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Biofuel supply chain and bottom-up market equilibrium model for production and policy analysis

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Biofuel supply chain and bottom-up market equilibrium model for production and policy analysis

by

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in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Industrial and Manufacturing Systems Engineering

Program of Study Committee:
Guiping Hu, Major Professor
Bruce Babcock
Lizhi Wang

Iowa State University
Ames, Iowa
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ABSTRACT

Renewable fuel is attracting increasing attention as a substitute for fossil based energy. The US Department of Energy (DOE) has identified pyrolysis based platforms as promising biofuel production pathways. Although the biofuel market remains in its early stage, it is expected to play an important role in climate policy in the future in the transportation sector. In this thesis, we will first propose a biofuel supply chain model to study the supply chain design and operational planning for advanced biofuel production, then a biofuel market model is developed to study the interactions between farmers, biofuel producers, blenders, and consumers along the biofuel supply chain in the market competitive setting.

For the biofuel supply chain model, the focused production pathway is corn stover fast pyrolysis with upgrading to hydrocarbon gasoline equivalent fuel. The model is formulated with a Mixed Integer Linear Programming (MILP) to investigate facility locations, facility capacities at the strategic level, and feedstock flow and biofuel production decisions at the operational level. In the model, we accommodate different biomass supply and biofuel demand scenarios with supply shortage penalty and storage cost for excess biofuel production. Numerical results illustrate the supply chain design and operational planning decision making for advanced biofuel production. Unit costs for advanced biofuel under changing of scenarios are also analyzed. The case study demonstrates the economic feasibility of biofuel production at a commercial scale in Iowa.

The second part of the thesis work focuses on analyzing the interaction between the key stakeholders along the supply chain. A bottom-up equilibrium model is built for biofuel market to study the competition in the advanced biofuel market, explicitly formulating the interactions between farmers, biofuel producers, blenders, and consumers. The model simulates the profit maximization of multiple market entities by incorporates their competitive decisions in farmers' land allocation, biomass transportation, biofuel production, and biofuel blending. As such, the equilibrium model is capable of and appropriate for policy analysis, especially for those that have complex ramifications and result in different reac-

tions from multiple stakeholders. For example, the model can be used to analyze the impact of biofuel policies on market outcomes, pass-through of taxes or subsidies, and consumers' surplus or producers' profit implications. The equilibrium model can also serve as an analytical tool to derive market prices of biomass, advanced biofuel, and the value of the Renewable Identification Numbers. Moreover, the model can be used to analyze the impact of the market structure or firms' ownership setting that may arise due to oligopoly competition in the advanced biofuel market.

CHAPTER 1. INTRODUCTION

The concerns of national energy security and environmental aspects have brought rising interests in biofuels in recent years. Biofuels are fuels that are produced from biological products including biomass, liquid fuels and biogases. Different policies have been proposed and implemented to stimulate local biofuel production. Renewable Fuel Standars (RFS) was created by US Environmental Protection Agency (EPA) proposed in 2005. RFS requires that at least 7.5 billion gallons of renewable fuels be blended with conventional gasoline by the year 2012. The revised RFS (RFS2) in 2007 requires that at least 21 billion gallons of advanced biofuel being produced and out of which at least 16 billions should be cellulosic biofuel [42] (Figure 1.1). Food, Conservation, Energy Act (FECA) of 2008 offers $1.01/gal of subsidy for cellulosic biofuel produced and consumed in US, and $45/ton of biomass collected, harvested, processed and transported as cellulosic feedstock. Other policies such as $0.45/gal of ethanol blending credit-Volumetric Ethanol Excise Tax Credit (VEETC), $0.54/gal tariff levied against imported ethanol expired December 2011 [55, 54]. Different from the successful development of the corn ethanol, advanced biofuel has not reached the target. In addition to the immaturity of production technology, the feedstock logistic cost and uncertain market structure have been raised among the major obstacles in advanced biofuel production arena. This is the major motivation for this study.

Second generation biofuels are made from nonedible plant residues such as corn stover, switchgrass, wood chips, etc. Not competing with food market on biomass supply and the potentiality to lower greenhouse gas emission are the two main advantages for second generation biofuels comparing with the first generation biofuels. Thermalchemical process is the major process under research to produce biofuels from biomass, out of which fast pyrolysis and hydrothermal liquefaction pathways are identified as the most promising pathways to produce liquid fuels [28]. Some economic analysis for different pathways are done to evaluate the feasibility of biofuel commercialization. Wright [60] presented the experiment and economic analysis results for corn stover fast pyrolysis to produce naphtha

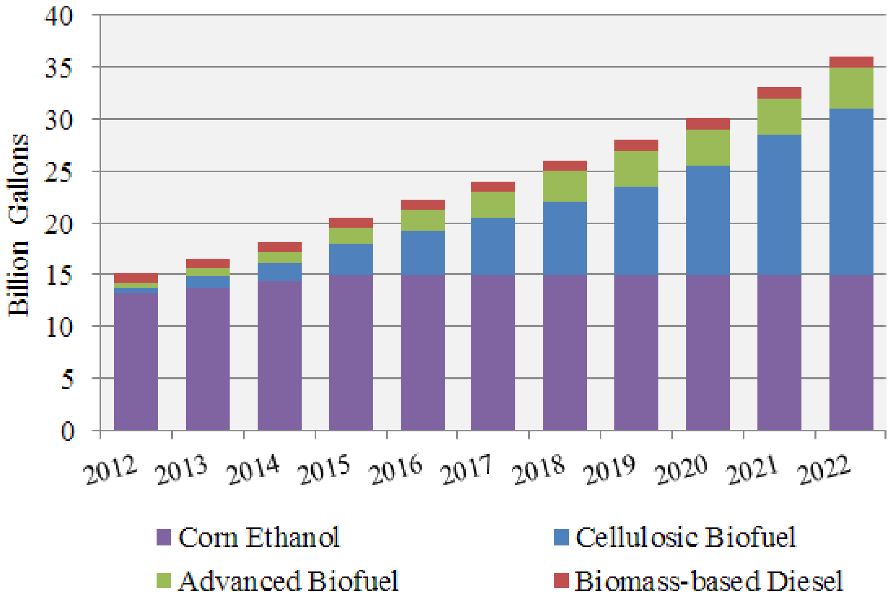

Figure 1.1 Revised Renewable Fuel Standards

and diesel range stock fuel. The report showes that the competitive product value (PV) for the biofuel is \$3.09/gal, which is promising for the investors of cellulosic biofuel industry. Pacific Northwest National Laboratory (PNNL) has also been doing economic analysis for woody biomass to produce biogasoline and biodiesel, the minimum fuel selling price is \$4.88/gal.

Some research has been done on biofuel supply chain. Typical models built in biofuel supply chain are facility location models to make decisions on the number facilities to build, facility capacity and logistic decisions such as transportation quantities of biomass and biofuels [5, 16, 17]. Some models considering biomass supply and biofuel demand, price uncertainty are also built[2, 23, 33]. Most of the optimization models make ideal assumptions that the farmers, producers and consumers are independent of each other and make optimal decisions according to the optimization model. However, in real world, farmers could exchange information with each other, or sign contract with producers to reduce risk in production. In the recent years, the agent-based simulation models have been applied to biofuel supply chain to simulate the whole biofuel supply chain, in which game theory, evolutionary programming, Monte Carlo Methods are also incorporated to better describe the supply chain [47, 32]. In this thesis, an optimization model is built to simulate the biofuel supply chain model, and cost analysis is done under different biofuel demand scenarios.

Since biofuel market is at early stage, besides cost analysis of biofuel production and facility building, a number of existing models has been applied to analyze social welfare and policy impact on biofuel market [14, 8, 58, 35]. Most of the models analyze the social welfare under the assumption that the market is competitive, while few models evaluate each entity's profit (farmers, biofuel producers, and biofuel blenders), and provide insights for their decision making. In this thesis, a complementarity model is developed to analyze the profitability from each stakeholder's perspective under different market structures and various policy scenarios.

The rest of the thesis is organized as follows. In Chapter 2, a biofuel supply chain design and operational planning model is formulated to analyze the facility location and sizing, biomass and biofuel transportation. Operational planning for a biorefinery facility under a variety of biofuel demand scenarios is also presented. In Chapter 3, we present a bottom-up equilibrium model to investigate the emerging biofuel market. Impacts of market structure and government policy are investigated to promote the marginal insights for investors and regulatory agencies. Chapter 4 concludes the thesis with a summary of the research findings and proposed future research directions.

CHAPTER 2. SUPPLY CHAIN DESIGN AND OPERATIONAL PLANNING MODELS FOR BIOMASS TO DROP-IN FUEL PRODUCTION

2.1 Introduction

Second generation biofuel is playing an increasingly important role as a substitute for fossil oil from environmental, economic, and social perspectives. Second generation biofuels are made from nonedible plant residues or whole plant, such as corn stover and switchgrass, and because of this, the production of biofuel will not have much impact on the food market. According to RFS2, at least 36 billion gallons of renewable fuels will be produced by 2022, and at least 21 billion gallons will be from advanced biofuels [45]. Several biomass feedstocks can be used to generate second generation biofuels, such as woody biomass, dedicated energy crops, and agriculture residues. Corn stover, as the main cellulosic biomass supply in the Midwest, is the biomass feedstock under consideration in this chapter. Due to infrastructure compatible considerations, the production pathways in this chapter focus on drop-in fuel production.

Drop-in biofuels are hydrocarbon fuels including gasoline, diesel, and jet fuels which are ready for vehicles to use without any modification to engines or fuel transportation networks. The general procedure to produce drop-in biofuel from second generation biomass is as follows. First, biomass feedstocks are collected and pretreated to prepare for storage and transportation [7]. Pretreatment includes reducing the moisture level and particle size of the biomass [10, 29]. Then preprocessed biomass is sent to biorefinery facilities by truck to be converted into biofuel and other byproducts [40]. Raw biofuel is refined and blended for final usage in Metropolitan Statistical Areas (MSAs), as shown in Figure 2.1 [15, 57].

There are two main processing platforms to convert biomass into biofuel: thermochemical and biochemical [61]. Thermochemical processes utilize heat to facilitate the depolymerization of biomass

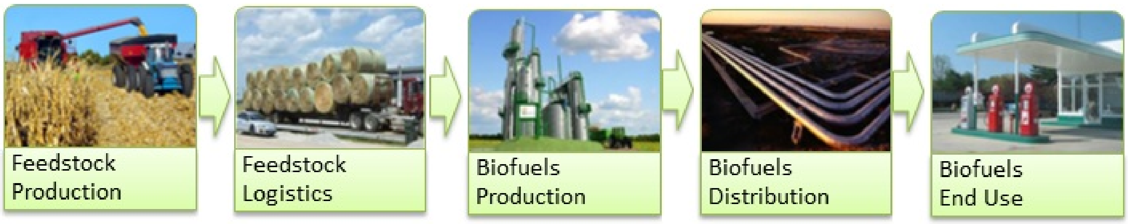

Figure 2.1 Biomass supply chain framework for biofuel production and distribution

compounds which are further processed into biofuel and co-products. Biochemical processes involve living organisms or their products to convert organic materials to fuels, chemicals, and other products. The thermochemical platform is becoming a more efficient and promising process to produce cellulosic based biofuel [20]. There are different thermochemical procedures to convert biomass into second generation biofuel. Detailed thermochemical processes and products, including fast pyrolysis and bio-crude oil upgrading processes, as well as economic analysis for these processes are presented in [11]. A comparison of different energy sources and biomass pyrolysis models is shown in [3] to provide a general idea of biomass pyrolysis processes. Different pyrolysis processes including conventional pyrolysis, fast pyrolysis, and flash pyrolysis are illustrated in [6]. In this chapter, we consider the fast pyrolysis pathway, and evaluate its unit cost.

Supply chain design and operational planning is one of the largest challenges to the cellulosic biofuels industry. It becomes very important to consider the supply chain of biofuel production systems [5]. Feedstock production and logistics constitute 35% or more of the total production costs of advanced biofuel [1, 39], and logistics associated with moving biomass from the land to the biorefinery can make up (50 to 75)% of the feedstock costs [25]. To facilitate the commercialization of biofuel production, it is important to investigate the optimal number and locations for biorefinery facilities, and to find the optimal allocation of corn stover feedstock and biofuel distribution. A general facility location and operation problem, maximizing profit for a biofuel supply chain is presented in [9] to determine the optimal selection of biomass, optimal number, sizes and locations of biorefineries, and preprocessing hub facilities. A MILP model proposed in [50] investigated the optimal production allocation, capacity, and operation of a global supply network by minimizing operational costs including production costs, material handling cost, transportation cost, and duties for material flowing within supply chain network subject to exchange rates.

Operational planning is also essential for biofuel supply chain and network design. Various papers focus on generating multi-period operational planning over one year. A stochastic multi-period model is proposed in [23] for biofuel production from switchgrass, and presented results on both biomass supply and biofuel demand stochastic scenarios. Seasonal results for second generation biofuel from switchgrass and a mixture of biomass, and analyzed the effects of biomass yields on biofuel production planning and profit change are presented in [64].

It is typical in literature to assume that biofuel demands are met. It is assumed in [5] that biofuel demands will always be met. An assumption that a biorefinery facility has to run at full capacity is made in [60]. These assumptions might not be true for realistic cases. Different ways that corn stover can be used are presented in [26], such as cellulosic ethanol plants, coal plants, beef and dairy cattle feed, and other industrial applications. With competition for biomass supply, it is possible that there is not enough biomass supply for biofuel production, which would make the mathematical models in [5, 60] infeasible. Alternatively, if biomass supply is sufficient enough to support biorefineries running at full capacity, more than enough biofuel will be produced, in which case true optimal planning for biorefinery facilities will not be reached.

In the proposed model, we do not force biofuel demand to be satisfied exactly, which enables us to solve this problem even if we don't have enough biomass supply to satisfy biofuel demand or if production is more expensive than biofuel market price. This allows us to make decisions about optimal biorefinery locations and sizes of biorefinery facilities, biomass and biofuel distribution, and operational planning about biofuel production. Another contribution of this study is the addition of an operational planning element. In this chapter, we use a multi-period optimization model to present detailed operational planning for biomass distribution and drop-in fuel production and distribution. In this chapter, sensitivity of different biofuel demand patterns is analyzed.

The rest of the chapter is organized as follows. In section 2.2, model assumptions and formulation for both an annual and an operational planning model are presented. In section 2.3, we show the source of data and numerical experiment results. In section 2.4, we summarize our results and present future work.

2.2 Model formulation

This study aims to minimize total cost for biofuel production using a Mixed Integer Linear Programming model (MILP). Instead of only optimizing the number of biorefinery facilities and locations assuming that biomass feedstock can satisfy biofuel demand of all MSAs [60], the proposed model aims to optimize the number of biorefinery facilities, facility sizes, locations, biomass, and drop-in fuel distribution considering various scenarios of biofuel production.

It is assumed that corn stover is collected and pretreated at farms; hence, no extra feedstock process facility is needed in the supply chain [17]. Trucks are assumed to be the biomass transportation mode with a fixed unit transportation cost. Pretreated biomass is transported to conversion and upgrading facilities. For the biofuel conversion process, it takes both fast pyrolysis and biofuel upgrading processes to produce biofuel. In reality, biofuel upgrading facilities may not be integrated with fast pyrolysis facilities. In this study, we assume that biofuel conversion and upgrading are conducted in the same facility. Final biofuel is assumed to be transported through existing pipelines. No extra pipelines need to be built, and the unit transportation fee is fixed. Biofuel demand is based on the population in the MSA areas as shown in Figure 2.2 [51]. In the following sections, we present an annual based optimization model and an operational planning model for the region of Iowa. Notations used in the model are shown in Table 2.1.

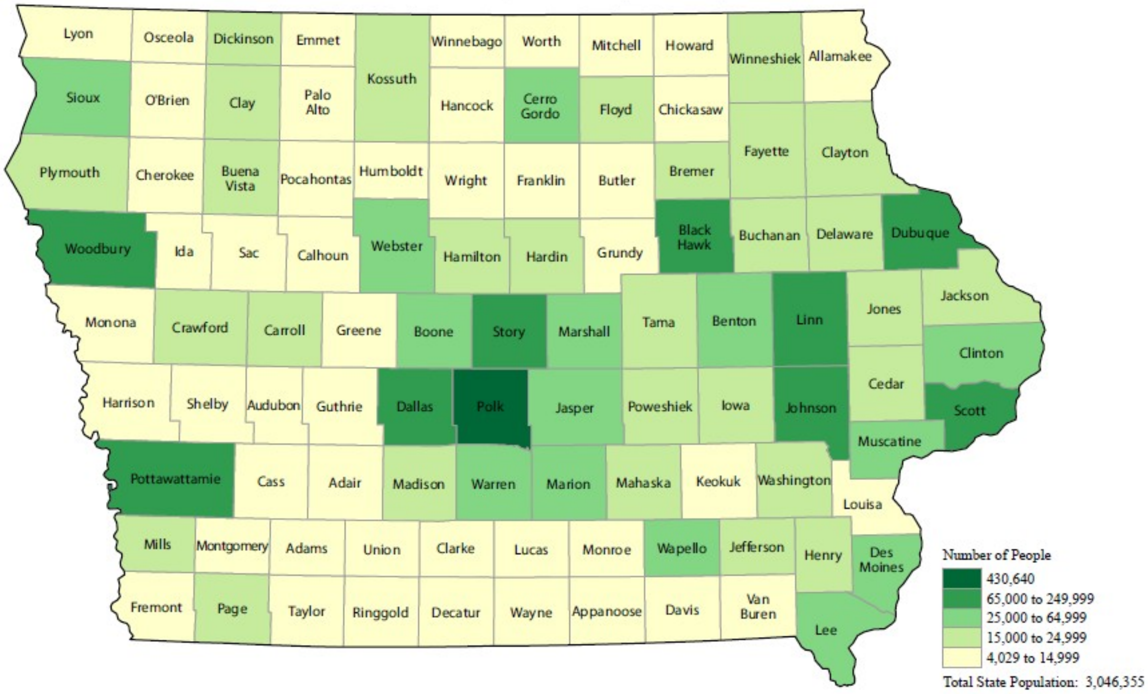

Figure 2.2 Iowa population distribution for 2010

2.2.1 Annually based model formulation

This annual based model aims to determine the number of facilities, facility sizes, and facility locations for a long term planning horizon. Various assumptions exist in literature. It is assumed in [60] that biomass supply can reach biorefiney capacity and that biorefinery facilities will always run full capacity. Assumption that all biofuel demand can be fulfilled exactly is made in [5]. Tsiakis et al. [50] assumed that all unfulfilled demand will be satisfied by outsourced fuel, no matter what the cost will be. Gebreslassie et al. [23] identified a constraint regarding biomass safety stock inventory levels to make sure that the biomass supply isn't disrupted. For this model, we assume that biorefinery facilities will run according to optimal allocation of biomass and biofuels, constrained by the capacity of storage and refinery facilities, but flexible for storage and production levels. The objective is to minimize total annual cost including biomass transportation, biofuel conversion, biofuel transportation, fixed facility cost, and biofuel shortage penalty. The level of biofuel demand fulfillment depends on the market price of biofuels. The schematic of this model is illustrated in Figure 2.3.

Figure 2.3 Biofuel supply chain framework

The annual based model formulation is shown in Equations (2.1a)-(2.1i).

$$
\begin{aligned}
\min \quad & \textstyle\sum_{i=1}^{N}\sum_{j=1}^{N}(C_i^{S,CL}+\tau D_{i,j}C_{i,j}^{S,T})f_{i,j}+\sum_{j=1}^{N}\sum_{k=1}^{M}(C_j^{G,C}+\tau\gamma D_{j,k}C_{j,k}^{G,T})q_{j,k} \\
& \textstyle +\sum_{k=1}^{M}\lambda_k(G_k-\sum_{j=1}^{N}q_{j,k})_{+}+\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C_l^B\delta_{j,l}}{\frac{(1+r)^H-1}{r(1+r)^H}} && (2.1a)\\
s.t. \quad & \textstyle\sum_{j=1}^{N}f_{i,j}\leq(1-S_i)A_i,\forall i\in I && (2.1b)\\
& \textstyle(1-\ell)\sum_{i=1}^{N}f_{i,j}\leq\sum_{l=1}^{L}U_l^B\delta_{j,l},\forall j\in I && (2.1c)\\
& \textstyle(1-\ell)\sum_{i=1}^{N}f_{i,j}Y_j=\gamma\sum_{k=1}^{M}q_{j,k},\forall j\in I && (2.1d)\\
& \textstyle\sum_{l=1}^{L}\delta_{j,l}\leq 1,\forall j\in I && (2.1e)\\
& \textstyle\sum_{j=1}^{N}\sum_{l=1}^{L}C_l^B\delta_{j,l}\leq Q && (2.1f)\\
& f_{i,j}\geq 0,\forall i,j\in I && (2.1g)\\
& q_{j,k}\geq 0,\forall j\in I,k\in K && (2.1h)\\
& \delta_{j,l}\in\{0,1\} && (2.1i)
\end{aligned}
$$

The objective function (2.1a) is to minimize costs for collecting, loading, and transporting feedstock and biofuel, the fixed cost for biorefinery facilities, as well as penalties for not satisfying demand for each MSA k; Constraint (2.1b) denotes that for each county i, the shipped-out feedstock should be no more than available feedstock; Constraint (2.1c) means that if biorefinery facility j operates, then feedstock shipped to j should be no more than the capacity; Constraint (2.1d) indicates the mass balance of biomass and biofuel for each biorefinery facility j. Biofuel produced should be equal to biofuel shipped; Constraint (2.1e) sets constraints on the facility, that at most one facility of one size can be built; Constraint (2.1f) is the budget limit constraint for the facility building.

This is a nonlinear model formulation with a nonlinear objective function. Here we propose to linearize the model formulation by adding continuous variables $y_{1,k}$:

$$\begin{aligned} \min \quad & \textstyle\sum_{i=1}^{N} \sum_{j=1}^{N} (C_i^{S,CL} + \tau D_{i,j} C_{i,j}^{S,T}) f_{i,j} + \sum_{j=1}^{N} \sum_{k=1}^{M} (C_j^{G,C} + \tau\gamma D_{j,k} C_{j,k}^{G,T}) q_{j,k} \\ & + \textstyle\sum_{k=1}^{M} \lambda_k y_{1,k} + \sum_{j=1}^{N} \sum_{l=1}^{L} \frac{C_l^B \delta_{j,l}}{\frac{(1+r)^H - 1}{r(1+r)^H}} \end{aligned} \tag{2.2a}$$

$$s.t. \quad \text{Constraints (2.1b)-(2.1f)}$$

$$y_{1,k} \geq G_k - \textstyle\sum_{j=1}^{N} q_{j,k}, \forall k \in K \tag{2.2b}$$

$$\text{Constraints (2.1g)-(2.1i)}$$

$$y_{1,k} \geq 0 \tag{2.2c}$$

Here λ_k is the penalty for biofuel demand shortage. We assume it to be the market price of gasoline. The total annual cost divided by the annual biofuel production would be the average unit cost for biofuel for this process.

2.2.2 Model formulation with operational planning

With an annual based optimization model, we can find the optimal biorefinery location, and biomass and biofuel distribution. However, for commercial biofuel industry producers, a multi-period model is more practical and can present a more detailed and realistic guide for resource allocation. Zhu et al. [63] presented a multi-period MILP model to show the feasibility of commercially producing biofuel from switchgrass. Gebreslassie et al.[23] investigated the operational planning of switchgrass under biomass supply and biofuel demand uncertainty given multiple conversion technologies, feedstock seasonality, and demand variation. In this section, we present a multi-period MILP model for corn stover with deterministic biomass supply and biofuel demand to make an optimal decision on the number, size, and locations of biorefinery facilities; biorefinery operating planning; biomass and drop-in biofuel storage, and distribution plans within a year. We note that the multi-period model will increase the computational effort due to the increase in size of the problem. The schematic is shown in Figure 2.4.

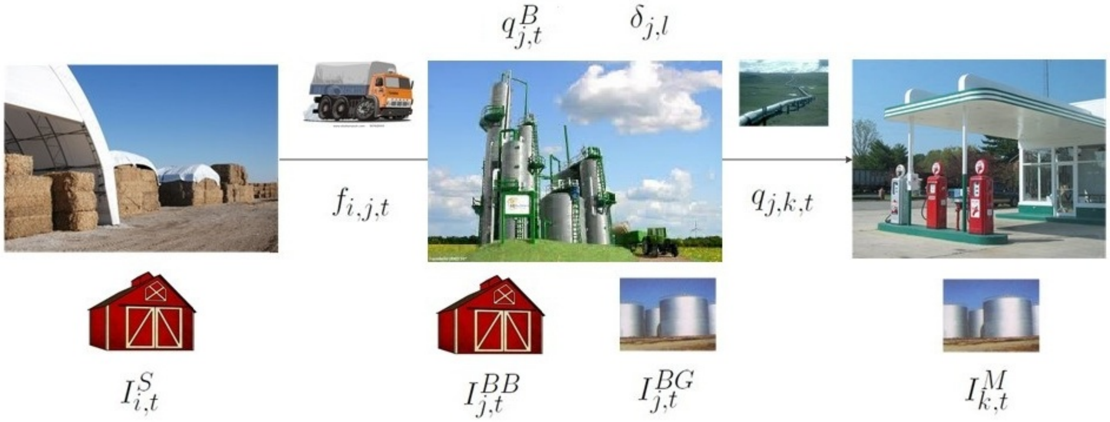

Figure 2.4 Multi-period model framework of biofuel production and distribution

$$\begin{aligned}
\min \quad & \textstyle\sum_{t=1}^{T}\{\sum_{i=1}^{N}\sum_{j=1}^{N}\tau D_{i,j}C_{i,j}^{S,T}f_{i,j,t}+\sum_{j=1}^{N}\sum_{k=1}^{M}\tau D_{j,k}C_{j,k}^{G,T}q_{j,k,t}\gamma \\
& \textstyle+\sum_{i=1}^{N}C^{S,CL}v_{i,t}+\sum_{i=1}^{N}h_i^{S}I_{i,t}^{S}+\sum_{j=1}^{N}h_j^{B,B}I_{j,t}^{B,B}+\sum_{j=1}^{N}h_j^{B,G}I_{j,t}^{B,G}+\sum_{k=1}^{M}h_k^{M}I_{k,t}^{M} \\
& \textstyle+\sum_{j=1}^{N}\frac{1}{\gamma}C_j^{G,C}q_{j,t}^{B}+\sum_{k=1}^{M}\lambda_{k,t}(G_{k,t}-\sum_{j=1}^{N}q_{j,k,t})_{+} \\
& \textstyle+\sum_{j=1}^{N}\sum_{l=1}^{L}\frac{C_l^{B}\delta_{j,l}}{\frac{(1+r)^{H}-1}{r(1+r)^{H}}}
\end{aligned} \tag{2.3a}$$

$$v_{i,t}\leq(1-S_i)A_{i,t},\forall i\in I,t\in T \tag{2.3b}$$

$$\delta_{j,l}\underline{U}_{l,t}^{B}\leq q_{j,t}^{B}\leq\delta_{j,l}\overline{U}_{l,t}^{B},\forall j\in I,t\in T,l\in L \tag{2.3c}$$

$$I_{i,t}^{S}=(1-\ell)I_{i,t-1}^{S}+v_{i,t}-\textstyle\sum_{j=1}^{N}f_{i,j,t},\forall i\in I,t\in T \tag{2.3d}$$

$$I_{j,t}^{B}=(1-\ell)I_{j,t-1}^{B}+\textstyle\sum_{i=1}^{N}f_{i,j,t}-r_{j,t},\forall j\in I,t\in T \tag{2.3e}$$

$$I_{j,t}^{G}=I_{j,t-1}^{G}+\frac{1}{\gamma}q_{j,t}^{B}Y_j-\textstyle\sum_{k=1}^{M}q_{j,k,t},\forall j\in I,t\in T \tag{2.3f}$$

$$I_{k,t}^{M}\geq I_{k,t-1}^{M}+\textstyle\sum_{j=1}^{N}q_{j,k,t}-G_{k,t},\forall k\in K,t\in T \tag{2.3g}$$

Constraints (2.1e),(2.1f).

$$0\leq I_{i,t}^{S}\leq U_i^{S},\forall i\in I,t\in T \tag{2.3h}$$

$$0\leq I_{j,t}^{B}\leq U_j^{B,B},\forall j\in I,t\in T \tag{2.3i}$$

$$0\leq I_{j,t}^{G}\leq U_j^{B,G},\forall j\in I,t\in T \tag{2.3j}$$

$$0\leq I_{k,t}^{M}\leq U_k^{M},\forall k\in K,t\in T \tag{2.3k}$$

$$I_{i,0}^{S}=I_{j,0}^{B,B}=I_{j,0}^{B,G}=I_{k,0}^{M}=0,\forall i,j\in I,k\in K \tag{2.3l}$$

$$f_{i,j,t}\geq 0,\forall i,j\in I,t\in T \tag{2.3m}$$

$$q_{j,k,t}\geq 0,\forall j\in I,k\in M,t\in T \tag{2.3n}$$

$$v_{i,t}\geq 0,\forall i\in I,t\in T \tag{2.3o}$$

$$q_{j,t}^{B}\geq 0,\forall j\in I,t\in T \tag{2.3p}$$

$$\delta_{j,l}\in\{0,1\},\forall j\in I,l\in L \tag{2.3q}$$

The objective function (2.3a) is to minimize total cost including farm to biorefinery transportation cost, biorefinery to MSAs transportation cost, biomass harvest cost, biomass storage cost at farm, biofuel cost at biorefinery and MSA, biofuel conversion cost, penalty for biofuel demand shortage, and fixed cost for building facilities. Constraint (2.3b) shows that for each month, biomass harvest cannot exceed available biomass. Constraint (2.3c) indicates that biorefinery facilities only operate when production reaches a certain level. In this study, both upper and lower bounds for production levels are set for the refinery facilities to operate. Constraints (2.3d)-(2.3g) are biomass and biofuel storage balance constraints at each facility. Decision variables in this model include equation (2.3h)-(2.3q).

2.3 Computational results

Iowa has been recognized as one of the leading states for biofuel production [53]. Currently, there are several commercial size biorefinery plants under construction in Iowa. In the computation analysis section, we illustrate the model formulation for the state of Iowa. Results of both the annual based model and the multi-period operational planning model are presented. Parameters and data sources are listed in Table 2.2.

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

2.3.1 Annual model results and analysis

In this scenario, biofuel shortage penalty λ is set at \$4/gal, the average market price of gasoline. This means that we need to purchase biofuel at \$4/gal at market to fulfill biofuel demand in all MSAs if there is any gasoline shortage.

- If there is no budget limit for building facilities, the optimal number of facilities that can be built with all biofuel demand satisfied is 23, with the average unit cost for producing biofuel at \$2.78/gal, and biomass and biofuel allocation as shown in Figure 2.5. The cost components are shown in Figure 2.7.

  From the figure, we see that there are 4 biorefinery facilities built in the same city with MSAs, and they are all running 2200 ton/day. 10 facilities are running 1650 ton/day and 13 facilities are running 2200 ton/day. This allocation of facilities is optimal in minimizing biomass and biofuel transportation distance. Gasoline demand in all MSAs is satisfied.

- If the budget is limited, then the minimum budget to satisfy all gasoline demand is 4200 million dollars. The optimal number of facilities we could build is 21, and more facilities are built in 2200

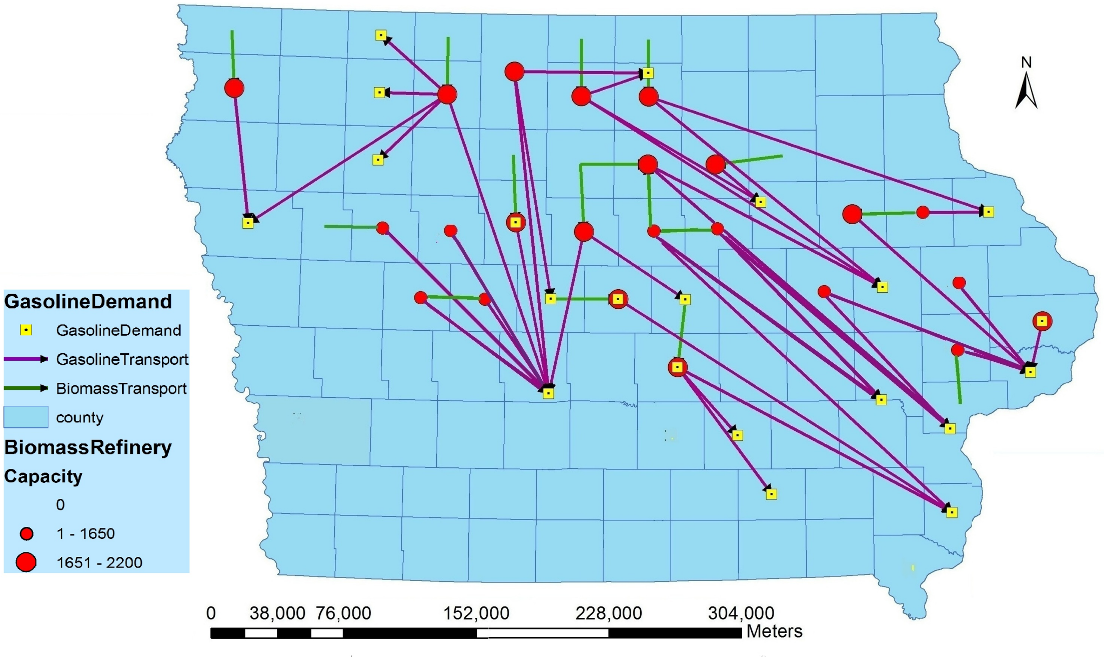

Figure 2.5 Annual model result with no capital budget limit

ton/day. The average unit cost of gasoline is \$2.79/gal. Biomass and biofuel allocations are shown in Figure 2.6. Cost allocation is shown in Figure 2.7.

If only 21 biorefinery facilities are built, only two facilities will run 1650 ton/day, and all others will run 2200 ton/day. In this scenario, all gasoline demand can still be satisfied. From Figure 2.7, we see that gasoline conversion cost, biomass collection cost, and facility building cost are three major cost components for gasoline production. If 21 facilities are built, transportation cost of biomass is higher.

- If the budget is not enough to build facilities to satisfy all demand, then nearby MSAs or MSAs with higher biofuel shortage penalty λ will be satisfied first. For example, if there is only enough budget to build one facility, and penalties for all MSAs are the same, then the optimal location to build this facility is Webster County (see Figure 2.8) which would supply biofuel to three nearby MSAs. If we give priority to MSA Burlington for biofuel demand by setting the biofuel shortage penalty in Burlington as $\lambda = 10$ and other MSAs as $\lambda = 4$, then the optimal location to build a facility is

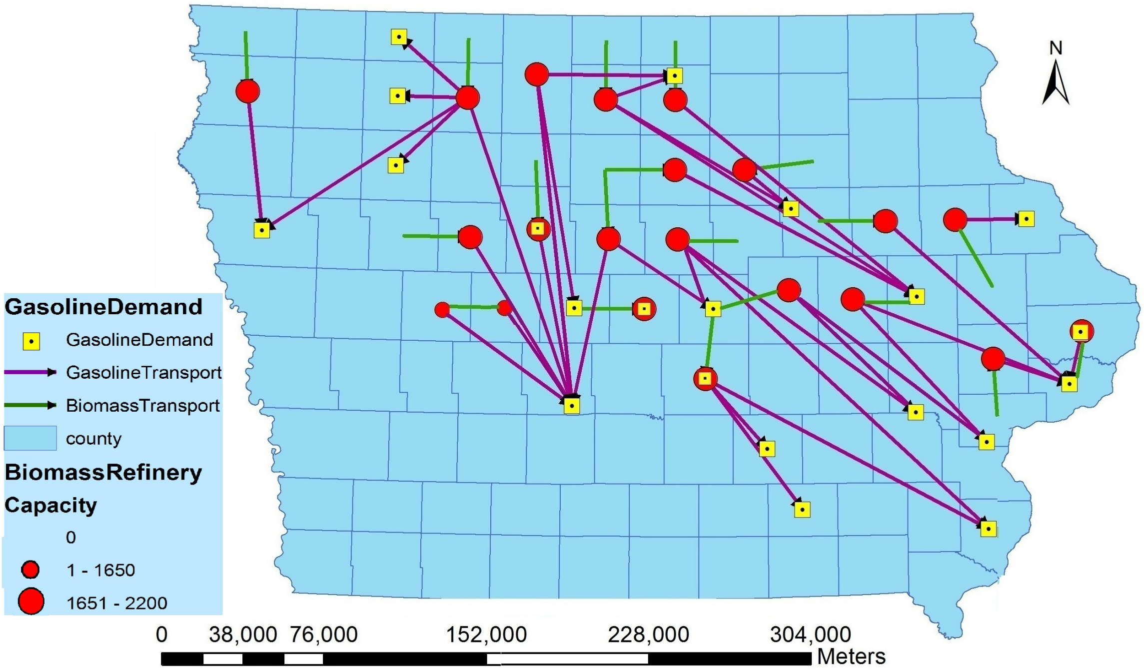

Figure 2.6 Annual model result with capital budget limit

Franklin County (see Figure 2.9), and we can see that biofuel demand in Burlington can still be satisfied even though transportation distance is longer.

2.3.2 Monthly model results and analysis

To better present the detailed allocation, feedstock, and biofuel storage over multiple operational periods, a multi-period model is analyzed and the optimal number of facilities, facility locations, biomass and biofuel allocation, storage levels at each storage facility, and unit production costs for biofuel are investigated.

In this example, we only consider scenarios for which there is no budget limit, since cases with a budget limit will get similar results with more facilities built at 2200 ton/day. For different demand patterns over twelve months, different biorefinery facility numbers, sizes and production level results are shown.

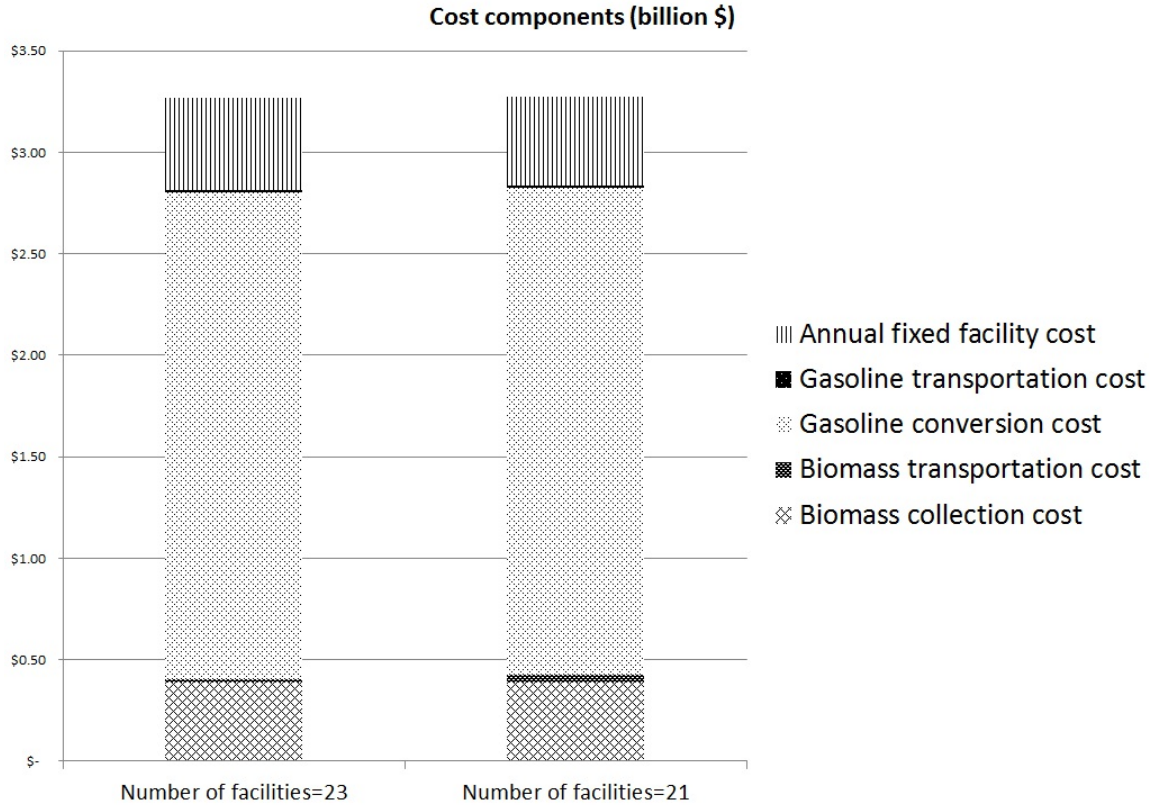

Figure 2.7 Comparison of total annual biogasoline production costs

- If the demand distribution is uniform, then optimal allocation is shown in Figure 2.10, with the optimal number of facilities being 23, including 10 facilities built for 1650 ton/day. The average unit cost of gasoline is $2.76/gal, and biofuel demands in all MSAs are satisfied. The cost components are presented in Figure 2.12. We see that biofuel conversion cost, fixed facility building cost, and biomass harvesting cost are three major costs in the supply chain of biofuel production. There is no storage cost in this case. Biofuel production distribution over all months is also uniform.

- For the increasing distribution in Figure 2.11, the optimal number of facilities is 24, with 2 facilities built at 1650 ton/day and all others built at 2200 ton/day. The average unit cost of gasoline is $2.98/gal, and all biofuel demands are satisfied. The cost components are shown in Figure 2.12. Biofuel production in all biorefinery facilities follows an nondecreasing distribution, and facilities produce extra biofuel in previous months to satisfy higher biofuel demand in later months.

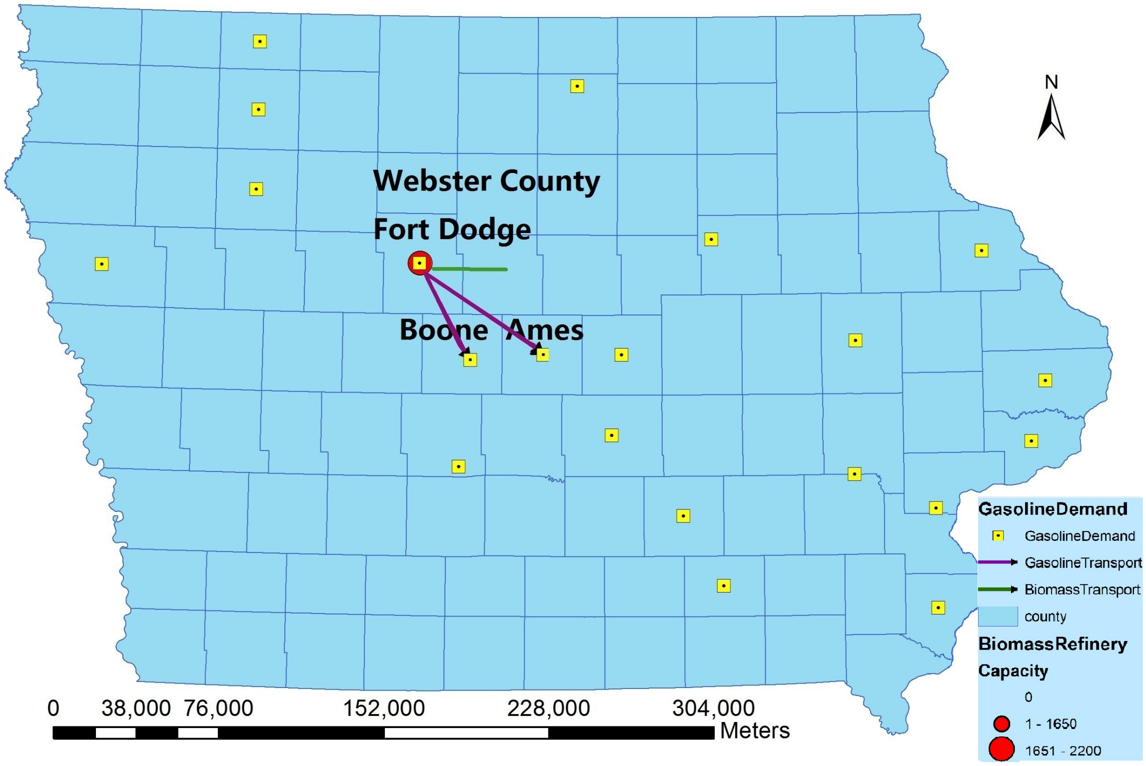

Figure 2.8 Biomass and biofuel distribution under uniform penalty

- For the decreasing distribution in Figure 2.11, if the biofuel shortage penalty is $4/gal, then the optimal number of facilities built is 20, with all 20 facilities built at the 2200 ton/day level. The average unit cost of gasoline is $3.32/gal including biofuel shortage cost, and $3.10/gal without considering a biofuel shortage cost. In this case, not all biofuel demands are satisfied, and 10 of 21 MSAs' biofuel demands are not satisfied in the first month. Biofuel production in each month follows a non-increasing distribution. Cost components in this scenario are seen in Figure 2.12. In this scenario, the biofuel shortage cost is an additional significant component for total cost.

- For the triangle distribution illustrated in Figure 2.11, the optimal number of facilities is 21, with 2 facilities built at 1650 ton/day and all others built at 2200 ton/day. 8 out of 21 MSAs' biofuel demands are not satisfied. The average unit cost of gasoline is $2.90/gal including biofuel shortage cost, and $2.80/gal without biofuel shortage cost. Biofuel demands in eight counties are not satisfied during February and March. The cost components are shown in Figure 2.12. Biofuel production in

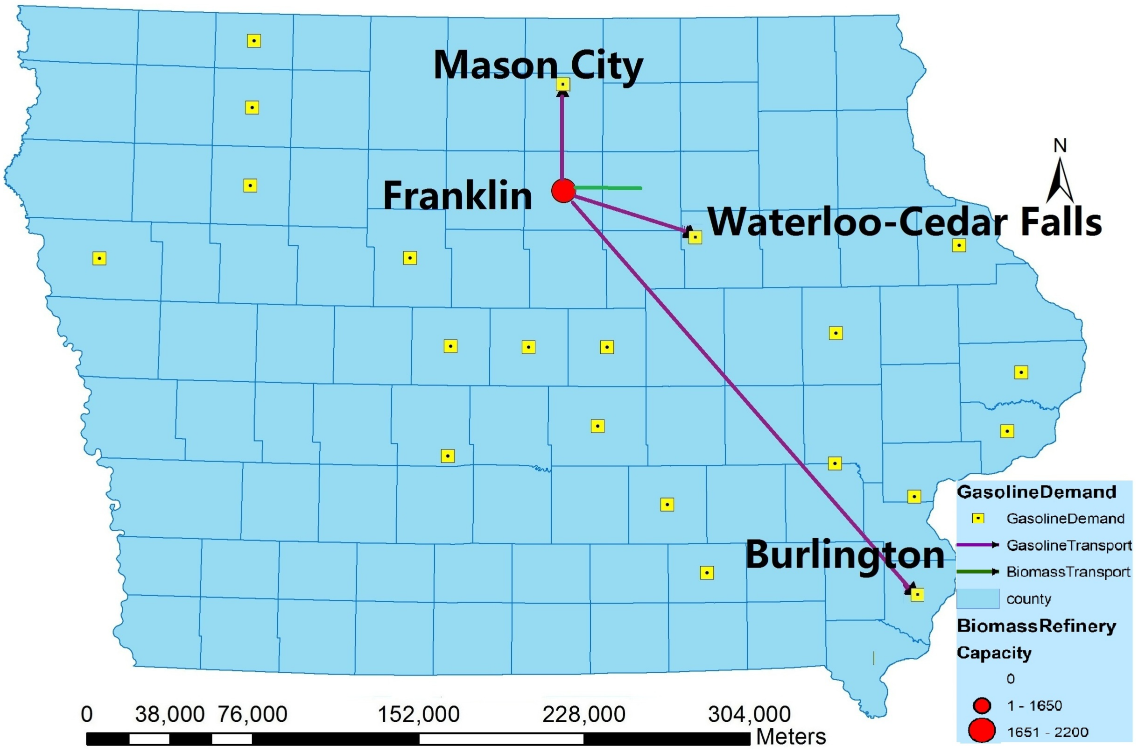

Figure 2.9 Biomass and biofuel distribution under uneven penalty

all biorefinery facilities follows a non-increasing distribution, and facilities produce extra biofuel in the first two months to satisfy higher biofuel demand in February and March.

2.4 Conclusion

Technology improvement in recent years has made it possible for commercial production of second generation biofuel. Supply chain design and operational planning represents one of the major challenges to cellulosic biofuel commercialization. This study aims to investigate the strategic and tactical planning of biorefinery facilities. This can assist the decision making process for inventors as well as government agencies to understand the impact of biofuel supply chain design and operational planning.

In this chapter, we present two models to optimize the number of biorefinery facilities, capacities, and locations. Biomass feedstock and biofuel distribution decisions are also investigated. The first model is an annual model for long term strategic planning. It shows the feasibility of biofuel production

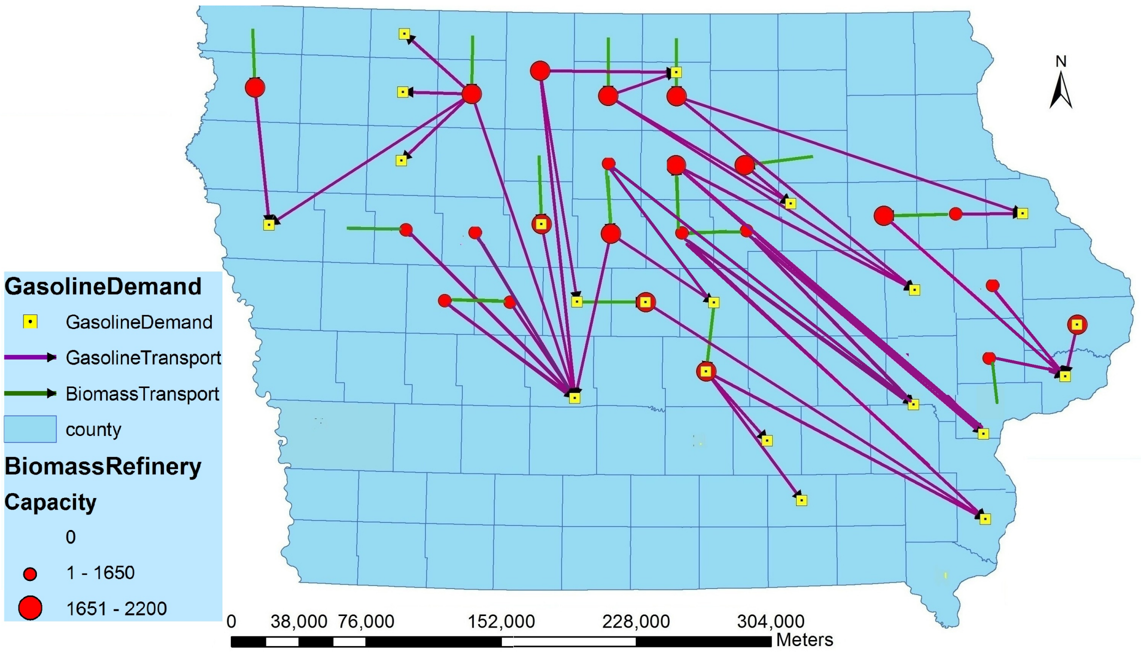

Figure 2.10 Monthly based model results under uniform gasoline demand

by presenting the facility location and biofuel unit production cost. Biomass collection cost, biofuel conversion cost, and fixed facility building cost are three major cost components in the model. If capital investment is not a limiting factor, it is optimal to build 23 facilities and fulfill the demand from all of the MSAs. If budget is limited, then the number of facilities will be a maximum number within the budget limit, with more facilities built at 2200 ton/day. In this model, we see the effect of a biofuel shortage penalty by presenting different facility locations and biofuel allocations. For MSAs with a higher penalty, the demand satisfaction is a trade-off between biofuel shortage penalties and biofuel transportation distance.

The second model provides detailed operational planning results about feedstock and biofuel allocation, and sensitivity of biofuel demand distribution. It is observed that biofuel demand can be satisfied at different levels for different demand distributions. For uniform and increasing distributions, all biofuel demand can be satisfied. However, for decreasing and triangle distributions, biofuel demands at the highest demand months will not be fulfilled even with more refinery facilities built. From this sensitivity analysis, we see that the commercialization of refinery facilities is feasible if the biofuel demand

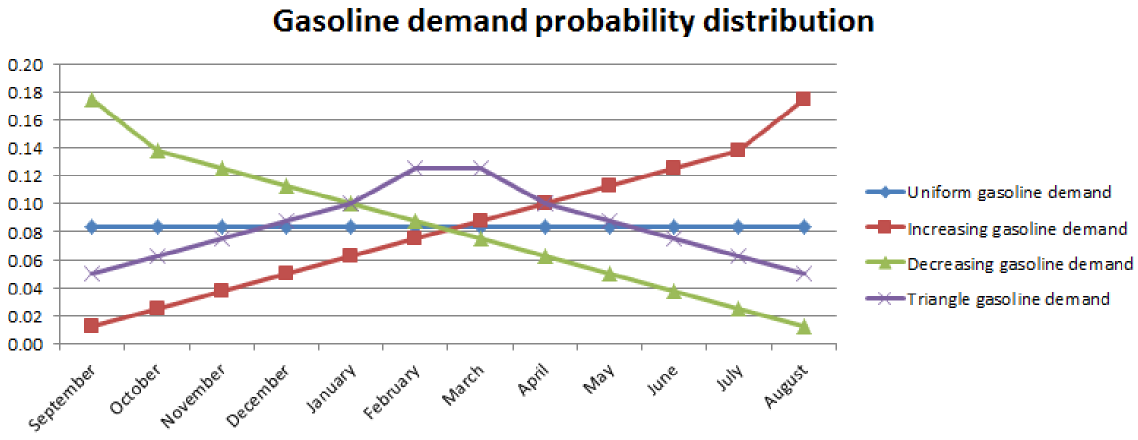

Figure 2.11 Gasoline demand distributions

distribution is steady or increasing over different months.

Assumptions have been made in this study. These assumptions suggest future research directions. One major assumption is that all facilities can be built at the same time. For future work, we could consider a sequential sitting problem for biorefinery facilities in the long term planning model. In this chapter, a deterministic scenario is the focus of the study. For future work, uncertainty can be incorporated into the model. For example, biomass feedstock supply could be random, considering weather conditions, seed quality, soil fertilization, etc. The biofuel demand utilized in this chapter was estimated based on the population in MSAs. Demand uncertainty could be another factor to make the model realistic for the supply chain and network optimization problem. The case study in this chapter only considered one type of biomass, one pretreatment technology, and one final product family. To better present the overall view of the biofuel supply chain, a more comprehensive model with multiple biomass and multiple processing technologies can be analyzed in the future.

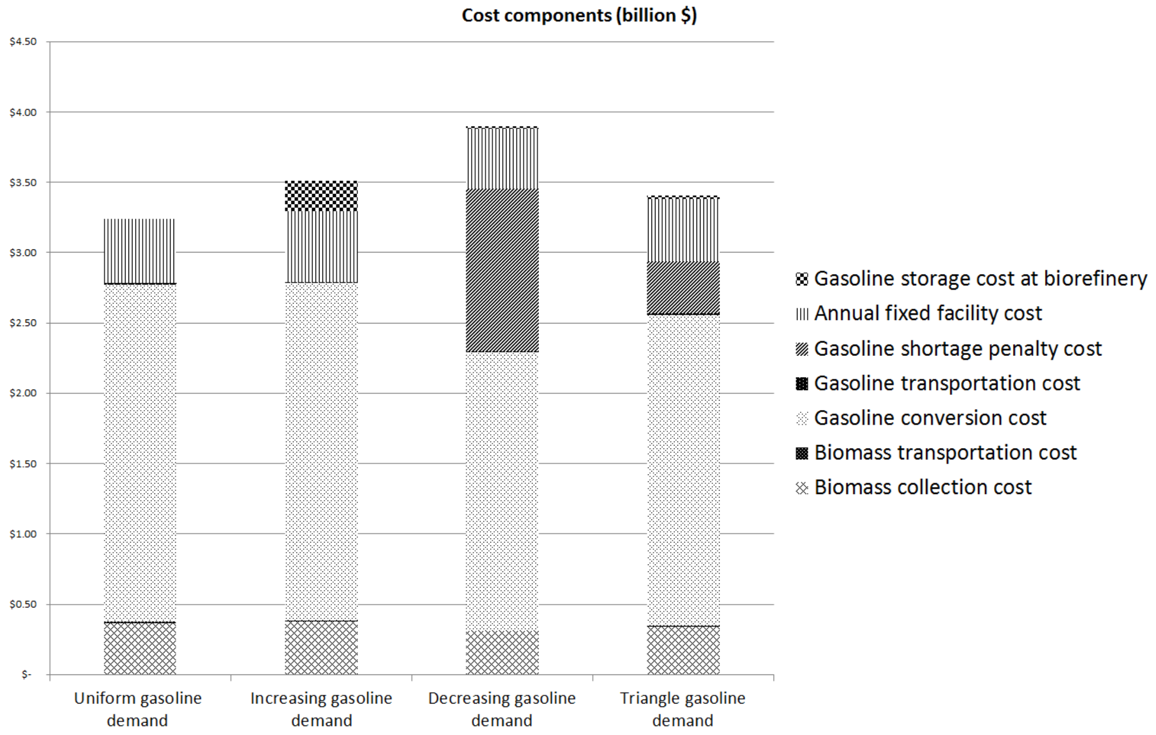

Figure 2.12 Comparison of total annual biogasoline production costs under different biofuel demand distributions

Table 2.1 Notations for biofuel supply chain model

Sets

I	i, j	i for biomass supply farm and j for biorefineries
K	k	Set for MSA customers (biofuel demand locations)
L	l	Set for biorefinery capacity level
T	t	Set of all time periods within a year

Feedstock parameters

N		Number of counties producing feedstock
A_i	ton	Available feedstock at county i in one year
$A_{i,t}$	ton	Available feedstock at county i in each time month
S_i		Sustainability factor for county i
$C_i^{S,CL}$	\$/ton	Feedstock collecting and loading cost at county i
h_i^S	\$/ton/month	Unit feedstock holding cost at county i
U_i^S	ton	Maximum storage capacity for county i
ℓ		Material loss factor for feedstock over one month
$D_{i,j}$	mile	Great circle distance from county i to county j
τ		Tortuosity factor
$C_{i,j}^{S,T}$	\$/ton/mile	Feedstock transportation cost from county i to county j

Biorefinery parameters

γ	ton/gal	Unit conversion coefficient of gallon to ton
U_l^B	ton	Fixed biorefinery capacity for each capacity level in one year
$\overline{U}_{l,t}^B$	ton	Fixed biorefinery capacity for each capacity level in each month
C_l^B	\$	Fixed biorefinery cost for each capacity level
Y_j		Biorefinery fuel process yield of feedstock at j
$C_j^{G,C}$	\$/gal	Unit conversion cost of biofuel at location j
Q	\$	Limit budget for all biorefinery facilities
H		Long term planning horizon in years
r		Annual interest for investment
$h_j^{B,B}$	\$/ton/month	Unit holding cost for biomass at biorefinery facility j
$h_j^{B,G}$	\$/gal/month	Unit holding cost for biofuel at biorefinery facility j
$\underline{U}_{l,t}^B$	ton	Minimum processing quantity per month of level l
$U_j^{B,B}$	ton	Maximum biomass storage level at biorefinery facility j
$U_j^{B,G}$	gal	Maximum biofuel storage level at biorefinery facility j

MSA and biofuel demand parameters		
M		Number of MSAs considered
G_k	gal	Total biofuel demand for MSA k
$G_{k,t}$	gal	Total biofuel demand for MSA k at month t
$C_{j,k}^{G,T}$	\$/ton/mile	Biofuel transportation cost from facility location j to MSA k
h_k^M	\$/gal/month	Unit holding cost for biofuel at MSA k
U_k^M	gal	Biofuel storage level at MSA k
Continuous variables		
$f_{i,j}$	ton	Flow of biomass feedstock from county i to county j
$f_{i,j,t}$	ton	Monthly flow of biomass feedstock from county i to county j
$q_{j,k}$	gal	Finished biofuel flow from county j to MSA k
$q_{j,k,t}$	gal	Monthly finished biofuel flow from county j to MSA k
$v_{i,t}$	ton	Feedstock harvest quantity in county i at time t
$q_{j,t}^B$	ton	Biomass process quantity in biorefinery j at time t
$I_{i,t}^S$	ton	Inventory level of feedstock in county i at time t
$I_{j,t}^{B,B}$	ton	Inventory level of feedstock in biorefinery facility j at time t
$I_{j,t}^{B,G}$	gal	Inventory level of biofuel in biorefinery facility j at time t
$I_{k,t}^M$	gal	Inventory level of biofuel in MSA k at time t

Binary variables	
$\delta_{j,l}$	Binary variable for biorefinery facility of level l built in county j

Table 2.2 Data source for biofuel supply chain model

Parameters	Data	Notes	References
Feedstock parameters			
N	99	Number of counties in Iowa	
A_i		Available feedstock in one year	NREL
S_i	0.718	Sustainability factor	[48]
$C_i^{S,CL}$	\$26.46-\$49.60/ton	Feedstock collecting and loading cost	[24, 38]
h_i^S	10% of product value	Unit feedstock holding cost	Assumed
U_i^S	1 000 000 ton	Maximum storage capacity	Assumed
ℓ	5%	Material loss factor for feedstock	Assumed
$D_{i,j}$		Great circle distance	
τ	1.27	Tortuosity factor	[44]
$C_{i,j}^{S,T}$	\$0.21/ton/mile	Feedstock transportation cost per unit	[46]
Biorefinery parameters			
γ	$\frac{2.47}{1000}$ ton/gal	Unit conversion coefficient of biogasoline from liter to tonne	
U_l^B	440, 1100, 1650, 2200 ton/day	Fixed biorefinery capacity in one year	[59]
C_l^B		Fixed biorefinery cost	[59]
Y_j	0.2180	Biorefinery fuel process yield of feedstock	Assumed
$C_j^{G,C}$	\$2.04/gal	Unit conversion cost of biofuel	[31]
H	30 years	Long term planning horizon in years	Assumed
r	10%	Annual interest for investment	Assumed
$h_j^{B,B}$	20% of product value	Biomass holding cost at biorefinery facility	Assumed
$h_j^{B,G}$	20% of product value	Biofuel holding cost at biorefinery facility	Assumed
$\overline{U}_{l,t}^B$		Fixed biorefinery capacity in each time period	
$\underline{U}_{l,t}^B$	60% of $\overline{U}_{l,t}^B$	Minimum processing quantity per month	
$U_j^{B,B}$	792,000 ton	Biomass storage capacity at biorefinery facility	Assumed
$U_j^{B,G}$	100,000,000 gal	Biofuel storage capacity at biorefinery facility	Assumed
MSA and biofuel demand parameters			
M	21	Number of MSAs considered	[19]
G_k		Biofuel demand	[19]
$G_{k,t}$		Biofuel demand	
$C_{j,k}^{G,T}$	\$0.016/ton/mile	Biofuel transportation cost per unit	[43]
h_k^M	30% of product value	Unit holding cost for biofuel	Assumed
U_k^M	50,000,000 gal	Biofuel storage level	Assumed

CHAPTER 3. A BOTTOM-UP BIOFUEL MARKET EQUILIBRIUM MODEL FOR POLICY ANALYSIS

3.1 Introduction

US ethanol production increased from 1,630 million gallons in the year 2000 to 13,900 million gallons in the year 2011; the number and capacity of ethanol plants also increased from 50 and 1,749 million gallons per day (mgy) in 2000 to 209 and 14,906 mgy in 2012 [41]. The expansion of infrastructure and production is mainly spurred by the biofuel demand induced by various public policies. The economic argument for favoring these policies is that when firms undertake research and development (R&D) for new technology that can not fully retain the economic rent due to the spillover effect. The associated externality of competing technologies, i.e., pollution emitted from producing conventional gasoline, is not fully internalized, and governmental intervention is needed to facilitate its development [49]. These policies differ by their “format,” i.e., quantity, price or hybrid instruments, or their points-of-implementation, i.e., farmers, blenders, producers, etc. Typically, a quantity instrument imposes a quota defining either the maximum or minimum quantities that need to be satisfied. For example, in fishery management an individual fishing quota sets a species specific allowable catch for an individual over a period of time. Price instrument defines a tax (subsidy) that collects from (gives to) an entity based on some activities of interest. An example is the Volumetric Ethanol Excise Tax Credit (VEETC), which expired in 2011. A hybrid system is a combination of the previous two instruments, which defines a “percentage” that needs to be satisfied. It acts as a subsidy for entities that over-comply with the requirement, and a tax for under-complying entities [22]. An example is the renewable portfolio standard that mandates certain percents of the electricity needs to be produced from renewable sources.

The major legislation promoting biofuels in the United States is Renewable Fuel Standards (RFS), which was created by the US Environmental Protection Agency (EPA) under the Energy Policy Act

(EPAct) in 2005. RFS mandates the production of renewable fuels, in which 7.5 billion gallons of renewable fuels are required to be blended into gasoline by 2012. The revised RFS (also known as RFS2) was issued in 2007, requiring that by 2022, more than 36 billion gallons of biofuel are produced, including 21 and 16 billions gallons from advanced biofuel and cellulosic biofuel, respectively. RFS or RFS2 essentially is a quantity instrument, and the point-of-implementation is the biofuel blenders. The compliance of RFS2 is determined by assigning each gallon of biofuel produced with a 38-character Renewable Identification Numbers (RINs). The RINs in biofuel are the analog of the emission permits in a cap-and-trade program. Each blender can sell its RINs if it exceeds the mandate of renewable biofuel production, while those who cannot meet the mandate must purchase adequate RINs from the market to cover its deficit. Under some mild conditions, e.g., competitive markets and perfect information, the marginal complacence cost should be equalized among all the blenders, and the aggregate cost is at its minimum for all blenders as a whole. The RIN prices are determined by supply and demand conditions of RINs in the market, reflecting their scarcity rent. Another complementary policy is the subsidy to biofuel producers or blenders proposed by The Food, Conservation, Energy Act (FCEA) of 2008. FCEA offers different levels of subsidy for the production of cellulosic feedstocks and for blending biofuels with gasoline. In particular, a \$1.01/gal of subsidy is provided for cellulosic biofuel produced and consumed in the US. [Act 15321, amending I.R.C. 40(a)]. With a \$45 subsidy per ton of biomass, the Biomass Crop Assistance Program supports farmers for collecting, harvesting, processing, and transporting cellulocis feedstocks [Section 9011]. Meanwhile, a tariff of of \$0.54 per gallon is levied on the imported sugarcane ethanol from Brazil to the US in order to protect the domestic industry. As seen, those policies differ not only by their *formate***,** e.g., quantity, price or hybrid, and their *point- of-compliance*, e.g., producers, blenders and farmers. Thus, models to address the impacts of these public policies must entail adequate flexibility to incorporate these details.

A number of existing models have been used to address the effects of various policies on the biofuel sectors. For example, Biofuel and Environmental Policy Analysis Model or BEPAM [14] is a spatial dynamic multi-market model that is formulated as a nonlinear program solving for prices endogenously. The model has been used to analyze the market impacts under RFS2, subsidies, import tariffs, and carbon tax policy. However, the model assumes the market is perfectly competitive, so the objective is to maximize the social surplus. The FASOM, Forest and Agricultural Sector Optimization Model, similar to BEPAM, a multiple-period model that accounts for forest and agricultural sectors, is formulated as a nonlinear program that maximizes the social surplus [8]. The model is simulated under perfectly competitive markets, however no important texture of the markets are contained in the model, such as blenders. Another model, FAPRI, developed by the Food and Agricultural Policy Research Institute, is a multi-market *top-down* partial equilibrium model that solves for market outcomes at both domestic and international markets at the macro level [58]. In a sense, the model is solved for a system of equations, with each representing the balance of supply and demand conditions for an underlying commodity. The strength of FAPRI is its ability to capture the interaction of multiple markets through its cross-elasticity formulation. Another popular model is BIOBREAK or Biofuel Breakeven model [35]. The model is a long run breakeven model that represents the feedstock supply system and biofuel refining process. This model estimates the breakeven price that biofuel refiners would pay for biomass and the breakeven price that biomass producers would be willing to accept for producing and delivering feedstock to biomass processing plants. Overall, these existing models do not entail adequate flexibility to incorporate market and policy details, e.g., market structure and point-of-implementation, that are crucial in determining the policy impacts.

Process-based models based on bottom-up principles have been used extensively to study the energy sector's response to proposed public policies or emerging markets. For example, models formulated as complementarity problems or mathematical programs with equilibrium constraints have been applied previously to assess the possible business partnership scenarios between feedstock suppliers and biofuel manufacturers [4]. In contrast to top-down models, process-based models are more flexible in representing optimization problems faced by different entities in the supply chain of energy production, institutional policies that impose on different entities, and market conditions. For example, a recent paper by Chen et al. [12] formulates the electricity sector as complementarity market models to study three proposed emission policies in California, in which each of the proposed policies has a different point of compliance. Process-based models represent supply curves using step functions. Each step corresponds to the marginal production cost of an individual technology or production unit. If production units are arrayed in the order of production costs, their "non-economic" performance, such as marginal emission rate, likely nonmonotonic and non-differentiable, can be appropriately represented by bottom-up models. There are at least two strengths of process-based modeling: explicitness and flexibility. The explicitness of the process-based approach allows for changes in technology, policies, input prices, and new entities in the supply chain or objectives to be modeled by altering decision variables, objective function coefficients or constraints. The transparency of the formulation and inputs of process-based models facilitates the review of model assumptions, and applies to a wide range of policy design parameters.

Some research has been done in biofuel supply chain to analyze the total production cost and risk for the biofuel industry. Eksioglu et al. [16] proposed a mathematical model to investigate the optimal size and location of biorefinery facilities as well as the short term logistic costs for biofuel production. You et al. [62] developed a multi-objective mixed integer linear programming model to optimize economic, environmental, and social benefits of a biofuel supply chain network. A multiperiod stochastic mixed integer linear programming model is built by Gebreslassie et al. [23] to optimize annualized cost and financial risk in the biorefinery supply chain under biomass supply and biofuel demand uncertainty. However, the decision of biorefinery facility locations and sizes based on available biomass in market and existing biofuel demand was not explicitly considered. Instead we focus on evaluating the profitability of different entities including farmers, producers, and blenders given that optimal location and size of biorefinery facilities are built, and farmers have the right to decide their biomass crop allocation and prices.

In this chapter, we develop a bottom-up equilibrium optimization model to study the supply chain of biofuel market, considering farmers, biofuel producers, blenders, and consumers. The model builds on individual's optimization problems and solves for farmers' land allocation, biomass transportation, biofuel production and biofuel blending activities. The prices in the market are determined endogenously by supply-demand conditions. The model also allows for consideration of market structure or firms' horizontal and vertical ownership that may arise to oligopoly competition at the different segments of the supply chain, e.g., blenders, biofuel producers, etc. [56]. This might be crucial for the development of the biofuel sector, owing to the fact that transportation constitutes a significant portion of the production costs, and a local monopoly or oligopoly could be possible when new entries are deterred by the limited biomass that can be procured within a reasonable transportation distance. Other factors such as lengthy permitting process and difficulty in accessing technology or capital might also possibly result in less competitive local markets. As experienced in other sectors, the extent to which the cost or subsidy passes on to consumers or producers depends on various factors, such as elasticity of supply and demand and market structure [13]. Therefore, models used to analyze public policy impacts on the biofuel sector should allow these factors to be explicitly accounted for in the analysis. To illustrate the strength of the bottom-up models, we focus on two aspects of the market conditions – market structure and choice of regulation or policy entity along the supply chain – and examine their impacts on the market outcomes.

The model is then applied to a case study in the state of Iowa. We have three central findings in the chapter. First, if a biofuel market is unregulated and allows blenders to exercise market power, then the blenders' are able to exercise market power and increase their own profits at the cost of social surplus by decreasing biofuel supply quantities to consumers, raising biofuel market prices, and lowering purchase prices of cellulosic biofuel. Therefore, it is important to study the potential social impact of market power and assess the necessity of market power regulation and mitigation. Second, when subsidy is given to farmers, producers, or blenders, it stimulates the total production level of biofuels, lower biofuel market prices faced by consumers, and increase consumer surplus and total social welfare. Moreover, the biofuel supply chain manages to pass subsidies through to all entities in the supply chain, and thereby incentivizes more invest in the biofuel industry. Although the subsidy passthrough may differ depending on the point-of-implementation, they are largely consistent percentage wise with the entities' profit. Third, our model is among the first to endogenously calculate RINs prices from a market equilibrium model, applying modeling and solution techniques of linear complementarity problems.

The rest of the chapter is organized as follows. Model introduction, formulation, and some solution techniques will be presented in Section 3.2. In Section 3.3, a small case study will be presented to better illustrate our model and the findings. Conclusions and future research will be discussed in Section 3.4.

3.2 Model formulation

In this study, we consider four entities in the biofuel supply chain: farmers, biofuel producers, biofuel blenders, and consumers. Farmers grow a variety of biomass crops to be harvested and sell to biofuel producers for biofuel production. We assume that throughout the supply chain, the transportation cost is paid by the downstream entities. For example, biofuel producers will pay for the biomass transportation fee from farmland to their facilities. Biofuel producers purchase crops from farmers through bilateral arrangement, convert different biomass into cellulosic ethanol and biogasoline, and then sell these to blenders, who then blend biofuels into drop-in fuel ready for vehicle use. Here we assume that production capacity of each producer is fixed. The prices of cellulosic ethanol and biogasoline are determined by the total supply and demand of ethanol and biogasoline. Ethanol is blended with gasoline into ethanol fuel mixtures such as E10 and E85 for vehicles consumption. In this study, we only consider ethanol fuel mixture product as the final blended product. Blenders blend cellulosic ethanol with conventional gasoline purchased from the market. Biogasoline is not blended, but purchased from producers and sold directly into the market. As a simplified case, in this study we assume each blender exclusively faces its own markets for both ethanol fuel mixture and biogasoline. Thus, other blenders cannot compete in markets besides their own. Finally, consumers of both ethanol fuel mixture and biogasoline are represented by separate inverse demand functions. We do not consider cross-elasticity between different fuel products, or cross different market platforms. However, in reality, a vehicle driver (when re-filling) gas would seek the lowest cost gas station when considering searching cost including time, fuel, etc.

In what follows, we first list the notations that we use in the chapter. We use lower case letters for variables and upper case letters for parameters. The optimization problem faced by each entity will be introduced first in Section 3.2.2-3.2.4, followed by the market equilibrium condition in section 3.2.5.

3.2.1 Notations and terminologies

Sets and Indices

F	Set of farmers
P	Set of producers
B	Set of blenders
C	Set of crops
$i \in \mathrm{F}$	Farmer i
$j \in \mathrm{P}$	Producer j
$k \in \mathrm{B}$	Blender k
$l \in \mathrm{C}$	Crop l

Parameters

L_i	Farmer i's total area of land available for biofuel crops [acre]
C^{F}_{il} (D^{F}_{il})	Intercept (slope) of farmer i's linear production cost function for crop l
Y_{il}	Farmer i's yield of crop l [ton/acre]
S^{F}_{l}	Government subsidy given to farmer i for each acre of biomass l planted [\$/acre]
T^{C}_{ijl}	Transportation cost of crop l from farmer i to producer j [\$/ton]
C^{E}_{jl} (D^{E}_{jl})	Intercept (slope) of producer j's linear production cost function for ethanol from biomass l
C^{BG}_{jl} (D^{BG}_{jl})	Intercept (slope) of producer j's linear production cost function for biogasoline from biomass l
R^{E}_{jl} (R^{BG}_{jl})	Producer j's conversion rate from crop l to ethanol (biogasoline) [gallon/ton]
U^{C}_{jl}	Producer j's process capacity for crop l [ton/year]
$S^{\mathrm{E,P}}$ ($S^{\mathrm{BG,P}}$)	Government subsidy given to producer j for each gallon of cellulosic ethanol (biogasoline) produced [\$/gal]
T^{E}_{jk} (T^{BG}_{jk})	Transportation cost of ethanol (biogasoline) from producer j to blender k [\$/gal]
A^{G}_{k} (B^{G}_{k})	Intercept (slope) of blender k's inverse supply function for gasoline [\$/gal]
A^{E}_{k} (B^{E}_{k})	Intercept (slope) of blender k's inverse demand function for E10 [\$/gal]
A^{BG}_{k} (B^{BG}_{k})	Intercept (slope) of blender k's inverse demand function for biogasoline [\$/gal]
U^{E}_{k} (U^{BG}_{k})	Blender k's process capacity for ethanol (biogasoline) [gallon/year]
C^{EG}_{k} (D^{EG}_{k})	Intercept (slope) of blender k's production cost function for each gallon of ethanol blended [\$/gal]
$S^{\mathrm{E,B}}$ ($S^{\mathrm{BG,B}}$)	Government subsidy given to blender k for each gallon of cellulosic ethanol (biogasoline) blended [\$/gal]
T^{REQ}_{k}	Total biofuel production mandate by government faced by blender k [gal]

Decision variables

a_{il}	Farmer i's area of land used to produce crop l [acre]
$x_{ijl}^{\mathrm{C,F}}$	Amount of crop l sold by farmer i to producer j [ton]
$x_{ijl}^{\mathrm{C,P}}$	Amount of crop l purchased by producer j from farmer i [ton]
$x_{jk}^{\mathrm{E,P}}$	Amount of cellulosic ethanol sold by producer j to blender k [gallon]
$x_{jk}^{\mathrm{E,B}}$	Amount of cellulosic ethanol purchased by blender k from producer j [gallon]
$x_{jk}^{\mathrm{BG,P}}$	Amount of biogasoline sold by producer j to blender k [gallon]
$x_{jk}^{\mathrm{BG,B}}$	Amount of biogasoline purchased by blender k from producer j [gallon]
t_{jl}^{E}	Amount of crop l converted to ethanol for producer j [ton]
t_{jl}^{BG}	Amount of crop l converted to biogasoline for producer j [ton]
p^{RIN}	RIN price for each gallon of biofuel in market [\$/gal]

Market clearing variables

p_{ijl}^{C}	Contract price between farmer i and producer j for crop l [\$/ton]
p_{jk}^{E}	Contract price between producer j and blender k for ethanol [\$/gal]
p_{jk}^{BG}	Contract price between producer j and blender k for biogasoline [\$/gal]

3.2.2 Farmer *i*'s profit maximization model

In this chapter, it is assumed that biomass can only be used for biofuel production but not sold into other markets. It is also assumed that farmers do not have market power in the supply chain. Unlike biofuel producers, decisions such as how much and which crop to plant are typically critical and need to be determined months ahead of harvest. The ability of farmers to behave strategically is limited by this "lead-time" effect. For profit here, we only consider farmers' profit for producing and selling biomass. Profits for selling food, livestock products, and other byproducts are not included. This implicitly assumes that the profits that a farmer can earn though other markets is less than the biofuel sector. The profit maximization model for farmer i is

$$\max_{a,x} \quad \sum_{jl} p_{ijl}^{\mathrm{C}} x_{ijl}^{\mathrm{C,F}} - \sum_{l}\left(C_{il}^{\mathrm{F}} a_{il} + \frac{1}{2} D_{il}^{\mathrm{F}} a_{il}^{2}\right) \tag{3.1}$$

$$s.t. \quad \sum_{l} a_{il} \leq L_i \qquad (\alpha_{i,0}) \tag{3.2}$$

$$\sum_{j} x_{ijl}^{\mathrm{C,F}} \leq Y_{il} a_{il} \qquad (\alpha_{il}) \quad \forall l \in \mathrm{C} \tag{3.3}$$

$$a_{il}, x_{ijl}^{\mathrm{C,F}} \geq 0 \qquad \forall j \in \mathrm{P}, l \in C. \tag{3.4}$$

Here $\sum_{jl} p^{\mathrm{C}}_{ijl} x^{\mathrm{C,F}}_{ijl}$ is farmer i's revenue for selling biomass. The term $\sum_l \left(C^{\mathrm{F}}_{il} a_{il} + \frac{1}{2} D^{\mathrm{F}}_{il} a^2_{il}\right) = \sum_l \int \left(C^{\mathrm{F}}_{il} + D^{\mathrm{F}}_{il} a_{il}\right) da_{il}$ is the total cost for biomass production. Land availability constraints is shown in constraint (3.2). Constraint (3.3) implies that shipped out biomass should not exceed available biomass produced in the farm.

3.2.3 Producer j's profit maximization model

In this model we consider two biofuel products: cellulosic ethanol and biogasoline. One assumption for the producers is that producers have no market power and biofuel selling prices are market clearing prices determined by the total supply and demand of biofuels.The profit maximization model for producer j is

$$\max_{x,t} \quad \sum_{k\mathrm{m}\in\{\mathrm{E,BG}\}} p^{\mathrm{m}}_{jk} x^{\mathrm{m,P}}_{jk} - \sum_{l\mathrm{m}\in\{\mathrm{E,BG}\}} \left[C^{\mathrm{m}}_{jl} R^{\mathrm{m}}_{jl} t^{\mathrm{m}}_{jl} + \frac{1}{2} D^{\mathrm{m}}_{jl} (R^{\mathrm{m}}_{jl} t^{\mathrm{m}}_{jl})^2 \right] - \sum_{il} \left(p^{\mathrm{C}}_{ijl} + T^{\mathrm{C}}_{ijl}\right) x^{\mathrm{C,P}}_{ijl} \tag{3.5}$$

$$s.t. \quad \sum_i x^{\mathrm{C,P}}_{ijl} \leq U^{\mathrm{C}}_{jl} \qquad (\beta_{jl}) \qquad \forall l \in \mathrm{C} \tag{3.6}$$

$$\sum_l R^{\mathrm{m}}_{jl} t^{\mathrm{m}}_{jl} \geq \sum_k x^{\mathrm{m,P}}_{jk} \qquad (\tau^{\mathrm{m}}_j) \qquad \forall \mathrm{m} \in \{\mathrm{E,BG}\} \tag{3.7}$$

$$t^{\mathrm{E}}_{jl} + t^{\mathrm{BG}}_{jl} \leq \sum_i x^{\mathrm{C,P}}_{ijl} \qquad (\gamma_{jl}) \qquad \forall l \in \mathrm{C} \tag{3.8}$$

$$x^{\mathrm{E,P}}_{jk}, x^{\mathrm{BG,P}}_{jk}, t^{\mathrm{E}}_{jl}, t^{\mathrm{BG}}_{jl} \geq 0 \qquad \forall k \in \mathrm{B}, l \in C. \tag{3.9}$$

In this model, equation (3.5) is producer j's profit function. Producer j's total revenue includes its revenue for selling ethanol ($\sum_k p^{\mathrm{E}}_{jk} x^{\mathrm{E,P}}_{jk}$) and biogasoline ($\sum_k p^{\mathrm{BG}}_{jk} x^{\mathrm{BG,P}}_{jk}$). Producer j's total cost for producing biofuels includes its production cost for biofuels ($\sum_{l\mathrm{m}\in\{\mathrm{E,BG}\}} \left[C^{\mathrm{m}}_{jl} R^{\mathrm{m}}_{jl} t^{\mathrm{m}}_{jl} + \frac{1}{2} D^{\mathrm{m}}_{jl} (R^{\mathrm{m}}_{jl} t^{\mathrm{m}}_{jl})^2 \right]$), purchasing, and transportation cost for biomass ($\sum_{il} \left(p^{\mathrm{C}}_{ijl} + T^{\mathrm{C}}_{ijl}\right) x^{\mathrm{C,P}}_{ijl}$). Turning to constraints, constraint (3.6) implies that total amount of biomass purchased by profucer j is limited by its biorefinery facility capacity. Constraint (3.7) shows that ethanol and biogasoline produced in biorefinery facilities are no more than biofuels sold to blenders. Constraint (3.8) implies that biomass used in biofuel production is no more than total biomass purchased from farmers.

3.2.4 Blender *k*'s profit maximization model

In this study, we assume that blenders purchase cellulosic ethanol from producers and conventional gasoline from the market, and then blend at the percentage of θ into ethanol fuel mixture for consumers' end use. Biogasoline is purchased from producers and sold at market without blending. Here, we assume that each blender faces its own markets for both ethanol fuel mixture and biogasoline. Therefore, each blender k has market prices $\overline{p}_k^{\mathrm{E}}$ and $\overline{p}_k^{\mathrm{BG}}$ for ethanol fuel mixture and biogasoline respectively. If blenders are under perfect competition (defined as PC), which means that no blender has market power, then blended ethanol and biogasoline market prices are exogenous variables for the models. Blender k's profit optimization model is

$$\begin{aligned}\max_{x} \quad & \sum_{jm\in\{\mathrm{E,BG}\}} x_{jk}^{\mathrm{m,B}}\overline{p}_k^{\mathrm{m}} - \sum_j (1-\theta)x_{jk}^{\mathrm{E,B}}\overline{p}_k^{\mathrm{G}} \\ & -\sum_j \left[(p_{jk}^{\mathrm{E}}+T_{jk}^{\mathrm{E}})\theta x_{jk}^{\mathrm{E,B}} + (p_{jk}^{\mathrm{BG}}+T_{jk}^{\mathrm{BG}})x_{jk}^{\mathrm{BG,B}}\right] - \left[C_k^{\mathrm{EG}}\theta\sum_j x_{jk}^{\mathrm{E,B}} + \frac{1}{2}D_k^{\mathrm{EG}}(\theta\sum_j x_{jk}^{\mathrm{E,B}})^2\right] \end{aligned} \tag{3.10}$$

$$s.t. \quad \sum_j \theta x_{jk}^{\mathrm{E,B}} \le U_k^{\mathrm{E}} \qquad (\kappa_k) \tag{3.11}$$

$$\sum_j x_{jk}^{\mathrm{BG,B}} \le U_k^{\mathrm{BG}} \qquad (\omega_k) \tag{3.12}$$

$$x_{jk}^{\mathrm{E,B}}, x_{jk}^{\mathrm{BG,B}} \ge 0 \qquad \forall j \in \mathrm{P}. \tag{3.13}$$

Equation (3.10) is blender k's profit function. The first two summations in the first line of equation (3.10) corresponds to blender k's revenue from selling ethanol fuel mixture and biogasoline ($\sum_{jm\in\{\mathrm{E,BG}\}} x_{jk}^{\mathrm{m,B}}\overline{p}_k^{\mathrm{m}}$) and the cost from purchasing conventional gasoline from market ($\sum_j(1-\theta)x_{jk}^{\mathrm{E,B}}\overline{p}_k^{\mathrm{G}}$). The second line presents the cost for purchasing and transporting cellulosic ethanol and biogasoline ($\sum_j\left[(p_{jk}^{\mathrm{E}}+T_{jk}^{\mathrm{E}})\theta x_{jk}^{\mathrm{E,B}} + (p_{jk}^{\mathrm{BG}}+T_{jk}^{\mathrm{BG}})x_{jk}^{\mathrm{BG,B}}\right]$). While blender k's total cost for blending cellulosic ethanol with conventional gasoline is $C_k^{\mathrm{EG}}\theta\sum_j x_{jk}^{\mathrm{E,B}} + \frac{1}{2}D_k^{\mathrm{EG}}(\theta\sum_j x_{jk}^{\mathrm{E,B}})^2$. Constraints (3.11) and (3.12) are capacity constraints for cellulosic ethanol and biogasoline.

If blenders all have market power (defined as MP), then the objective function of this profit maximization model only differs from equation (3.10) on the first line. Instead of taking exogenous prices $\overline{p}_k^{\mathrm{E}}$, $\overline{p}_k^{\mathrm{BG}}$, and $\overline{p}_k^{\mathrm{G}}$ from market, blenders are able to influence ethanol fuel mixture and biogasoline prices by deciding its output level. We elaborate their difference when introducing their KKT conditions in the next section.

3.2.5 Market equilibrium conditions

In this section, the market equilibrium conditions of the profit maximization models will be presented to solve the farmer, producer, and blender individual profit maximization model simultaneously. The operator $\perp$ refers to the complementarity condition. $0 \le x \perp y \ge 0$ implies that $x \ge 0$, $y \ge 0$, and $x^T y = 0$.

- The KKT conditions for farmer i's profit maximization model (3.1)-(3.4) under both market structures PC and MP are as follows

$$0 \le a_{il} \quad \perp -Y_{il}\alpha_{il} + \alpha_{i,0} + C^{\mathrm{F}}_{il} + D^{\mathrm{F}}_{il} a_{il} \ge 0 \quad \forall i \in \mathrm{F}, l \in \mathrm{C} \tag{3.14}$$

$$0 \le x^{\mathrm{C,F}}_{ijl} \quad \perp \alpha_{il} - p^{\mathrm{C}}_{ijl} \ge 0 \quad \forall i \in \mathrm{F}, j \in \mathrm{P}, l \in \mathrm{C} \tag{3.15}$$

$$0 \le \alpha_{i,0} \quad \perp L_i - \textstyle\sum_l a_{il} \ge 0 \quad \forall i \in \mathrm{F} \tag{3.16}$$

$$0 \le \alpha_{il} \quad \perp Y_{il} a_{il} - \textstyle\sum_j x^{\mathrm{C,F}}_{ijl} \ge 0 \quad \forall i \in \mathrm{F}, l \in \mathrm{C}. \tag{3.17}$$

- The KKT conditions for producer j's profit maximization model (3.5)-(3.9) under both market structures PC and MP are as follows

$$0 \le x^{\mathrm{m,P}}_{jk} \quad \perp \tau^{\mathrm{m}}_j - p^{\mathrm{m}}_{jk} \ge 0 \quad \forall j \in \mathrm{P}, k \in \mathrm{B}, \mathrm{m} \in \{\mathrm{E,BG}\} \tag{3.18}$$

$$0 \le x^{\mathrm{C,P}}_{ijl} \quad \perp -\gamma_{jl} + \beta_{jl} + p^{\mathrm{C}}_{ijl} + T^{\mathrm{C}}_{ijl} \ge 0 \quad \forall i \in \mathrm{F}, j \in \mathrm{P}, l \in \mathrm{C} \tag{3.19}$$

$$0 \le t^{\mathrm{m}}_{jl} \quad \perp \gamma_{jl} - R^{\mathrm{m}}_{jl}(\tau^{\mathrm{m}}_j - C^{\mathrm{m}}_{jl}) + D^{\mathrm{m}}_{jl}(R^{\mathrm{m}}_{jl})^2 t^{\mathrm{m}}_{jl} \ge 0 \quad \forall j \in \mathrm{P}, l \in \mathrm{C}, \mathrm{m} \in \{\mathrm{E,BG}\} \tag{3.20}$$

$$0 \le \beta_{jl} \quad \perp U^{\mathrm{C}}_{jl} - \textstyle\sum_i x^{\mathrm{C,P}}_{ijl} \ge 0 \quad \forall j \in \mathrm{P}, l \in \mathrm{C} \tag{3.21}$$

$$0 \le \tau^{\mathrm{m}}_j \quad \perp \textstyle\sum_l R^{\mathrm{m}}_{jl} t^{\mathrm{m}}_{jl} - \sum_k x^{\mathrm{m,P}}_{jk} \ge 0 \quad \forall j \in \mathrm{P}, \mathrm{m} \in \{\mathrm{E,BG}\} \tag{3.22}$$

$$0 \le \gamma_{jl} \quad \perp \textstyle\sum_i x^{\mathrm{C,P}}_{ijl} - t^{\mathrm{E}}_{jl} - t^{\mathrm{BG}}_{jl} \ge 0 \forall j \in \mathrm{P}, l \in \mathrm{C}. \tag{3.23}$$

- The KKT conditions for blender k's profit maximization model (3.10)-(3.13) under market structures PC and MP are as follows If blenders have no market power (PC), then the KKT conditions are

$$
\begin{aligned}
0 \le x^{\mathrm{E,B}}_{jk} \quad & \perp -\overline{p}^{\mathrm{E}}_k + (1-\theta)\overline{p}^{\mathrm{G}}_k + \kappa_k + \theta p^{\mathrm{E}}_{jk} + \theta T^{\mathrm{E}}_{jk} \\
& \quad + \theta C^{\mathrm{EG}}_k + D^{\mathrm{EG}}_k \theta^2 \textstyle\sum_j x^{\mathrm{E,B}}_{jk} \ge 0 \qquad \forall j \in \mathrm{P}, k \in \mathrm{B} \qquad (3.24) \\
0 \le x^{\mathrm{BG,B}}_{jk} \quad & \perp -\overline{p}^{\mathrm{BG}}_k + \omega_k + p^{\mathrm{BG}}_{jk} + T^{\mathrm{BG}}_{jk} \ge 0 \qquad \forall j \in \mathrm{P}, k \in \mathrm{B} \qquad (3.25) \\
0 \le \kappa_k \quad & \perp U^{\mathrm{E}}_k - \textstyle\sum_j x^{\mathrm{E,B}}_{jk} \ge 0 \qquad \forall k \in \mathrm{B} \qquad (3.26) \\
0 \le \omega_k \quad & \perp U^{\mathrm{BG}}_k - \textstyle\sum_j x^{\mathrm{BG,B}}_{jk} \ge 0 \qquad \forall k \in \mathrm{B} \qquad (3.27)
\end{aligned}
$$

When market power of the blenders is considered (MP), the KKT constraints replacing (3.24) and (3.25) are

$$
\begin{aligned}
0 \le x^{\mathrm{E,B}}_{jk} \quad & \perp -A^{\mathrm{E}}_k + (1-\theta)A^{\mathrm{G}}_k + \left[2B^{\mathrm{E}}_k - 2(1-\theta)^2 B^{\mathrm{G}}_k\right] \textstyle\sum_j x^{\mathrm{E,B}}_{jk} + \kappa_k + \theta p^{\mathrm{E}}_{jk} \\
& \quad + \theta T^{\mathrm{E}}_{jk} + \theta C^{\mathrm{EG}}_k + D^{\mathrm{EG}}_k \theta^2 \textstyle\sum_j x^{\mathrm{E,B}}_{jk} \ge 0 \qquad \forall j \in \mathrm{P}, k \in \mathrm{B} \, (3.28)
\end{aligned}
$$

and

$$0 \le x^{\mathrm{BG,B}}_{jk} \quad \perp -A^{\mathrm{BG}}_k + 2B^{\mathrm{BG}}_k \textstyle\sum_j x^{\mathrm{BG,B}}_{jk} + \omega_k + p^{\mathrm{BG}}_{jk} + T^{\mathrm{BG}}_{jk} \ge 0 \quad \forall j \in \mathrm{P}, k \in \mathrm{B} \qquad (3.29)$$

respectively.

- Market clearing conditions:

Biomass prices p^C_{ijl} between farmers and producers are obtained from the market clearing conditions of total biomass supply equals total biomass demand. Similar market clearing conditions also exist for ethanol and biogasoline prices p^{E}_{jk} and p^{BG}_{jk} between producers and blenders.

$$
\begin{aligned}
& p^{\mathrm{C}}_{ijl} \text{ free,} \qquad & x^{\mathrm{C,F}}_{ijl} = x^{\mathrm{C,P}}_{ijl} \qquad & \forall i \in \mathrm{F}, j \in \mathrm{P}, l \in \mathrm{C} \qquad (3.30) \\
& p^{\mathrm{E}}_{jk} \text{ free,} \qquad & x^{\mathrm{E,P}}_{jk} = \theta x^{\mathrm{E,B}}_{jk} \qquad & \forall j \in \mathrm{P}, k \in \mathrm{B} \qquad (3.31) \\
& p^{\mathrm{BG}}_{jk} \text{ free,} \qquad & x^{\mathrm{BG,P}}_{jk} = x^{\mathrm{BG,B}}_{jk} \qquad & \forall j \in \mathrm{P}, k \in \mathrm{B}. \qquad (3.32)
\end{aligned}
$$

The following constraints are the exogenous constraints for model (3.10)-(3.13) to determine market prices for blended ethanol fuel mixture and biogasoline under the scenario that blenders are under perfect competition (PC).

$$
\begin{aligned}
\overline{p}^{\mathrm{m}}_k &= A^{\mathrm{m}}_k - B^{\mathrm{m}}_k \sum_j x^{\mathrm{m,B}}_{jk} \qquad & (\rho^{\mathrm{m}}_k) \qquad & \forall \mathrm{m} \in \{\mathrm{E,BG}\} \qquad (3.33) \\
\overline{p}^{\mathrm{G}}_k &= A^{\mathrm{G}}_k - (1-\theta) B^{\mathrm{G}}_k \sum_j x^{\mathrm{E,B}}_{jk} \qquad & (\rho^{\mathrm{G}}_k). \qquad & \qquad (3.34)
\end{aligned}
$$

The corresponding KKT conditions are

$$\rho_k^{\mathrm{m}} \text{ free}, \qquad \overline{p}_k^{\mathrm{m}} = A_k^{\mathrm{m}} - B_k^{\mathrm{m}} \textstyle\sum_j x_{jk}^{\mathrm{m,B}} \qquad \forall k \in \mathrm{B}, \mathrm{m} \in \{\mathrm{E,BG}\} \tag{3.35}$$

$$\rho_k^{\mathrm{G}} \text{ free}, \qquad \overline{p}_k^{\mathrm{G}} = A_k^{\mathrm{G}} - (1-\theta) B_k^{\mathrm{G}} \textstyle\sum_j x_{jk}^{\mathrm{E,B}} \qquad \forall k \in \mathrm{B}. \tag{3.36}$$

The above conditions (3.33)and (3.34) are redundant conditions under market structure MP since they are already being substituted in the objective function of blender k's profit maximization model (3.10).

In summary, if no blender has market power (PC), then the equivalent complementarity model to solve profit maximization models of farmers, producers and blenders simultaneously includes (3.14)-(3.27), (3.30)-(3.32), and (3.35)-(3.36). If blenders all have market power (MP), then the equilibrium model is consisted of equations (3.14)-(3.23), (3.26)-(3.27), (3.28)-(3.29), and (3.35)-(3.36).

3.2.6 Formulations under various policies

Various policies have been implemented by government to promote biofuel production. [1] Four policies corresponding to RFS2, biofuel subsidy and RINs are considered in this section, including subsidy on blenders, on producers, on farmers, and both subsidy and biofuel mandate on blenders. The RIN is an endogenously determined quantity when blenders are allowed to meet their mandate by purchasing RINs from the market. These policies can be incorporated in the models in Sections 3.2.2-3.2.4 as follows.

(a) If the subsidy is given to the blenders for producing each gallon of cellulosic ethanol and biogasoline, the term $\sum_j \left(S^{\mathrm{E,B}} \theta x_{jk}^{\mathrm{E,B}} + S^{\mathrm{BG,B}} x_{jk}^{\mathrm{BG,B}} \right)$ needs to be inserted into objective function (3.10). In a sense, the subsidy will be used to offset the production cost.

(b) If the subsidy is given to producers for producing each gallon of cellulosic ethanol and biogasoline, then the objective (3.5) needs to add the subsidy term $\sum_{\mathrm{m}\in\{\mathrm{E,BG}\}} S^{\mathrm{m,P}} \sum_l R_{jl}^{\mathrm{m}} t_{jl}^{\mathrm{m}}$.

(c) If the subsidy is handed out to farmers for growing each acre of biomass, the objective (3.1) of farmers' problem needs to add the subsidy term $\sum_l S_l^{\mathrm{F}} a_{il}$.

---

[1] RFS2 proposed by EPA requires that at least 16 billion gallons of cellulosic biofuels will be consumed by the year 2022 [42]. FCEA offers \$1.01/gal of subsidy for cellulosic biofuel produced and consumed in US [21]. The policies that importers have to pay \$0.54/gal tariff on imported ethanol, and US ethanol producers get \$0.45/gal tax credit expired on January, 2012.

(d) If a mandate T_k^{REQ} is imposed on blender k, then in addition to (a), the term $p^{\mathrm{RIN}}\left[\sum_j(\theta x_{jk}^{\mathrm{E,B}}+x_{jk}^{\mathrm{BG,B}})-T_k^{\mathrm{REQ}}\right]$ needs to be added to (3.10), which may be a revenue (if positive) or a cost (if negative). The variable p^{RIN} is the RINs market price that will be determined by the following complementarity condition.

$$0 \le p^{\mathrm{RIN}} \quad \perp \sum_k \left[\sum_j(\theta x_{jk}^{\mathrm{E,B}}+x_{jk}^{\mathrm{BG,B}})-T_k^{\mathrm{REQ}}\right] \ge 0. \tag{3.37}$$

3.3 Case study

We apply the model in Section 3.2 to a case study. In particular, we focus on the effect of various policies and different market assumptions on the equilibrium market outcomes. The purpose is to illustrate the capacity of the proposed models.

Our analysis is based on 10 scenarios, a combination of policy choices and market structures. We denote policy B,P, and F for the cases that government subsidy is given to the blenders, producers and farmers, respectively. Additionally, policy B&M represents the case in which RFS and subsidy are jointly implemented through the blenders. In terms of market assumptions, PC and MP correspond to that the blenders behave competitively and strategically (market power) respectively. A combination of market and policies assumptions is referred to as PC, MP-B, P, F, B&M.

The main data source is summarized in Section 3.3.1. The results are presented in Section 3.3.2. The model is implemented on Intel(R) Pentium(R) D CPU, Memory 4.00GB, 64-bit Operating System using interface GAMS and solver PATHNLP.

3.3.1 Data source

We rely upon the data from a previous study that examines optimal facility location, capacity, and biomass and biofuel allocation in paper [65]. We choose three counties (F1-F3) Franklin, Kossuth, and Webster as farmers, four counties (P1-P4) Cerro Gordo, Hamilton, Jasper, and Palo Alto for producers, and five cities (B1-B5) as blenders for Cedar Rapids, Davenport-Moline-Rock Island, Des Moines, Iowa City, and Waterloo-Cedar Falls. The farmers (blenders) are the first three (five) leading counties (cities) with most biomass supply (biofuel demand) from [52] and [19]. The producers are four of the biggest biorefinery facilities in numerical results of [65]. The locations of the above counties and cities are displayed in Figure 3.1. The species of biomass we consider in this study is corn stover and switchgrass. Producers are assumed to produce only cellulosic ethanol and biogasoline. Blenders are assumed to blend cellulosic ethanol and conventional gasoline into E10 (with 10% of cellulosic ethanol and 90% of biogasoline). Data sources for all parameters in this model are listed in Table 3.1.

3.3.2 Numerical results

In this section, results of several scenarios are presented. Section 3.3.2.1 presents base case results for the biofuel market. Farmers' optimal land allocation strategy, producers' biofuel production plan, blenders' optimal biofuel blend, biomass prices between farmers and producers, cellulosic biofuel prices between producers and blenders, and blended biofuel market prices faced by consumers are presented to provide a general picture of the biofuel market under the current parameter set and market structure assumptions. The effect of the blenders' market power will be illustrated in Section 3.3.2.2. Two scenarios are compared: the scenario that no blender has market power and the scenario that blenders have market power. The purpose is to investigate the impact of the blenders' market power on farmers' land allocation decision, total biofuel production level, and the market prices of blended biofuels that consumers face. Section 3.3.2.3 presents the effects of different policies under the scenario that blenders have no market power. Insights and suggestions will be provided on government policy-making to encourage biofuel industry investment and also to improve total social welfare. In addition, the analysis of policies under the scenario that all blenders have market power is also done in this section.

3.3.2.1 Base scenario

Base scenario is the case that all of the stakeholders take price as given and compete in markets (PC). In reality, this is analog to be moderate to large markets that can behave strategically.

Figure 3.1 shows some results under the market structure PC. In this figure, the solid arrows are biomass transportation from the farmers to producers, and dash arrows are biofuel transportation from the producers to blenders. Transportation quantities are shown in Tables 3.2 and 3.3, respectively.

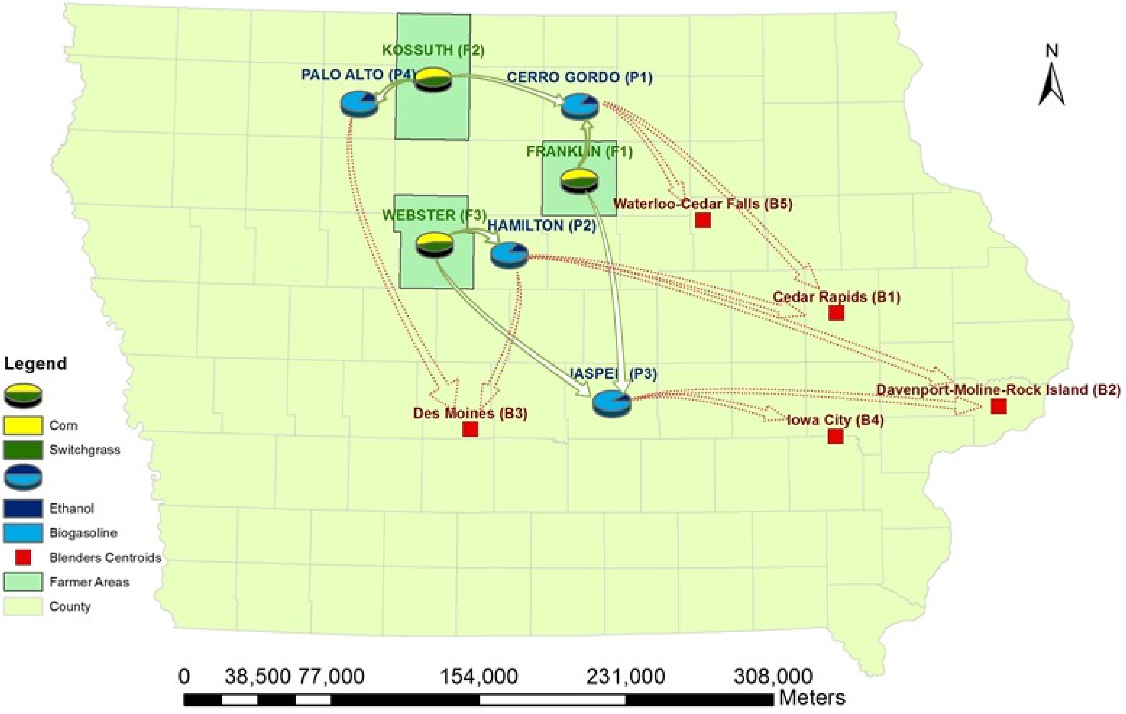

Figure 3.1 Supply chain results for base scenario case study

Table 3.2 shows the quantities of biomass shipped from farmers to producers. For instance, the transportation quantity from farmer F1 to producer P1 is 128 k tons. The corn stover prices for farmers F1, F2, and F3 are \$59.61, \$53.89, and \$58.63/ton, respectively. The switchgrass prices for farmers F1, F2, and F3 are \$67.00, \$62.89, and \$66.02/ton, respectively. The price difference of corn stover and switchgrass reflects their relative yields and production costs. In this model, biomass shipment cost is paid by the producers. Recall that these prices do not reflect transportation cost. Had the transportation been included, the pair of farmers and producers with a positive shipment quantity would have the same total gate prices. This is because there is not shipping capacity, and any price differential will be arbitraged away. Any zero shipment implies a higher gate price. For example, producer P3 purchases corn stover from farmers F1 and F3 since the corn stover gate price for F1 and F3 are equivalent: F1: \$59.61+\$19.07=\$78.68/ton, and F3: \$58.63+\$20.05=\$78.68/ton in which \$19.07 and \$20.05 are transportation cost to producer P3 from farmer F1 and F3, respectively. However the gate price from F2 is \$53.89+\$30.55=\$84.44/ton, which is much higher than that of F1 and F3, so there is no biomass transported from F2 to P3.

Table 3.3 shows the transportation quantities of ethanol and biogasoline from producers to blenders. For instance, transportation quantity from producer P1 to blender B1 is 1,275 k gallons. The ethanol selling price from producers P1 and P2 equals to \$2.97, and \$3.00 and \$2.94/gal for P3 and P4. The biogasoline selling price from producers P1, P2, and P3 is \$4.40, and \$4.39/gal for P4. Analogous to the situation between farmers and producers, biofuel shipment cost is also paid by the downstream blenders. Similarly, from the perspective of each blender, we can see that each blender tends to purchase biofuel from producers with cheaper gate prices. Take blender B1, for example, if blender B1 decides to purchase cellulosic ethanol from producers P1, P2, P3 and P4, respectively. This is because gate prices for P1 and P2 are: \$2.97+\$0.066=\$3.036/gal, \$3.00+\$0.048=\$3.048/gal for P3 and \$2.94+\$0.103=\$3.043/gal, respectively. Blender B1 would prefer to purchase cellulosic ethanol from P1 and P2 first if they can provide adequate biofuel. If the producer with the lowest gate price cannot provide enough biofuel, blenders would choose to purchase from producers with the second lowest gate price. Likewise, blender B2 would choose to purchase 1,918 k gallons of cellulosic ethanol (Table 3.3) from producer P2 first with the lowest price \$2.97+\$0.109=\$3.079/gal. However because producer P2 cannot provide enough ethanol, the blender B2 would have to purchase an additional 107 k gallons from the producer P3 with a price \$3.082/gal(=\$3.00+\$0.082).

3.3.2.2 Blenders market power effect

This section reports the results from comparing the market structure that allows blenders to exercise market power (MP) to the structure under which blenders behave competitively as in Section 3.3.2.1 (PC). These results are summarized in Tables 3.4-3.10 for scenario PC-P0 and MP-P0, the two rows of scenarios PC-P0 and MP-P0.

Blenders play a crucial role in the supply chain of the biofuel industry. A blender, who is a buyer of biofuel from producers, can exercise "monopsony" power by reducing cellulosic biofuel purchased quantities in order to lower the payment to producers. On the other hand, they can act as a seller to sell ethanol fuel mixtures to consumers, thereby exercising "monopsony" power by restricting their sales to raise the price. For example, It is suggested in Table 3.9 that blender B1 can effectively reduce its procurement quantities of cellulosic ethanol from producers by 49.82% (from 1,371 k gallons in PC, to 688 k gallons in MP) and suppress cellulosic biofuel purchasing price (Table 3.7) by 5.93% (from

\$2.97+\$0.066=\$3.036/gal in PC, to \$2.79+\$0.066=\$2.856/gal in MP). At the same time, blenders can exercise monopoly power by withholding its sales to consumers by 6,830 k gal (ten times of cellolosic ethanol purchasing quantities because of the blending percentage of E10), and push up the market price of E10 from \$3.37/gal in PC to \$10.80/gal in MP (Table 3.8). Overall, profits of the blenders are increased by \$105.61, \$155.75, \$230.52, \$62.89, and \$ 68.12 million for blenders B1-B5, respectively (Table 3.10). The increase in their profits is at the expense of both biofuel producers and consumers. The consumer surplus drops by \$888.52 million. As a result of lower biofuel consumption, producers will decrease biofuel production level (Table 3.5), and hence farmers reduce their biomass production, as alluded to in Table 3.4.

Note that land use of corn stover is more than switchgrass for both scenarios. This is because average cost of corn stover (\$36.67/ton) is less than switchgrass (\$51.60/ton). Table 3.5 shows that general ethanol production level is lower than biogasoline production level. The reason for this is that for each ton of biomass purchased from farmers the conversion cost for biogasoline (\$2.55/gal) is higher than cellulosic ethanol (\$2.15/gal for corn stover and \$ 1.87/gal for switchgrass), and the selling prices of biogasoline is even higher than cellulosic biogasoline. (Selling prices of biogasoline are \$4.40/gal for producers P1, P2, and P3 and \$4.39/gal for P4, while the selling prices for cellulosic ethanol are \$2.97/gal for P1 and P2, \$3.00 and \$2.94/gal for P3 and P4 respectively.) Overall, biogasoline makes more profit than cellulosic ethanol do. Additionally, less corn stover is used to produce cellulosic ethanol, which is because corn stover unit conversion cost is higher than switchgrass, and ethanol production yield is lower. However, for biogasoline, unit conversion costs are the same and switchgrass has a higher bio-oil yield. Hence, more corn stover is used to produce biogasoline than switchgrass.

Turning to social surplus in Table 3.10 under market structure PC, in which blenders behave competitively, leads to a higher total social surplus (=consumers' surplus + blenders' surplus + biofuel producers' surplus + farmers' surplus) of \$300.19 million. (Recall that payment between farmers and biofuel producers, between biofuel producers and blenders, and between blenders and consumers, all represent internal wealth transfer between entities in the market, and these payments will cancel out in total surplus calculation.) Comparing these two market structures that blenders behave competitively and when blenders are allowed to exercise market power. Blenders' total profits increase by \$622.91 million at the expenses of other entities: farmers (-\$6.63 million), producers (-\$27.91 million), and consumers (-$888.52 million).

3.3.2.3 Effects of different policies and point of implementation on market outcome

This section focuses on comparing the results when the recipients of the biofuel subsidy are different: biofuel blenders PC-B, biofuel producers PC-P, farmers PC-F, and subsidy and biofuel mandate are both imposed on blenders PC-B&M under the structure that all blenders behave competitively (PC). To make the comparison meaningful, the aggregated subsidy is equivalent across the four scenarios. The two key questions are: (1) whether policies with different points of implementation lead to different market outcomes, and (2) what the distributional effects are on any of the market participants. The main results are displayed in Tables 3.4-3.10 for scenario PC-B, PC-P, PC-F, and PC-B&M.

Several observations emerge from Tables 3.4-3.10. First, market outcomes under the scenarios when the government subsidy is provided to blenders and producers (PC-B and MP-P) are equivalent. For example, market price for five demand areas for E10 is $3.27, $3.30, $3.35, $3.24, and $3.24/gal, respectively (Table 3.8) which is lower than the scenario when no policy is imposed on the biofuel market(PC-P0) which are $3.27, $3.40, $3.44, $3.34, and $3.34/gal for the five demand areas. Second, while the prices of cellulosic ethanol and biogasoline are different when the producers sell to blenders when incorporating transportation cost, they become equivalent. Similar results have been discussed in Section 3.3.2.1 for blenders' biofuel gate prices. Third, when the farmers are the recipient of the subsidy, they would expand their land use because the subsidy is based on per acre. For example, when subsidy is given to farmer F1, the land use for corn stover grows from 93 thousand acres to 140 thousand acres (Table 3.4). The expansion of land use leads to an increase in biomass production and so as cellulosic biofuel production (Table 3.5). Fourth, under the scenario that blenders receive subsidies, the blenders will raise the cellulosic biofuel prices (from producers) because the subsidy they receive depends on the quantities of blended fuel. For instance, producer P1 increases cellulosic ethanol prices between producers and blenders from $2.97/gal to $2.98/gal, and raises biogasoline prices between producers and blenders from $4.40/gal to $4.47/gal. On the other hand, if the subsidy to biofuel producers is implemented, the selling prices (to blenders) would be lower owing to the fact that the subsidy is based on total biofuel that is converted by producers. For producer P1, the cellulosic ethanol selling price lowers from $2.97/gal to $1.97/gal, and the biogasoline selling price lowers from $4.40/gal to $3.46/gal.

In either case, the gate price for consumers will be equivalently lower than the case with subsidy. In other words, consumers will experience the pass-through of the subsidy, regardless of who the recipient is. Finally, when farmers receive subsidy, it leads to higher consumer prices. For example, market price of E10 for blender B1 is $3.37/gal if no subsidy is imposed on the biofuel market. If subsidy is given to producers (or blenders) and farmers, the market prices are $3.27 and $3.30/gal respectively.

Next we exam the pass-through of the subsidy of various entities under different points of implementations. As discussed earlier, PC-B and PC-P lead to the same market outcome. Overall, all the entities benefit from the subsidy. The respective profit increases are $1.04, $4.70, $0.06, and $82.90 million for farmers, producers, blenders, and consumer surplus compared to PC-P0. Therefore, consumers receive most benefit from the subsidy. On the other hand, when the subsidy is given to the farmers, farmers are able to retain significant profit of the benefit by increasing its profit from $9.13 to $18.53 million. As in the scenarios PC-B and PC-P, both producers and blenders only benefit marginally. The consumers remain receiving most benefit as its surplus increment to $1259.50 million compared to PC-P0. Finally, when the subsidy is given to the farmers, market price of E10 and biogasoline is higher than the subsidy is offered to producers or blenders. The reason is that high subsidy on farmers lead to higher land use on corn stover and switchgrass grow. However some part of corn stover is not sold to producers even their prices are zero. This is probably because the marginal production cost of corn stover is too high when too much corn stover is used for biogasoline production. Therefore lower production level of biofuels will lead to higher biofuel market prices.

If blenders have market power (MP), similar results as in Section 3.3.2.3 can be seen. Different policies have similar effects on the biofuel supply chain under both market structure PC and MP. For each policy, similar effect as presented in Section 3.3.2.2 can be seen in Tables 3.4-3.10. If blenders have market power, then they can increase their profits greatly by exercising market power and their total profit will take a relatively larger percentage in the total profits as shown in Table **??**. For example, if subsidy is given to blenders under market structure MP, then blenders' total profit will be $ 671.32 million out of $ 685.99 million for the whole biofuel market. We present the effect of various policies under market structure MP for the completeness of information.

3.3.3 Effect of combined policy

If subsidy and biofuel mandate are both imposed on blenders, then compared to scenario PC-B, more government subsidy will be given to the biofuel market since subsidy for per gallon of biofuel stays the same while higher biofuel production level is observed. Therefore more cellulosic biofuels are blended and sold into market, and hence market price of E10 and biogasoline will be lower relative to the scenario that only subsidy is imposed on blenders. For example, biogasoline market price for blender B5 decreases from $3.46/gal to $3.45/gal. Demanded from blenders and hence cellulosic biofuels production level will increase as a result as shown in Table 3.5. (i.e. Producer P1 produces biogasoline from 134.89 thousand gallons under scenario PC-P to 134.96 thousand gallons under scenario PC-B&M). Farmers will expand land use for biofuel crops to meet higher biomass demand (i.e. Farmer F1 will expand its land use for corn stover from 97.40 under scenario PC-P to 97.45 thousand acres under scenario PC-B&M). In our case, the RINs price in marker is $0.01/gal. The price goes up when a higher bifuel mandate from government is implemented.

3.4 Conclusion

Although still subject to debates, biofuel sector is expected to play an crucial role in reducing greenhouse gas in the transportation sector. One emerging concern that has received little attention is that the academic or government community are lack of tools with adequate details and flexibility to examine the implication of various policy designs or market competitions in biofuel supply chain. In particular, policies with different point-of-implementation or interaction of various concurrent policies in the presence of oligopoly market structure might lead to suboptimal market outcomes that discourage biofuel production.

In this chapter, we develop a bottom-up equilibrium optimization model to study the supply chain of biofuel market, considering farmers, biofuel producers, blenders and consumers. The model builds on individual's optimization problem and solves for farmers' land allocation, biomass transportation, biofuel production and biofuel blending activities. The prices in the market are determined endogenously by supply-demand conditions. The model also allows for consideration of market structure or firms' horizontal and vertical ownership that may arise to oligopoly competition at the different segments of the supply chain. We applied the models to a case study of the state of Iowa, considering scenarios with a combination of policies with different points-of-implementation and market structure.

We have two central findings in this chapter. First, policies with different points-of-implementation could lead to different market outcomes. In particular, when subsidy is given to the farmers, farmers would choose to expand crop land, produce more biomass, leading to drops in biomass prices. Perhaps surprisingly, it results in higher fuel prices. Because aggregate subsidy is the same across policies, excessive biomass produced by farmers means that less per-unit pass-through that the producers can benefit from. This results in a lower production of biofuel, and higher biofuel prices. Here all biomass purchased by producers are used for biofuel production. However, not all biomass produced in farmers are sold to producers. There are leftovers in farms. (Even farmers give out biomass for free, producers still need to pay transportation fee for biomass. If their marginal production cost is too high, there is no way they will produce more biofuel, and hence there is no need to purchase extra biomass from farmers.). On the other hand, when subsidies are given to either blender or producer, it could yield the same market equilibrium. In all the cases, consumers will benefit from lower fuel prices, owing to the passthrough of the subsidies. Second, when the blenders in the supply chain are allowed to exercise monopoly power to upstream producers and monopoly power to the downstream consumers, they can earn substantial profits at expenses of other entities in the markets.

Our study is subject to a number of limitations. First, our model assumes that all biomass produced is sold to producers for biofuel production. In real world, farmers have the option to sell it to biofuel market or other markets for heating or electricity generation, which we did not consider. Second, only two biofuel products are considered in the model (ethanol fuel mixture and biogasoline). They are assumed to be not substitutable and therefore each biofuel has its own market. Third, in our model, we assume that each blender serves its own local biofuel market instead of sharing a market with all other blenders. For future work we could consider that each blender can supply different biofuel markets and each market can be supplied by different blenders. Fourth, our model assume that biomass yield is know before hand, which is not the case in reality. If biomass yield is uncertain in the model, then farmers' decision on land allocation and whole biofuel supply chain could be different. These limitations will leave considerations to our future research.

Table 3.1 Data source for bottom-up biofuel market model

Parameters	Data	Data source	
L_i	Total area of land available	F1: 372,460.8 acres	[52]
		F2: 622,540.8 acres	
		F3: 457,996.8 acres	
C_{il}^{F}	Intercept of farm production cost	Corn stover: \$74.07/acre	[30]
		Switchgrass: \$133.14/acre	
D_{il}^{F}	Slope of farm production cost	5×10^{-4}	Assumed
Y_{il}	Crop l yield	Corn stover: 2.02 ton/acre	[30]
		Switchgrass: 2.58 ton/acre	
S_l^{F}	Subsidy for biomass l	\$155.69/acre for PC	Aggregated
		\$145.44/acre for MP	Aggregated
T_{ijl}^{C}	Unit transportation cost of crop l	\$0.19/ton/mile	[46]
C_{jl}^{E}	Intercept of ethanol production cost	Corn stover: \$2.15/gal	[37]
		Switchgrass: \$1.87/gal	[27]
D_{jl}^{E}	Slope of ethanol production cost	1×10^{-7}	Assumed
C_{jl}^{BG}	Intercept of biogasoline production cost	\$2.55/gal	[31]
D_{jl}^{BG}	Slope of biogasoline production cost	1×10^{-7}	Assumed
R_{jl}^{E}	Ethanol conversion rate from	Corn stover: 79 gal/ton	[37]
		Switchgrass: 83 gal/ton	[27]
R_{jl}^{BG}	Biogasoline conversion rate from	Corn stover: 79 gal/ton	[31]
		Switchgrass: 83 gal/ton	[31]
U_{jl}^{C}	Producer capacity	2200 ton/day	[36]
$S^{\mathrm{E,P}}$	Subsidy for ethanol	\$1.01/gal	[21]
$S^{\mathrm{BG,P}}$	Subsidy for biogasoline	\$1.01/gal	[21]
T_{jk}^{E}	Unit transportation cost of ethanol	\$0.1654/ton.mile	[43]
T_{jk}^{BG}	Unit transportation cost of biogasoline	\$0.0176/ton.mile	[43]
p_k^{G}	Inverse supply function of gasoline	\$3.315/gal	[18]
p_k^{E}	Inverse demand function of E10	B1: $18.2857 - 0.1088 \times 10^{-5} q_1^E$	[34] [19]
		B2: $18.2857 - 0.0735 \times 10^{-5} q_2^E$	
		B3: $18.2857 - 0.0495 \times 10^{-5} q_3^E$	
		B4: $18.2857 - 0.1831 \times 10^{-5} q_4^E$	
		B5: $18.2857 - 0.1691 \times 10^{-5} q_5^E$	
p_k^{BG}	Inverse demand function of biogasoline	B1: $19.8857 - 0.1183 \times 10^{-5} q_1^E$	[34] [19]
		B2: $19.8857 - 0.0800 \times 10^{-5} q_2^E$	
		B3: $19.8857 - 0.0539 \times 10^{-5} q_3^E$	
		B4: $19.8857 - 0.1991 \times 10^{-5} q_4^E$	
		B5: $19.8857 - 0.1838 \times 10^{-5} q_5^E$	
U_k^{E}	Blender ethanol capacity	5×10^8 gal/year	Assumed
U_k^{BG}	Blender biogasoline capacity	5×10^8 gal/year	
C_k^{EG}	Intercept of ethanol blending cost	\$0.1/gal	Assumed
D_k^{EG}	Slope of ethanol blending cost	5×10^{-7}	Assumed
$S^{\mathrm{E,B}}$	Subsidy for cellulosic ethanol blended	\$1.01/gal	[21]
$S^{\mathrm{BG,B}}$	Subsidy for biogasoline sold	\$1.01/gal	[21]
T_k^{REQ}	Total biofuel production mandate	Assumed	

Table 3.2 Biomass shipment allocation under market structure PC (in thousand tons)

	Corn stover				Switchgrass			
	P1	P2	P3	P4	P1	P2	P3	P4
F1	128	0	59	0	142	0	63	0
F2	0	0	0	141	0	0	0	150
F3	0	131	49	0	0	146	46	0

Table 3.3 Biofuel shipment allocation under market structure PC (in thousand gallons)

	Cellulosic ethanol					Biogasoline				
	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
P1	1,275	0	0	0	884	11,283	0	0	0	8,425
P2	96	1,918	357	0	0	1,805	10,468	7,799	0	0
P3	0	107	0	816	0	0	8,881	0	7,776	0
P4	0	0	2,641	0	0	0	0	20,932	0	0

Table 3.4 Biomass land use (in thousand acres)

	Corn stover			Switchgrass		
	F1	F2	F3	F1	F2	F3
PC-P0	93	70	89	79	58	74
PC-B	97	74	93	84	61	79
PC-P	97	74	93	84	61	79
PC-F	140	140	140	79	58	74
PC-B&M	97	74	93	84	61	79
MP-P0	51	38	47	40	30	35
MP-B	54	40	50	42	31	37
MP-P	54	40	50	42	31	37
MP-F	95	95	95	40	29	35
MP-B&M	59	44	55	46	34	41

Table 3.5 Biomass processed for ethanol and biogasoline production (in thousand tons)

		Cellulosic ethanol				Biogasoline			
		P1	P2	P3	P4	P1	P2	P3	P4
PC-P0	Corn stover	0	0	0	4	128	130	108	137
	Switchgrass	26	28	11	28	116	118	98	122
PC-B	Corn stover	0	0	0	3	135	137	115	144
	Switchgrass	26	28	11	29	123	125	105	129
PC-P	Corn stover	0	0	0	3	135	137	115	0
	Switchgrass	26	28	11	29	123	125	105	129
PC-F	Corn stover	5	7	0	2	139	140	120	139
	Switchgrass	23	26	9	26	117	119	99	123
PC-B&M	Corn stover	0	0	0	3	135	137	115	144
	Switchgrass	26	28	11	29	123	125	105	129
MP-P0	Corn stover	0	0	0	0	72	74	52	77
	Switchgrass	15	18	1	15	58	60	40	61
MP-B	Corn stover	0	0	0	0	76	78	56	81
	Switchgrass	15	18	1	15	62	64	44	65
MP-P	Corn stover	0	0	0	0	76	78	56	81
	Switchgrass	15	18	1	15	62	64	44	65
MP-F	Corn stover	0	0	0	0	79	80	59	79
	Switchgrass	15	18	1	15	58	60	40	61
MP-B&M	Corn stover	0	0	0	0	83	85	63	89
	Switchgrass	15	18	1	16	69	71	51	73

Table 3.6 Sales weighted biomass prices between farmers and producers (in $/ton)

	Corn stover			Switchgrass		
	F1	F2	F3	F1	F2	F3
PC-P0	59.61	53.89	58.63	67.00	62.89	66.02
PC-B	60.78	54.97	59.79	67.85	63.50	66.86
PC-P	60.78	54.97	59.79	67.85	63.50	66.86
PC-F	0.00	0.00	0.00	11.00	6.92	10.02
PC-B&M	60.79	54.98	59.81	67.86	63.51	66.87
MP-P0	49.35	46.14	48.37	59.35	57.33	58.36
MP-B	50.01	46.62	49.03	59.78	57.64	58.79
MP-P	50.01	46.62	49.03	59.78	57.64	58.79
MP-F	0.00	0.00	0.00	12.23	10.23	11.25
MP-B&M	51.26	47.52	50.28	60.60	58.24	59.61

Sales weighted price is the price calculated by $\frac{\sum_j \text{Price}_j \times \text{quantity}_j}{\sum_j \text{quantity}_j}$

Table 3.7 Sales weighted ethanol and biogasoline prices between producers and blenders (in $/gal)

	Cellulosic ethanol				Biogasoline			
	P1	P2	P3	P4	P1	P2	P3	P4
PC-P0	2.97	2.97	3.00	2.94	4.40	4.40	4.40	4.39
PC-B	2.98	2.98	3.01	2.95	4.47	4.47	4.47	4.47
PC-P	1.97	1.97	2.00	1.94	3.46	3.46	3.46	3.46
PC-F	2.28	2.28	2.31	2.25	3.73	3.73	3.74	3.73
PC-B&M	2.98	2.98	3.01	2.95	4.47	4.47	4.47	4.47
MP-P0	2.79	2.79	2.82	2.76	3.83	3.83	3.83	3.82
MP-B	2.80	2.80	2.83	2.77	3.86	3.86	3.87	3.86
MP-P	1.79	1.79	1.82	1.76	2.85	2.85	2.86	2.85
MP-F	2.22	2.23	2.26	2.19	3.26	3.26	3.26	3.25
MP-B&M	2.81	2.81	2.84	2.78	3.93	3.93	3.94	3.93

Table 3.8 E10 and biogasoline market prices (in $/gal)

	E10					Biogasoline				
	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
PC-P0	3.37	3.40	3.44	3.34	3.34	4.40	4.41	4.40	4.40	4.40
PC-B	3.27	3.30	3.35	3.24	3.24	3.46	3.47	3.46	3.46	3.46
PC-P	3.27	3.30	3.35	3.24	3.24	3.46	3.47	3.46	3.46	3.46
PC-F	3.30	3.33	3.38	3.27	3.27	3.74	3.74	3.74	3.74	3.74
PC-B&M	3.27	3.30	3.34	3.24	3.24	3.45	3.46	3.45	3.46	3.45
MP-P0	10.80	10.81	10.82	10.79	10.79	11.86	11.86	11.86	11.86	11.86
MP-B	10.75	10.76	10.77	10.74	10.74	11.37	11.38	11.37	11.37	11.37
MP-P	10.75	10.76	10.77	10.74	10.74	11.37	11.38	11.37	11.37	11.37
MP-F	10.77	10.78	10.79	10.77	10.76	11.57	11.58	11.57	11.57	11.57
MP-B&M	10.65	10.67	10.67	10.65	10.65	10.45	10.45	10.45	10.45	10.45

Table 3.9 Blender *k*'s cellulosic ethanol and biogasoline purchasing quantity (in thousand gallons)

	Cellulosic ethanol					Biogasoline				
	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5
PC-P0	1,371	2,025	2,998	816	884	13,088	19,349	28,731	7,776	8,425
PC-B	1,380	2,038	3,018	822	890	13,882	20,523	30,473	8,248	8,936
PC-P	1,380	2,038	3,018	822	890	13,882	20,523	30,473	8,248	8,936
PC-F	1,378	2,034	3,012	820	888	13,648	20,177	29,960	8,109	8,786
PC-B&M	1,381	2,039	3,018	822	890	13,890	20,534	30,489	8,253	8,941
MP-P0	688	1,017	1,509	409	443	6,785	10,031	14,893	4,031	4,368
MP-B	693	1,024	1,519	412	446	7,196	10,639	15,796	4,276	4,632
MP-P	693	1,024	1,519	412	446	7,196	10,639	15,796	4,276	4,632
MP-F	691	1,021	1,514	411	445	7,026	10,388	15,424	4,175	4,523
MP-B&M	701	1,037	1,538	417	452	7,976	11,792	17,509	4,739	5,135

Table 3.10 Profit of market entities under various policies (in $ million)

Profit	PC-P0	PC-B	PC-P	PC-F	PC-B&M	MP-P0	MP-B	MP-P	MP-F	MP-B&M
F1	3.73	4.13	4.13	6.48	4.13	1.06	1.17	1.17	2.64	1.41
F2	2.06	2.31	2.31	5.76	2.31	0.58	0.65	0.65	2.46	0.77
F3	3.35	3.73	3.73	6.29	3.74	0.86	0.97	0.97	2.54	1.18
Total	9.13	10.17	10.17	18.53	10.18	2.50	2.79	2.79	7.64	3.36
P1	9.95	11.13	11.13	11.00	11.14	2.87	3.20	3.20	3.17	3.86
P2	10.35	11.56	11.56	11.29	11.57	3.10	3.43	3.43	3.32	4.11
P3	6.98	7.99	7.99	7.90	8.00	1.42	1.65	1.65	1.64	2.14
P4	11.25	12.55	12.55	11.54	12.56	3.23	3.60	3.60	3.29	4.35
Total	38.53	43.23	43.23	41.72	43.27	10.62	11.88	11.88	11.42	14.46
B1	0.47	0.48	0.48	0.47	0.33	106.08	113.58	113.58	110.42	112.29
B2	1.03	1.04	1.04	1.03	0.82	156.78	167.86	167.86	163.19	165.96
B3	2.25	2.28	2.28	2.27	1.95	232.77	249.22	249.22	242.29	246.39
B4	0.17	0.17	0.17	0.17	0.08	63.06	67.51	67.51	65.63	66.74
B5	0.20	0.20	0.20	0.20	0.10	68.32	73.15	73.15	71.11	72.32
Total	4.10	4.16	4.16	4.14	3.29	627.01	671.32	671.32	652.65	663.70
ω	1,201.50	1,284.40	1,284.40	1,259.50	1,285.20	312.98	335.14	335.14	325.80	380.43
ϕ	0.00	91.11	91.11	91.11	91.16	0.00	47.10	47.10	47.10	51.81
σ	1,253.30	1,250.90	1,250.90	1,232.70	1,250.80	953.11	1,021.10	1,021.10	997.52	1,061.90

Here

ω =Consumer surplus.

$$\omega = \frac{1}{2}\sum_{k\mathrm{m}\in\{\mathrm{E,BG}\}} B_k^{\mathrm{m}}\Big(\sum_j x_{jk}^{\mathrm{m,B}}\Big)^2 \tag{3.38}$$

ϕ =Subsidy expense.

$$\phi = \sum_l S_l^{\mathrm{F}} a_{il} + \sum_{\mathrm{m}\in\{\mathrm{E,BG}\}} S^{\mathrm{m,P}} \sum_l R_{jl}^{\mathrm{m}} t_{jl}^{\mathrm{m}} + \sum_j \left(S^{\mathrm{E,B}}\theta x_{jk}^{\mathrm{E,B}} + S^{\mathrm{BG,B}} x_{jk}^{\mathrm{BG,B}}\right) \tag{3.39}$$

σ =Total social surplus.
If blenders behave competitively (PC), then

$$\begin{aligned}
\sigma = {} & \sum_{jk\mathrm{m}\in\{\mathrm{E,BG}\}} x_{jk}^{\mathrm{m,B}}\overline{p}_k^{\mathrm{m}} + p^{\mathrm{RIN}}\sum_k\left[\sum_j\left(\theta x_{jk}^{\mathrm{E,B}} + x_{jk}^{\mathrm{BG,B}}\right) - T_k^{\mathrm{REQ}}\right] \\
& - \left[\sum_{il} C_{il}^{\mathrm{F}} a_{i,l} + \frac{1}{2}\sum_{il} D_{il}^{\mathrm{F}} a_{il}^2\right] - \sum_{jl\mathrm{m}\in\{\mathrm{E,BG}\}}\left[C_j^{\mathrm{m}} R_{jl}^{\mathrm{m}} t_{jl}^{\mathrm{m}} + \frac{1}{2} D_{jl}^{\mathrm{m}}\left(R_{jl}^{\mathrm{m}} t_{jl}^{\mathrm{m}}\right)^2\right] \\
& - \left[\sum_{jk} C_k^{\mathrm{EG}}\theta x_{jk}^{\mathrm{E,B}} + \frac{1}{2}\sum_k D_k^{\mathrm{EG}}\Big(\theta\sum_j x_{jk}^{\mathrm{E,B}}\Big)^2\right] - (1-\theta)\sum_{jk} x_{jk}^{\mathrm{E,B}}\overline{p}_k^{\mathrm{G}} \\
& - \sum_{ijl} T_{ijl}^{\mathrm{C}} x_{ijl}^{\mathrm{C,P}} - \sum_{jk}\left[T_{jk}^{\mathrm{E}}\theta x_{jk}^{\mathrm{E,B}} + T_{jk}^{\mathrm{BG}} x_{jk}^{\mathrm{BG,B}}\right] + \omega
\end{aligned} \tag{3.40}$$

If blenders have market power (MP), then in total social surplus the term $\overline{p}_k^{\mathrm{m}}$ will be replace by equation (3.33), and $\overline{p}_k^{\mathrm{G}}$ will be replaced by equation (3.34).

CHAPTER 4. SUMMARY AND DISCUSSION

In this thesis, two system analysis and optimization models are formulated for biofuel supply chain, and emerging biofuel market to provide managerial insights for stakeholders in the advanced biofuel production industry. The first piece of the thesis work focuses on the design of supply chain, and the operational planning for the individual biorefinery facility. The objective of the biofuel supply chain design model is to assist the decision making on facility locations, capacities, and the operational planning to minimize the total system cost. A case study in Iowa is conducted to analyze a variety of scenarios on biofuel production and demand shortage. In addition, the operational planning for various biofuel consumption seasonality patterns are analyzed. The results for the biofuel supply chain indicate that the unit production cost could be lower enough to be commercially feasible. A biofuel market model with the stakeholders along the supply chain will be emerging along the process of commercialization. This motivates the research for the second piece of work in this thesis. A bottom-up equilibrium model is formulated for the biofuel market to maximize the profits of all stakeholders (farmers, biofuel producers, and biofuel blenders) simultaneously under different market structures. The impacts of different existing and proposed government policies are analyzed.

The biofuel supply chain and market model is based on a few simplifying assumptions, which point us the future research directions. For farmers, we assume that their profits are only from selling biomass to produce biofuels, while other profits such as food and byproducts are not included. Additionally, in reality, farm lands with high fertility levels are usually planned to grow commodity crops such as corn and soybean. Marginal lands with lower fertility level, however, may be more appropriate for delicate energy crops such as switchgrass and miscanthus due to the profitability of food products. We will include all profits for food, biomass and other byproducts into farmer's model in future. In addition, we assumed the yield and production costs are fixed, while in reality, both of which are uncertain due to the weather and soil condition. Therefore it is important for farmers to make strategic decisions to manage the risk. Mechanisms such as crop insurances and contracts with the biofuel producers should be analyzed. Vertical ownership of farmers and producers may also be emerging in the advanced biofuel market. Furthermore, biomass can be used in various industry sectors such as electricity generation market, animal feeding, soil fertilizer, etc.

For the biofuel producers, the biorefinery facility locations are fixed and production capacity is assumed to be 2200 ton/day as in the literature [60]. As the technology evolves and market matures, it is necessary to integrate the optimal capacity decisions in the supply chain design model in Chapter 2 with the biofuel market model in Chapter 3. A number of existing pathways are identified by PNNL as promising pathways to produce biofuels such as gasoline and diesel range fuels. Our current biofuel market model assumes that there are two pathways producing cellulosic ethanol and biogasoline with the same capacity level (2200 ton/day). The choice of pathways and capacity for each pathway should be available for each biofuel producer to maximize its profit. Like farmers, biofuel producers also have the choice of selling biofuels directly into consumer markets or to biofuel blenders in the market or contract prices.

Biofuel blenders have the choice of producing various blended fuels by blending a variety of biofuels with conventional fuels. The biofuel market model assumed that each blender can only supply its local market, and the blended fuels are not substitutable. A more realistic assumption is that biofuels are substitutable, and blended fuels are substitutable with conventional fuels. Furthermore, under competitive market, each blender have the choice of supply blended fuels to any consumer market. Uncertainties in the fuel demand is also every important in decision making for all entities in the biofuel market.

The market power for farmers, biofuel producers, and biofuel blenders should be investigated. Different market structures such as centralized structure analogues to electricity market, and bilateral market structure in Chapter 3 should be further studied for us to propose a more appropriate structure for future biofuel market. A framework to investigate the biofuel market under federal and local policies could be developed to study the interaction between RIN price and biofuel mandate. Further analysis of the biofuel market such as the oligopoly vs. duopoly structure of the market, and the impacts of new entries in biofuel market should be conducted.

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