-severity conditions and depolymerizes the bio-oil into low-molecular weight hydrocarbons. Hydroprocessed 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. Onsite hydroprocessing and refining incurs high capital and operating costs but yields high-value biobased gasoline and diesel fuel that can utilize the existing transportation fuel infrastructure for transport to the point of final consumption [14]. Alternatively, pyrolysis bio-oil can be hydrotreated onsite and then transported to a conventional petroleum refinery, where it is hydrocracked and refined to biobased gasoline and diesel fuel. While this second distributed processing scenario incurs lower capital and operating costs than the first centralized processing scenario, the bio-oil producer will not receive as much value for the hydrotreated bio-oil as its counterpart, the refinery.

Several previous studies report the costs of producing biobased hydrocarbons via fast pyrolysis and upgrading [14-16], few investigate the impact of biofuel supply chain network design, such as facility locations and capacities. Fast pyrolysis facility location and capacity decisions are essential in the biofuel supply chain network design, due to the high capital costs, longevity, and inflexibility to make changes for fast pyrolysis facilities. Wakeley et al. evaluate [17] transportation impacts using a linear optimization model and conclude that feedstock and ethanol transport are significant cost components in corn- and cellulose-based biofuel production.

Supply chain management is a relatively well-studied research area. The literature in supply chain design, modeling, and policy analysis is summarized by Shah [18]. Tsiakis et al. proposed [19] a mixed integer linear programming (MILP) model for the design and operation of general supply chain networks. The model minimizes total costs involved (including infrastructure costs, production cost, material handling costs, and transportation costs, etc.) due to quality, production and supply restrictions, and material flow balance. A broad review on generic supply chain models and their applications to the biofuel and petroleum-based fuel industries over the last decade is provided in An et al. [20]. A mathematical programming model for the optimal placement of distributed biorefineries is presented in Bowling et al. [21], with the objective of maximizing total net profit considering transportation costs and operating and capital costs for the facilities. Ekşioğlu et al. proposed [22] 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. Kocoloski et al. discussed [23] the impact of facility sizing and location on the cellulosic ethanol industry, and the infrastructure investment is modeled with a mixed integer program (MIP). Some research in simulating the biomass supply chain for biomass processing, transportation, and storage has also been conducted [24, 25]. However, the supply chain design for neither a fast pyrolysis facility and biorefinery network, nor facility capacities has been studied in the literature, which is the motivation of this study. This is the first analysis to investigate the supply chain design and configuration for a distributed processing network for a thermochemical production pathway.

This study considers the production of gasoline and diesel fuel from corn stover via decentralized fast pyrolysis and mild hydrotreating with centralized hydrocracking and refining. A mixed-integer linear programming (MILP) model is formulated to optimize the fast pyrolysis and hydroprocessing facility locations and capacities. As a case study, the state of Iowa is selected. The economic feasibility of building a new biorefinery in Iowa is compared to utilizing an existing petroleum refinery in Louisiana.

The rest of this chapter is organized as follows: Section 2 presents two location-allocation models dealing with the two refinery choices (building one in Iowa or utilizing an existing one in Louisiana). Problem statement, mathematical notations, and model formulation are introduced. The numerical examples are illustrated in Section 3 with scenario descriptions, data sources, and the result analysis. The economic comparisons between the two scenarios are also illustrated. Section 4 concludes with a discussion of the results and a summary of managerial findings.

2. Methodology

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

2.1 Problem statement

A typical biofuel supply chain includes feedstock production, feedstock transportation, biofuel conversion, and biofuel distribution. Figure 3.1 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 3.1. The hydrotreated bio-oil then undergoes hydrocracking (a reaction with hydrogen under more severe conditions than hydrotreating to 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 due to the economies of scale [14]. A decision has to be made as to whether to utilize existing refining capacity in a non-optimal location (refinery in Louisiana in the Iowa case study) or an optimally located new refinery. The refinery siting 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.

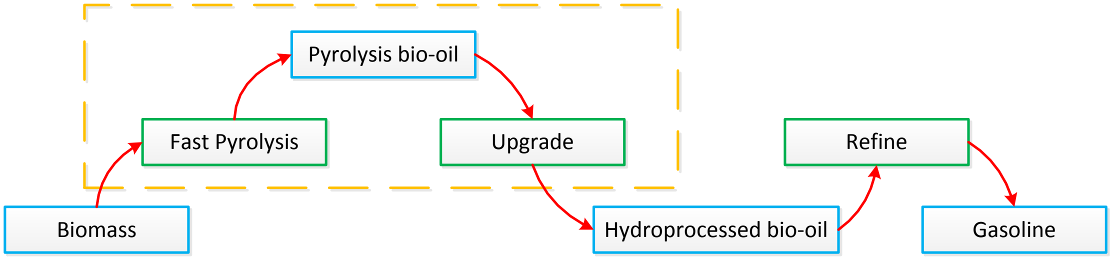

***Figure 3.1** Fast pyrolysis – upgrading – refining process of biomass converting to transportation fuel*

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 refinery is built in Iowa. The mathematical model identifies the optimal location of the centralized refinery in Scenario 2.

2.2 Mathematical notations in the model

The mathematical notations utilized in the model are listed in **Table 3.1**. **Figure 3.2** summarizes the notations utilized in the model formulation.

Table 3.1 *Subscripts, parameters, and decision variables*

Subscripts		
$\boldsymbol{i}^{1,2}$	$1,2,\ldots,N$	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 bio-refinery capacity levels
$\boldsymbol{r}^{2}$	$1,2,\ldots,R$	Candidate refinery 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, ton of upgraded bio-oil per dry ton of biomass
$\boldsymbol{\theta_2}^{1,2}$		Conversion ratio, ton of gasoline per 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 refinery 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 refinery 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

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

		candidate facility location j
$g_r{}^{2}$	*binary*	If a refinery exists in candidate refinery location r

[1] Parameters (or variables) for modeling scenario 1: utilizing existing refinery location
[2] Parameters (or variables) for modeling scenario 2: building a new refinery at an optimal location

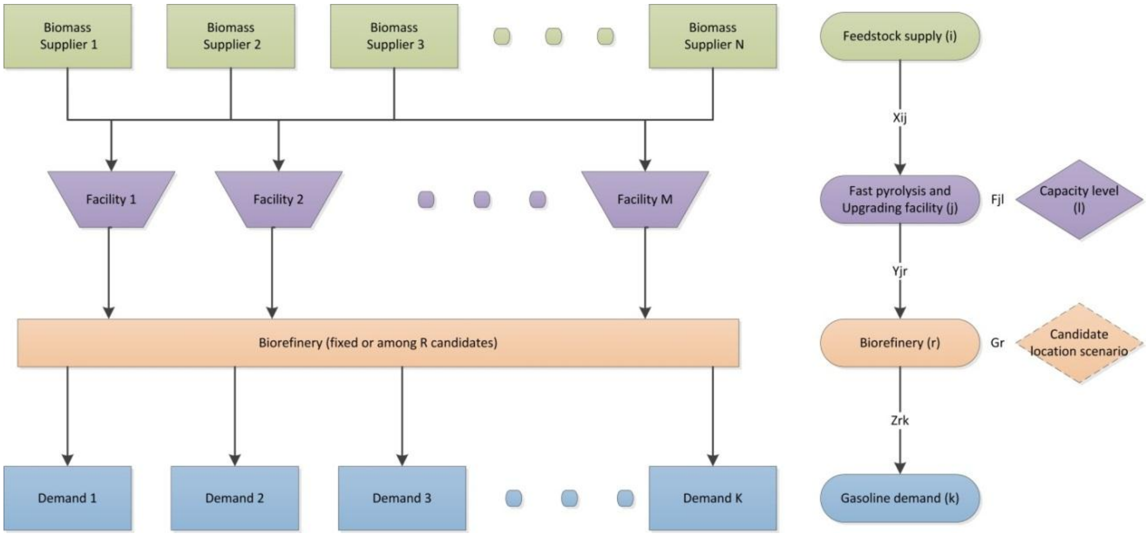

Figure 3.2 *Notation diagram for facility location and capacity decision model*

2.3 Mixed integer linear programming model

A mixed integer linear programming (MILP) model is developed to identify the optimal locations and capacities for fast pyrolysis facilities in order to minimize the total system cost along the supply chain. Two scenarios are considered for the centralized upgrading and refining facility siting. In Scenario 1, the upgrading and refining is taking place in an existing non-optimally located facility, where Scenario 2 considers an optimally located centralized refining facility.

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 where the hydrotreated bio-oil is hydrocracked and refined at an existing refinery.

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

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

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 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 .

$$\sum\nolimits_{j=1}^{M} x_{ij} \le Spp_i, \forall i \qquad \{\text{biomass availability}\} \tag{1a}$$

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

$$\sum\nolimits_{i=1}^{N} x_{ij} \le \sum\nolimits_{l=1}^{L} f_{jl} C_l\,, \forall j \qquad \{\text{facility capacity}\} \tag{1c}$$

$$\sum\nolimits_{l=1}^{L} f_{jl} \le 1, \forall j \qquad \{\text{one facility at each site}\} \tag{1d}$$

$$\theta_2 \sum\nolimits_{j=1}^{M} y_j = \sum\nolimits_{k=1}^{K} Dmn_k \qquad \{\text{satisfaction of demand}\} \tag{1e}$$

$$x_{ij}, y_j \ge 0, f_{jl} \in \{0,1\}, \forall i, j, l, r \tag{1f}$$

Scenario 2: Build a new biorefinery

In Scenario 2, in addition to optimizing the locations and capacities of the decentralized fast pyrolysis facilities, the objective 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 cost. The difference is that instead of incurring the transportation cost of mildly hydrotreated bio-oil to an existing refinery site, the system incurs the transportation costs to the optimally located biorefinery. The annual cost reduction from Scenario 1 to Scenario 2 is to analyze the economic feasibility of building a centralized biorefinery.

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

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 refinery is being planned to cover the upgrading and refining need; and (2h) the produced transportation fuel is shipped from the local biorefinery.

$$\sum_{j=1}^{M} x_{ij} \le Spp_i, \forall i \qquad \{\text{biomass availability}\} \tag{2a}$$

$$\sum_{r=1}^{R} y_{jr} = (1 - loss)\theta_1 \sum_{i=1}^{N} x_{ij}, \forall j \qquad \{\text{biofuel conversion}\} \tag{2b}$$

$$\sum_{i=1}^{N} x_{ij} \le \sum_{l=1}^{L} C_l f_{jl}, \forall j \qquad \{\text{facility capacity}\} \tag{2c}$$

$$\sum_{l=1}^{L} f_{jl} \le 1, \forall j \qquad \{\text{one facility at each site}\} \tag{2d}$$

$$y_{jr} \le M_r g_r, \forall j, r \qquad \{\text{refinery capacity }\} \tag{2e}$$

$$\sum_{r=1}^{R} g_r = 1 \qquad \{\text{one refinery to build}\} \qquad (2f)$$

$$\theta_2 \sum_{j=1}^{M} \sum_{r=1}^{R} y_{jr} = \sum_{k=1}^{K} Dmn_k \qquad \{\text{satisfaction of demands}\} \qquad (2g)$$

$$z_{rk} = Dmn_k g_r, \forall r, k \qquad \{\text{biofuel distribution}\} \qquad (2h)$$

$$x_{ij}, y_{jr} \geq 0, f_{jl}, g_r \in \{0,1\}, \forall i, j, l, r \qquad (2i)$$

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 authors decide not to include the bio-oil conversion cost in the objective function but incorporate it into the scenarios' comparison.

3. Numerical examples

The state of Iowa is chosen as the region of interest in the numerical example. Corn stover accounts for the major cellulosic biomass in Iowa. The goal of the biofuel supply chain design is to identify the locations and capacities for the distributed fast pyrolysis facilities in Iowa. Two scenarios are investigated regarding the centralized refinery locations: (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.

3.1 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 [26]. The county level corn production is from the National Agricultural Statistics Service (NASS) [27]. The National Resources Conservation Service (NRCS) Soil Quality Team suggests that farmers must be careful when removing residues, which perform many positive functions for soils in the agro-ecosystem [28]. Papendick et al. shows [29] 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 3.3. 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 based on different ranges of corn stover collection quantities [30]. Biomass losses are incorporated for the collection and transportation process. It is assumed to be 5 wt% (weight percentage) in this study.

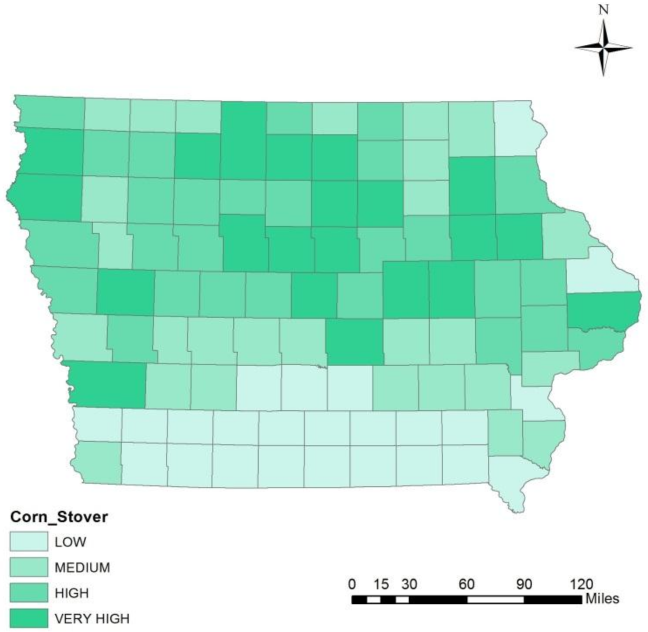

Figure 3.3 *County-level corn stover supply distribution (2007)*

The main product is 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 by the Energy Information Administration (EIA) [31]. The individual gasoline demand of MSAs in Iowa is shown in Figure 3.4.

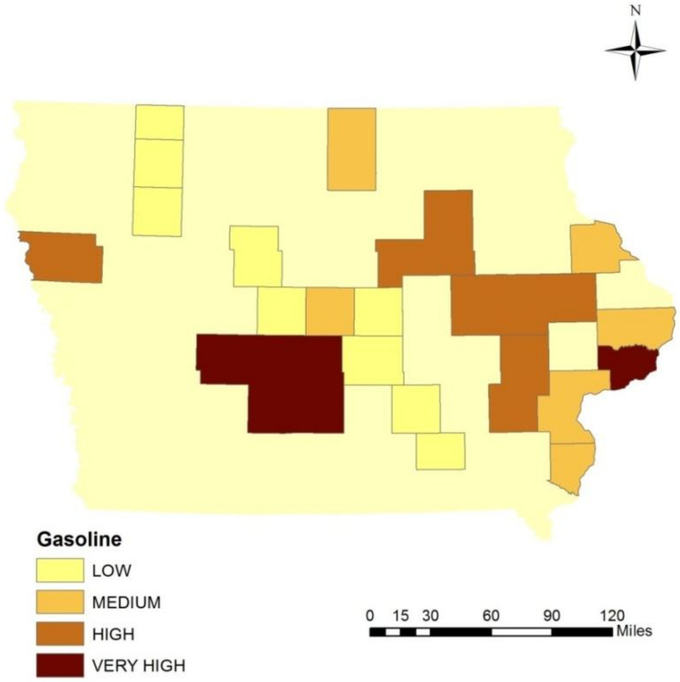

Figure 3.4 *MSA-level gasoline demand distribution (2009)*

The candidate locations for the distributed fast pyrolysis facilities are at the county centroids. In Scenario 2 where the centralized refinery site is to be determined, the candidate refinery 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 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) [32].

Stover transported via truck incurs a distance fixed cost of \$4.39/ton and a distance variable cost of \$0.19/ton-mile [33]. 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 [34]. The transportation cost of gasoline via pipeline is assumed to be equal to the national average oil pipeline cost of \$0.027/ton-mile [34].

The distributed fast pyrolysis facility in this study converts corn stover using fluid bed pyrolyser and other common equipment found in thermochemical conversion facilities. 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 [14]. Unit conversion cost is estimated with total annual operating cost of a hydrogen-purchase fast pyrolysis and upgrading scenario at approximately \$1.18/gallon [14].

In the numerical examples, we consider four available capacity levels: 400 ton/day, 1000 ton/day, 1500 ton/day, and 2000 ton/day. The capital facility cost is the total project investment minus working capital and land. The capital cost of the fast pyrolysis facility with a capacity of 2,000 metric tons per day of stover feedstock is \$200 million (assuming a hydrogen purchase plant) [14], 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 to minimize the annual total 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%.

3.2 Numerical results

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 biorefinery in Louisiana.

The optimal distributed fast pyrolysis facility locations are illustrated in Figure 3.5. Different shaped points mark the facility locations of different capacity levels: a pentagon represents a 400 ton/day facility, a triangle represents a 1000 ton/day facility, a square represents a 1500 ton/day facility, and a circle represents a 2000 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 magnitude of the fuel demand from the MSAs. The predetermined refinery location is in Louisiana.

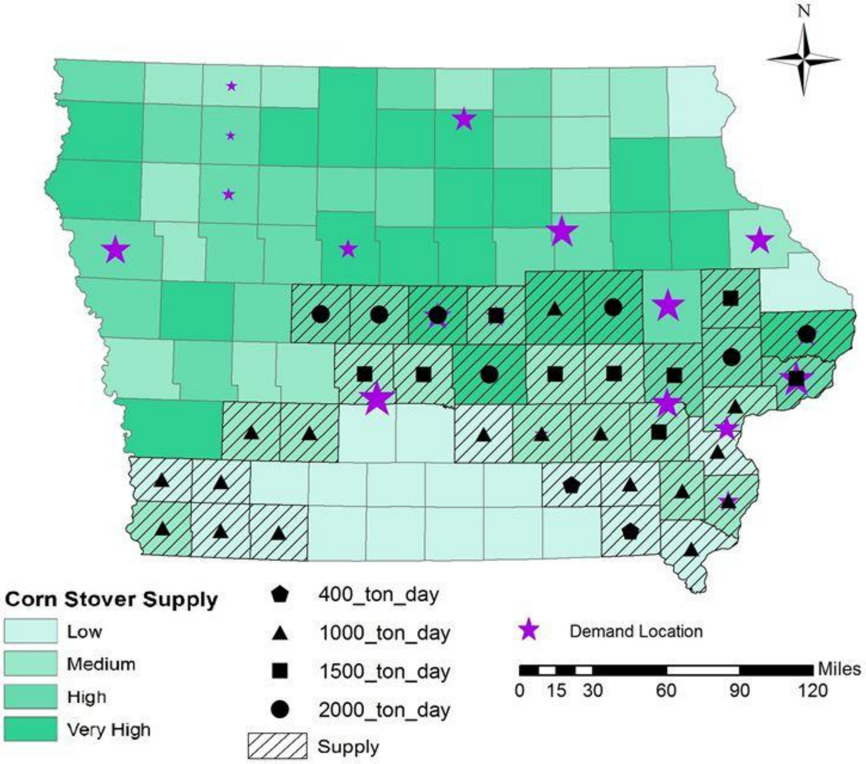

Figure 3.5 *Optimal fast pyrolysis facility locations for scenario 1*

The numbers of facilities of each capacity level are:

400 ton/day	1000 ton/day	1500 ton/day	2000 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 $2.51 billion. Itemized costs are listed in Table 3.2.

Table 3.2 *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	

Scenario 2: Build new refinery in Iowa

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

Figure 3.6 shows the supply chain network configuration for Scenario 2. Different shapes are used to mark locations of different capacity facilities (pentagon – 400 ton/day, triangle – 1000 ton/day, square – 1500 ton/day, circle – 2000 ton/day), and the cross-shaded county is chosen to build the biorefinery. Feedstock transport from counties outside of the facility-located county is illustrated with arrows.

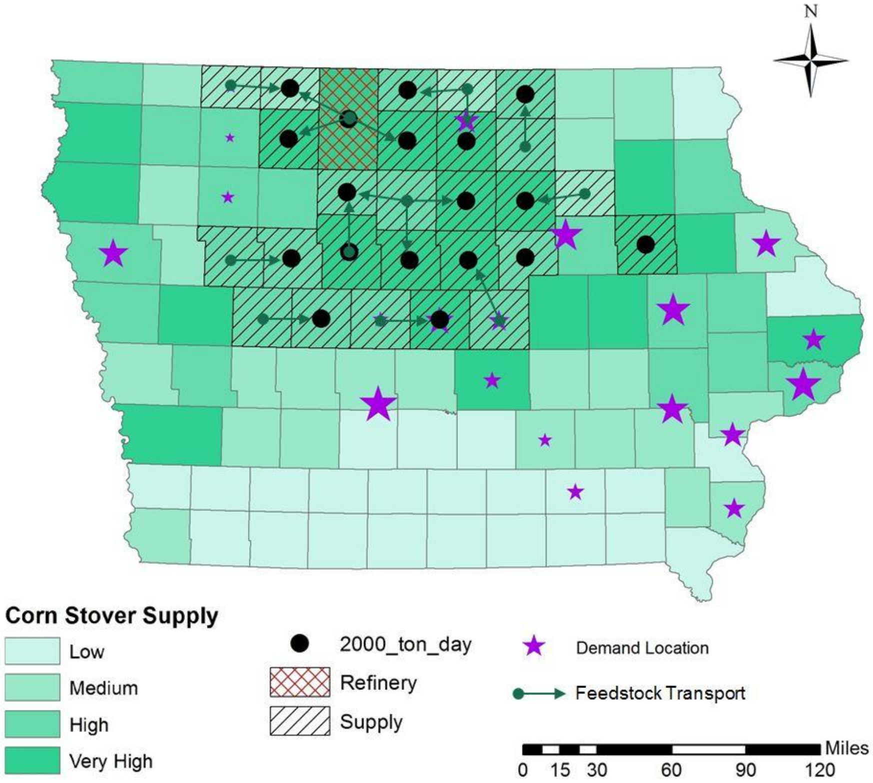

***Figure* 3.6** *Optimal fast pyrolysis facility and biorefinery locations for scenario 2*

The numbers of facilities of each capacity level are:

400 ton/day	1000 ton/day	1500 ton/day	2000 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 3.3.

***Table 3.3** 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	

3.3 Analysis and discussion of results

<u>Comparison between two scenarios</u>

In section 3.2, 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 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 3.5 and Figure 3.6, 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 ton/day, because a larger capacity facility is more cost-effective due to the facility capital scaling factor (the economics 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.

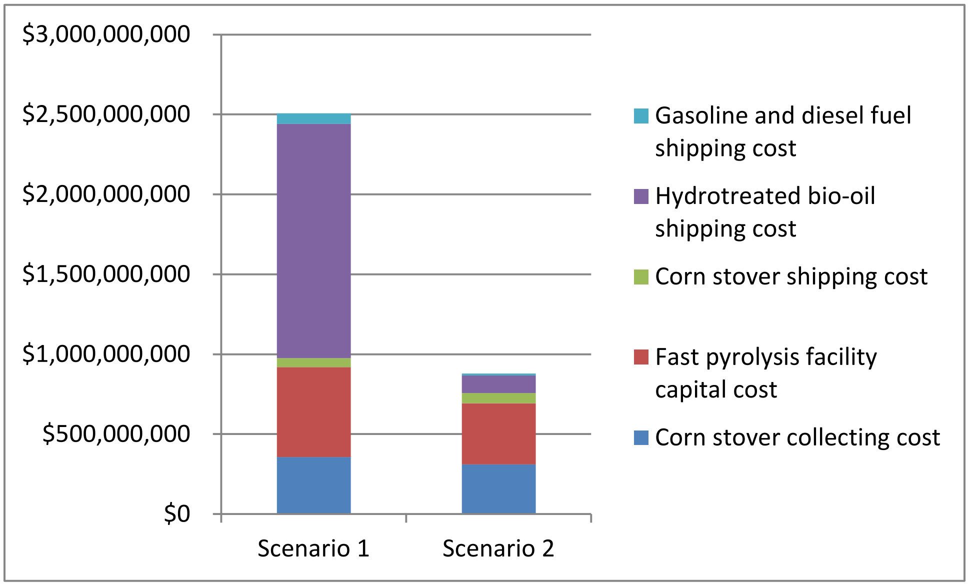

Figure 3.7 *Itemized annual costs for scenarios 1 and 2*

It is also demonstrated in Figure 3.5 and Figure 3.6 that optimal facility locations tend to be closer to the refinery. 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 their low biomass availability of those counties. If a fast pyrolysis facility is built, high biomass shipping cost will subsequently occur. 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 refinery are optimally located in the northern counties due to high feedstock availability in northern Iowa. This reduces both the distance of stover shipping and the total production cost. Figure 3.7 includes a bar chart for the comparison of the itemized costs for Scenarios 1 and 2. In Table 3.4, the itemized costs, total production cost, and unit cost per gallon of liquid fuel for both scenarios are illustrated.

Table 3.4 *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

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 3.7 and Table 3.4 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 due to the difference in biofuels transportation distance between the refinery in Louisiana and the one in Iowa as shown in Table 3.5.

***Table 3.5** Comparison of average distances between facility, refinery and demand locations between scenarios*

	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

The annual reduction of $1.62 billion (calculated from Table 3.4) could break even the amortized capital cost of a 30-year refinery with $15.3 billion total capital cost, which shows the economic potential of building a new refinery in Iowa rather than shipping hydrotreated bio-oil to an existing refinery.

Sensitivity on biomass availability

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

Different refinery location

In Scenario 2, the refinery location is an important decision for stakeholders. We have presented the results when the refinery is optimally located in Iowa. In this section, the impact of the Iowa refinery location is investigated.

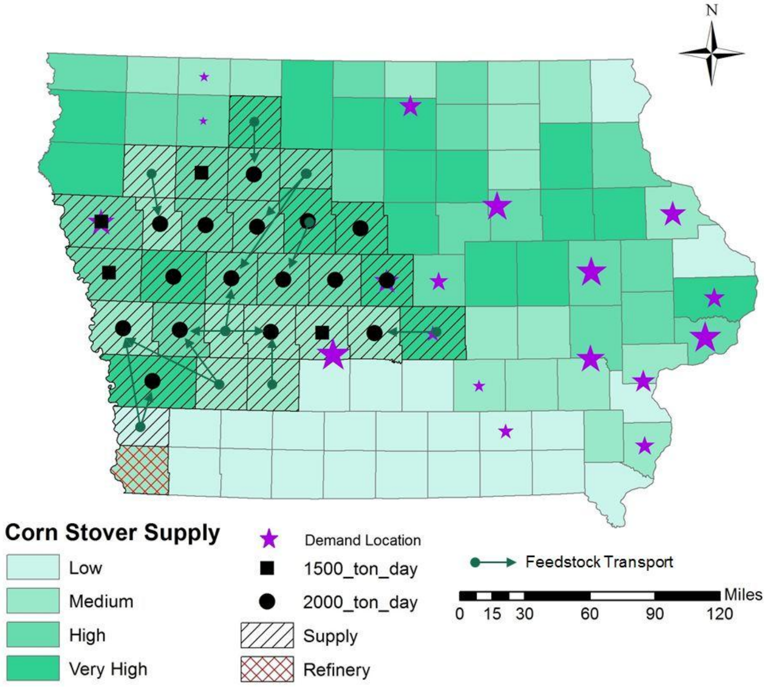

Figure 3.8 *Optimal facility configurations for the pessimistic case*

The authors study the pessimistic scenario where the worst location is selected for the Iowa biorefinery. The supply chain configuration result is shown in Figure 3.8. The cost comparison between the optimal case and this pessimistic case is shown in Table 3.6. As shown in Figure 3.8, 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, shipping cost increase significantly. Some facilities have smaller capacities because they are located in counties with insufficient biomass supplies, and this causes additional facility capital cost. It can be seen from Table 3.6 that the optimally located refinery can significantly reduce total annual cost, and most especially shipping cost.

Table 3.6 *Itemized costs comparison between optimal refinery 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

Summary

Supply chain network design and optimization are essential to the successful deployment of the 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 in the biofuel industry, and can 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 the costs along 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 refinery in Iowa has the advantage of reducing the shipping costs of the hydrotreated bio-oil and the end product biofuel. Building a refinery in Iowa could reduce the unit cost of gasoline from $3.31 to $1.93 per gallon. The total cost reduction per year, $1.62 billion, demonstrates the potential economic feasibility of building a new refinery in Iowa.

4. Conclusion

Mixed integer linear programing models are formulated to analyze facility location and capacity decisions for the production of gasoline and diesel fuel. The pathway under investigation is fast pyrolysis of corn stover and hydroprocessing to produce biofuel. The economic feasibility of building a new upgrading refinery in Iowa is analyzed. It should be noted that the optimization models provide the flexibility to adaptively analyze biofuel supply chain design problems at various scales. For future research, the framework developed in this study can be extended to study operational planning and sequential facility siting problems. Furthermore, uncertainties can also be incorporated.

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CHAPTER 4 A SEQUENTIAL FAST PYROLYSIS FACILITY LOCATION-ALLOCATION MODEL

Modified from a paper to be submitted to *AMPS 13: Sustainable Production and Service Supply Chain*

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Abstract

The revised Renewable Fuel Standard (RFS2) mandates the U.S. to consume16 billion gallons per year (BGY) of biofuels from cellulosic biomass 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.

1. Introduction

Biofuels has been recognized as important sources of 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

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2007, cellulosic based biofuels are gaining more attention. These biofuels may help with meeting goals of different types of policies[2]. Cellulosic biofuels technologies are still mainly on the experimenting stage [3, 4], studies on biomass logistics and biofuel supply chain management are also emerging [5-8].

In this paper, a sequential location problem of fast pyrolysis facilities is investigated. Formulations are presented in Methodology, and Iowa case study results and discussions are shown in Results and Discussion. Paper concludes with Conclusions with major findings and future work suggestions.

2. Methodology

2.1 Problem descriptions

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. **Figure 4.1** illustrates the supply network setting.

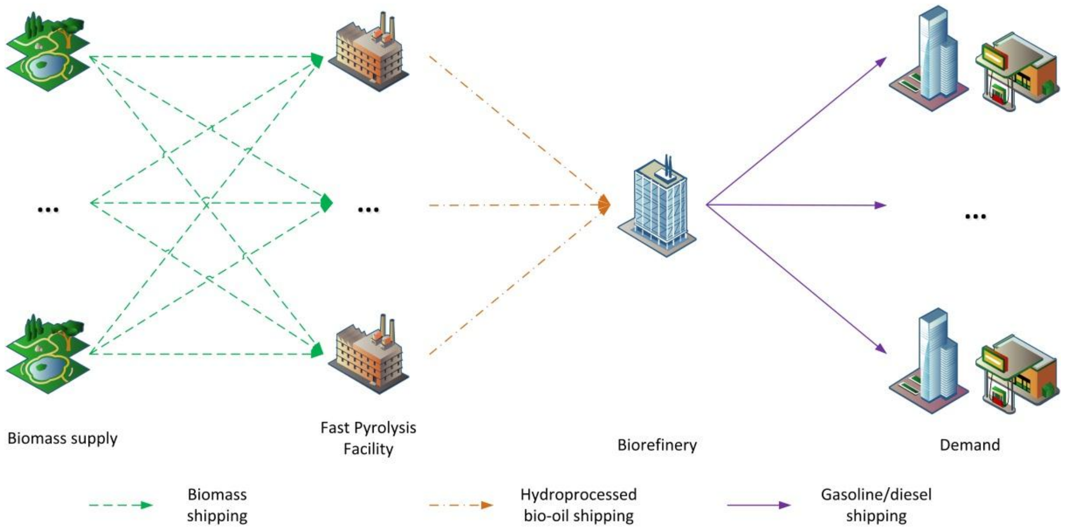

Figure 4.1 *Supply chain structure for cellulosic biomass pyrolysis – hydroprocessing – refining process*

2.2 Major assumptions

Major assumptions used in modeling are listed below:

1. Facility construction time is one-year and 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 fast pyrolysis facilities are at optimal locations and capacities.
3. The facility location and material (feed and products) allocation decisions are made to maximize the total profit of all the 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.

2.3 Model formulation

Notations:

i	index for biomass supply locations
j	index for candidate fast pyrolysis facility locations (all county centroids in Iowa)
k	index for gasoline demand locations (all MSA[1] centroids in Iowa)
l	index for fast pyrolysis facility capacity level
t	index for time period (decision making time)

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[1] MSA: metropolitan statistical area

GP_t	projected gasoline price [9]
BCC_i	unit biomass collecting cost [10]
BSC_{ij}	unit biomass shipping cost [11, 12], $BSC_{ij} = FSC + VSC \times D_{ij}$, which is a combination of fixed shipping cost and variable shipping cost (related to shipping distance)
HSC_j	unit hydroprocessed bio-oil shipping cost [12, 13]
GSC_k	unit gasoline shipping cost [13]
FOC_l	fixed facility operating cost [4]
GCC	gasoline conversion cost, derived from variable facility operating cost, related to facility operating level (proportional to gasoline production amount) [4]
FFC_l	fast pyrolysis facility capital cost, using scaling factor of 0.6 [4]
AFC_l	amortized fast pyrolysis facility capital cost, derived from facility capital cost, with facility life of 20-year [4]
SPP_{it}	maximum biomass supply amount, total corn stover available amount [14, 15] times maximum removal proportion [16]
$loss$	biomass loss during transportation, assumed to be 5 wt% here
θ_1	conversion ratio from cellulosic biomass to hydroprocessed bio-oil [4]
θ_2	conversion ratio from hydroprocessed bio-oil to gasoline diesel fuel [4]
$\overline{Dmn_k}$	total gasoline demand level [17]
Dmn_t	gasoline demand, $Dmn_t = \sum_k \overline{Dmn_k} \times pr_t$, 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, with maximizing the net present value (NPV) of the total profit of the next 10 years (2013-2022) being the objective. 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:

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

Major constraints include: biomass supply availability constraints (1a), biofuel conversion balance constraints (1b,1e), fast pyrolysis facility existence and capacity limit constraints (1c), a maximum of one facility per candidate facility construction location constraints (1d), no destruction of facility constraints (1h), minimum demand requirement and demand upper bound constraints (1f, 1g), available construction budget related constraints (1i-1k), and initialization of current situation of fast pyrolysis facility situation constraints (1l).

$$\sum_{j=1}^{M} x_{ijt} \leq Spp_{it}, \ \forall i,t \qquad (1a)$$

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

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

$$\sum_{l=1}^{L} \delta_{jlt} \leq 1, \ \forall j,t \qquad (1d)$$

$$\theta_2 \sum_{j=1}^{M} y_{jt} = \sum_{k=1}^{K} z_{kt}, \quad \forall t \qquad (1e)$$

$$\sum_{k=1}^{K} z_{kt} \geq \sum_{k=1}^{K} Dmn_{kt}, \quad \forall t \qquad (1f)$$

$$\overline{Dmn_{kt}} \geq z_{kt}, \quad \forall k,t \qquad (1g)$$

$$\delta_{j,l,t} \geq \delta_{j,l,t-1}, \quad \forall j,l,t \geq 2 \qquad (1h)$$

$$\sum_{j=1}^{M}\sum_{l=1}^{L} FFC_l \delta_{j,l,2} \leq F_1 \qquad (1i)$$

$$\sum_{j=1}^{M}\sum_{l=1}^{L} FFC_l\left(\delta_{j,l,t+1} - \delta_{j,l,t}\right) \leq A_{t-1}(1+r) + F_t, \forall T-1 \geq t \geq 2 \qquad (1j)$$

$$A_t = A_{t-1}(1+r) + F_t - \sum_{j=1}^{M}\sum_{l=1}^{L} FFC_l\left(\delta_{j,l,t+1} - \delta_{j,l,t}\right), \forall T-1 \geq t \geq 2 \qquad (1k)$$

$$\delta_{j,l,1} = 0, \quad \forall j,l \qquad (1l)$$

$$x_{ijt}, y_{jt}, z_{kt} \geq 0, \delta_{jlt} \in \{0,1\}, \ \forall i,j,k,l,t \qquad (1m)$$

2.4 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 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 amount are shown in **Figure 4.2**. The county that is assumed to locate the existing biorefinery is represented using cross-shaded lines. Stars are 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 achieved is $5.28 billion.

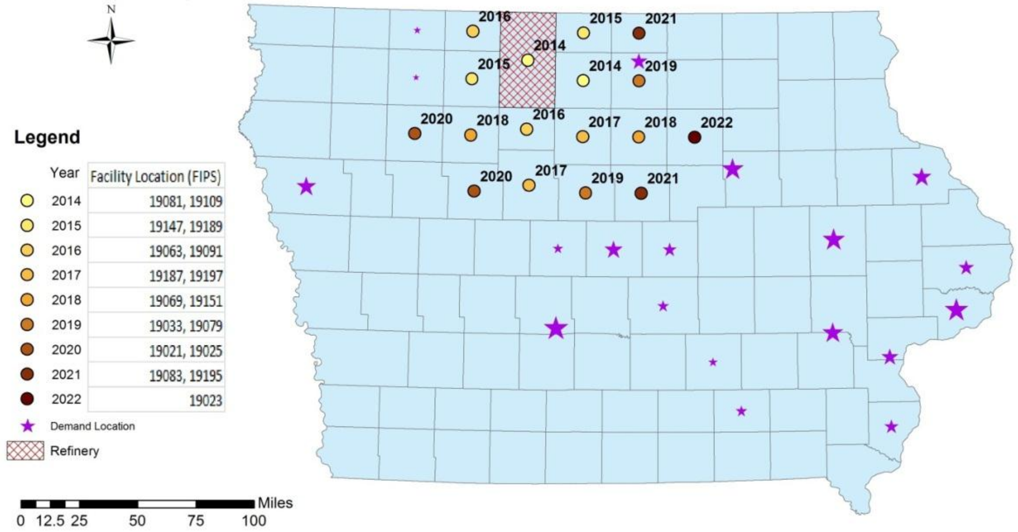

Figure 4.2 *Sequential facility construction under annual fund of twice capital cost of 2000 metric ton/day facility*

If annual available fund increase to 2.5 times capital cost of 2000 metric ton/day facility, the results are shown in Figure 4.3. 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 achieved is $6.03 billion.

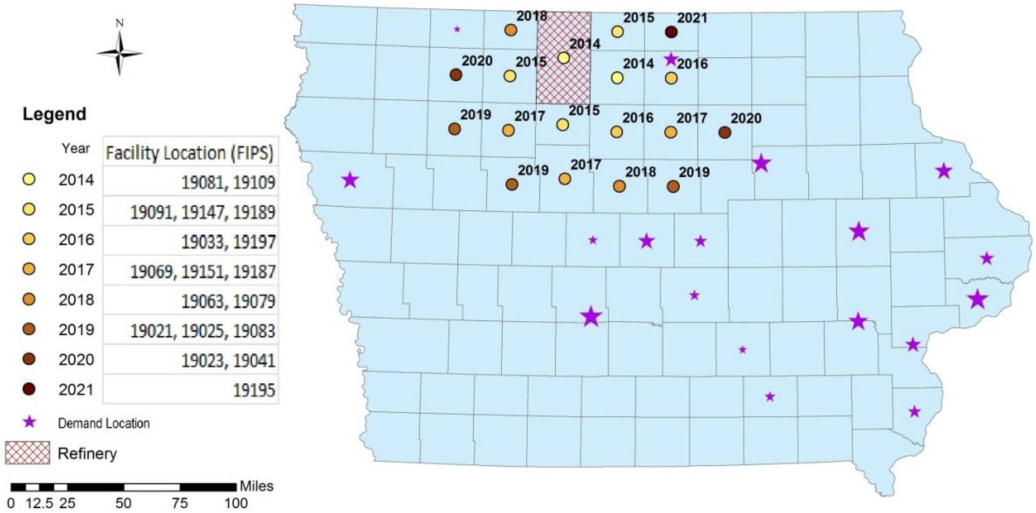

Figure 4.3 *Sequential facility construction under annual fund of 2.5 times capital cost of 2000 metric ton/day facility*

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 biorefinery location. From the yearly allocation results, most biomass supply could be satisfied within the county where the facility is located; 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.

3. Conclusion

Biofuels have become increasingly attractive to replace petroleum fuel. 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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CHAPTER 5 GENERAL CONCLUSION

In the United States, current federal biofuel policy is largely based on the Renewable Fuel Standard (RFS), which mandates the production and blending of different classes of biofuels. The revised Renewable Fuel Standard, RFS2, focuses more on cellulosic biofuels. Motivated by these regulatory policies, this thesis work has been focused on the economic assessment of biofuel production pathway and biofuel supply network design. The goal is to assist decision making for advanced biofuel production in the U.S.

In Chapter 2, the economic feasibility for a commercial scale facility based on fast pyrolysis fractionation is evaluated. The project IRR is 8.78% for the baseline scenario. Sensitivity analysis shows that fluctuations in biomass feedstock cost, major products yield and market prices could have the most significant impact on the project IRR. Based on the analysis, more attentions could be paid to pyrolysis oil recovery conditions and upgrading technologies, to increase economic potential of such facilities.

Motivated by the importance of supply chain network design for biofuel production, Chapter 3 and 4 focus on the decision making models for facility siting and sizing. The optimization models results suggest that with rich cellulosic biomass, such as Iowa, producing hydrocarbon liquid fuels via fast pyrolysis, hydroprocessing and refining could be profitable. The investment of a refining facility could be economically justified for the long-term development of cellulosic biofuel industry. Furthermore, refining facility location is essential to average annual profit, and has large impact on facility locations and construction sequences.

For future research directions, uncertainties on feedstock supply, conversion yield and biofuel demand can be incorporated. Environmental considerations could be included with additional constraints. Lifecycle assessment would be needed to analyze the detail environmental impacts. Such extensions could contribute to more comprehensive insights into the future development of the cellulosic biofuel industry.