LOGISTIC STRATEGIES FOR AN HERBACEOUS CROP RESIDUE-BASED ETHANOL PRODUCTION INDUSTRY: AN APPLICATION TO NORTHEASTERN NORTH DAKOTA

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ABSTRACT

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A mixed integer programming model is developed to determine a logistical design for maximizing rates of return to harvest, storage, transportation, and biorefining of herbaceous crop residue for production of biofuels and feed for ruminant animals. The primary objective of this research is to identify the optimal location, scale, and number of pretreatment and biorefinery plants in northeastern North Dakota. The pretreatment and biorefinery plants are modeled under the assumption that they utilize recent technological advancement in AFEX and Simultaneous Saccharification and Fermentation, respectively. Potential feedstocks include wheat straw, barley straw, Durum straw, and corn stover. Results indicate that the minimum ethanol rack price that will effectively trigger the production of cellulosic ethanol is $1.75 per gallon.

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CHAPTER 1

INTRODUCTION

Introduction

The feasibility of producing ethanol from herbaceous crop residues (HCR) is highly dependent on the logistical supply chain system. Recent advances in conversion technologies show viable potential for the production of ethanol from HCR at a commercial scale. Driving forces behind the promotion of energy from renewable resources, such as transportation fuels and electricity generation include: (1) sharp increases and volatility in crude oil prices, (2) environmental concerns including global warming, (3) disputes over food versus fuel use of grains, and (4) concerns over the dwindling reserves of fossil fuel (Carolan, Joshi, and Dale 2007). Recent federal government mandates in the Energy Policy Act (EPA) of 2005 and Energy Independent and Security Act (EISA) of 2007 have profoundly enhanced the production of renewable energy. Both federal mandates have established challenging goals: the EPA calls for the production of 35 billion gallons of ethanol by 2017, and the EISA is requiring 16 billion gallon of cellulosic fuels by 2022.

Despite continuous investment in corn-based ethanol production facilities, sustainability of corn-based ethanol is questionable. The high price of corn grain, the limited amount of land available for corn production, and the low conversion efficiency of corn to ethanol, among other factors, have negatively affected the long-term feasibility of corn-based ethanol production. The current corn-based ethanol industry is heavily dependent upon federal and state subsidy. Without these subsidies, it is doubtful that corn-based ethanol could compete with the price of gasoline. An average of $0.54 per gallon of corn-based ethanol production cost is covered by these subsidies (DiPrado, 1998). Corn-based ethanol is expected to dominate renewable energy production in the short-run. However, ethanol from HCR is expected to provide more promising outcomes for the production of renewable energy (Carolan, Joshi, and Dale, 2007).

As a consequence of the economic and technological problems associated with corn-based ethanol, there is a need for alternative cost-effective feedstocks such as HCR, dedicated crops (switch-grass), forest residues, and municipal waste. A considerable amount of important research is currently investigating each of these alternatives. Of these alternatives, HCR provides the lowest cost biomass feedstock (Leistritz et al., 2006). One focus in the Northern Great Plains is exploring the technical and economic feasibility of HCRs, which include wheat straw, barley straw, corn/stovers, and durum straw, among others, as feedstock for ethanol production.

There are many advantages associated with using HCR for ethanol production. The technical yield of energy (outputs/inputs) produced from lignocellulosic conversion may be as high as 11.31 to 1, far exceeding the relatively low yield of corn-based ethanol, which is 1.40 to 1 (Vadas, Barnett, and Undersander, 2008). HCR provides a value added incentive to farmers in a joint agricultural production function: grains can be used for feed or food, and crop residues are available for energy and animal feed. Potential exists for numerous co-products from using crop residue conversion, including wheat straw for ethanol production, as well as cellulose nanofibers, chemical (succinic acid), and electricity production (Leistritz et al., 2006).

Although ethanol from HCR may be more profitable than corn-based ethanol production, economic analyses of the logistics of production, biomass harvesting, transportation, storage of feedstock, decentralized versus centralized pre-treatment operations, biorefinery scale and location, and transportation of product to wholesale fuel blenders are essential to assessing the profitability of the new industry. Essential analysis of the complete logistical system to determine optimal investment in each stage of the process has not been conducted for the HCR-based system, especially with consideration of the economic, agronomic, and engineering uncertainty inherent in the system.

Past research has focused on the technical production aspects for producing ethanol from HCR. Significant attention has been paid to identifying the most feasible pretreatment technology and conversion process (Yang and Wyman, 2008; Wyman, 2007; Sendich et al. 2008). Carolan et al. (2007), which addresses the focused on pretreatment of straw prior to ethanol production; however they analyzed scale economies from decentralized pretreatment facilities. Wright and Brown (2007) analyzed different sizes of biofineries, and Leistritz et al. (2006) estimated the cost of production of ethanol and possible co-production (e.g., cellulosic nanofiber) and examined the economic feasibility of the processes and the scale of production. However, only a few researchers have looked at the actual supply chain process (from the harvesting of feedstock to the production of ethanol) in determining the economic feasibility of a biorefinery. Kaylen et al (2007) and Mapemba et al (2007) considered harvest and transport of feedstock in a localized model of lignocellulosic ethanol production under various economies of scale and processing plant location alternatives.

The scarcity of logistical models of lignocellulosic ethanol industry reflects the novelty of the potential industry, especially given the extensive literature on plant location and infrastructure investment problems. Labbe and Loveaux (1997) present an overview of the location problem. Similar applications to the one in this research include models of the location of cattle feeding, slaughtering and processing in the United States (Faminow and Sarhan, 1983), determining the optimal number of slaughter plants and feedlot locations in Florida in conjunction with distribution regions of the final product (Moseley, Spreen, and Pheseant, 1986), and locating slaughterhouses subject to scale economies in Norway (Broek et al., 2006).

A notable feature of this research includes decentralized pretreatment facilities over the study region—the northeastern region of North Dakota and part of three northwestern Minnesota counties. Crop residues are bulky and pose significant cost for transportation to biorefineries. However, there is a trade-off between the pretreatment facility location and the transportation costs of unprocessed straw (Carolan, et al., 2007). Determining optimal biorefinery location, scale, and decentralized pretreatment facilities that provide feedstock to the biorefineries therefore requires a systematic approach to balance the processing and transport costs of biomass materials.

Rationale and Significance of Study

With the many challenges corn-based ethanol faces, it is important to consider the uncertainty and volatility of the market when making any new ethanol investment decisions. With the impending commercialization of lignocellulosic ethanol production, it is vital to assess location and plant scale decisions that incorporate both engineering and economic uncertainties from field production to feedstock to final markets for ethanol.

Given the newness of HCR ethanol technology, investors will be hesitant to invest in new ethanol processing plants if they do not understand the risk associated with their decision. This project will incorporate current factors of uncertainty in developing optimal infrastructure, plants, and the logistical supply chain involved in the production of lignocellulosic ethanol. Sensitivity analysis will provide insights arising from different scenarios of input factor cost and ethanol selling prices to address the uncertainty of the economic and technical environment. The results and the logistical model developed will be an important reference in the decision making process for implementing an HCR-based biorefinery system. The system model will be inclusive and adoptable in different geographical settings following necessary re-specification of the agronomic, engineering and economic parameters underlying the model.

Objective

The objective of this paper is to identify the optimal number of biorefinery and pretreatment plant(s), the optimal location(s) and scale of ethanol production in northeastern North Dakota, and the optimal harvest strategies of straw from farm fields. Sensitivity analysis addresses the effect of variability in both the input and output prices. A mixed integer programming (MIP) model will be used in determining optimal activity location and scale.

Organization

The next section discusses previous studies related to economic geography and the locational pattern of manufacturing industries, mixed integer programming models used to identify optimal location and economies of scale, and literature related to cellulosic ethanol production. Chapter 3 presents the theoretical framework for profit maximizing firms along the supply chain. Results from the model are presented in Chapter 4. Chapter 5 provides the conclusion and limitations of this thesis.

CHAPTER 2

LITERATURE REVIEW

Introduction

In recent years, sharp increases in the price of conventional petroleum fuel and environmental concerns such as Global Warming have led to major research and development in the commercialization of renewable energy. The future of corn-based ethanol is questionable, since it depends heavily on federal and state subsidies to be competitive with petroleum fuel (DiPardo, 2004). Speculations and results from pilot programs on the commercialization of ethanol from crop residues seem to have a potentially promising future. Numerous studies done on minimum (cellulosic) ethanol selling prices (MESP) have demonstrated competitive figures: Wright and Brown (2007) report MESP at $1.19 per gallon; MBI International (2006) and Leistritz et al (2007) report MESP at $1.80 per gallon, and Newton-Sendich et al (2007) report MESP at $1.03. All of these prices are competitive with convention petroleum prices.

Numerous studies have focused on the technical aspect of this industry, in an endeavor to develop the necessary technology for commercial size biorefineries. However, the success of all industry depends on both technical and economic feasibility. The economics of this industry rely on the location (in terms of its proximity to both feedstock and final market, to minimize transportation cost) and the scale of biorefineries. The literature reviewed in this chapter examines the fundamental theory of location and its effect on economic feasibility, followed by mixed integer programming (MIP) models of optimal location and scale economies. The chapter concludes with an overview of what technology currently exists and then examines possible sources of feedstock for cellulosic ethanol production.

Early Development of Location Theory and Economic Geography

The theory of economic geography can be traced back to specific models which are direct descendants of the research that Johann von Thunen conducted in 1826 and the work that Weber carried out in 1909. Both Thunen's model of land use and Weber's theory of location identifies the least cost location concept as the optimal location (Greenhut, 1956). Thunen's model focused on the type of agricultural production with respect to the proximity of the central market. The central market is located in what is described as an "Isolated State", a state that is self sufficient and has no external influence. The State and surrounding land (in scheme of concentric circles) is unoccupied, unused, and is homogeneous (having uniform landscape, soil, climate, and price). Farmers are profit maximizing market participants. Thus, they will cultivate the crop that provides the highest return for that given plot of land (Friedrich, 1929). For every given location in this system there is a tradeoff between the form of production and the transport cost. Both transportation cost and land cost are functions of distance. As the distance from the central market increases, transport costs also increase. However, in this scenario, land rent decreases. It was Thunen's basic model of land use that introduced the importance of geographic location to production (Friedrich, 1929). Although Thunen's model was the first to identify location as an influential factor in the efficiency and effectiveness of an industry, in his desire to make the model more understandable, he simplified the reality of the situation (Friedrich 1929).

Alfred Weber developed the first general theory of industrial location that considered spatial distribution of inputs. Weber's theory contradicts Thunen's; in Weber's model the type of industry is given and the goal is to determine the location, while Thunen's goal is to determine the industry when the location is given. However, similar assumptions and approaches are demonstrated in both theories.

Weber, who looked at manufacturing industries, states that the optimal location of an industry[1] is the location where the firm incurs the minimum total cost (Greenhut, 1956). There are three factors that are used to determine where an industry should be located. They are as follows: 1. the transport cost, which uses the "material index", to determine where it is more feasible to incur this cost. Material index is the ratio of the weight of the raw material to that of the final product. If the weight of the final product is less than that of the raw material, then the firm will locate near the raw material. If the weight of the raw material is less than that of the final product, then the firm will locate near its market. 2. The labor cost – if the production of a firm is heavily dependent on that of low-skilled labor, location may justify greater transport distances. 3. Agglomeration – the concentration of firms in a locale. Through agglomeration, firms are able to achieve scale economies by sharing labor, infrastructure, facilities, and other factor inputs. The factor that exerts the dominant pull and minimizes the total cost of production and distribution of the manufactured good will determine where the industry will be located. For example, if

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[1] Industries here and throughout this paper are referring to manufacturing industries.

the value added benefit of agglomerating is greater than the increase in cost of transportation and labor that might gained from locating in a central market, then the rational choice is to agglomerate cost (Friedrich, 1929; Greenhut, 1956).

The Thunen-Weber theory led many geographers to explore this theory of location. Two of the most prominent and important approaches were the work of Hoover 1913 and Losch 1930. Hoover's cost analysis theory was developed on the framework of cost, similar to Thunen-Weber's theory. The distinctive feature of this theory was demand determinant, which was used to determine optimal location along with the cost factors of Thunen-Weber's theory. This model also uses a monopolistic economy, rather than the competitive economy. Cost factors in this theory were a combination of transportation cost (similar to that of Thunen and Weber) and production cost, which includes agglomerative and institutional cost (land rent, property tax, and climate). The average transportation cost is projected to decrease as the distance increases. The purpose of the aforementioned theory is to decrease the importance of transportation cost and to maximize the ability of the model to cover a larger geographical region. The basis of analysis of this theory wasn't solely to minimize the general factor cost, rather, the focus was on all possible forces that could affect the plant location. Factors such as property tax and climate that were neglected in Weber and Thunen's theories due to the more simplistic nature of their model played a major role in Hoover's analysis. Both property taxes and climate increase land cost. Property taxes are expenses incurred that affect returns on the investment. The climate is an inherent expense that comes with a location. If its too hot, air conditioning is necessary to improve working conditions, and if its too cold, heating becomes necessary. Similar to Thunen and Weber, Hoover's "optimal location choice was a problem of substitution between the two costs: production and transportation with the ultimate objective being the minimization of expenses" (Greenhut, 1956). The critique of this theory is that abstract information about market demand was considered to be satisfactory and be influential in determining the optimal location (Greenhut, 1956).

August Losch's theory of maximum profit location provides a contrasting approach to that of the Thunen-Weber theory. Losch's theory is built on a similar framework and concept as the theory developed by Thunen and Weber. However, the optimal location in this theory is said to be where net profit is the greatest. Net profit is of two-sided orientation— function of minimum cost, and maximum revenue. Thus, the optimal location doesn't rely "...neither upon expenses nor upon gross receipt alone...but the final and sole determining factor is their balance: the net profit" (Losch, 1954). Losch states that "every one-sided orientation is wrong." Hence the Thunen-Weber theory (orientation by cost) is consistent with the aforementioned statement. Evidence that supports the previous statement is contained in the fact that there is no point of minimum transportation cost once there is variability in the demand and price. However, "the average transport cost would be lowest if nothing we sold beyond the location on the plant" (Losch, 1954).

New Economic Geography

The Thunen-Weber theory and other prominent geographers' theories of optimal location were very instrumental and influential in the development of what we know as "new economic geography". The new economic geography (NEG) is a general equilibrium framework that seeks to explain the rationale behind the spatial distribution of agglomeration. The foundation of this monopolistic competitive economic model is built upon the trade-off between increasing returns and mobility cost. The model utilizes transport cost to demonstrate the importance of identifying the optimal location (Fujita, and Mori, 2005). The new economic geography consists of three classes of models— core-periphery model, regional and urban model, and international model. However, only the core-periphery model is relevant to us in this paper.

The core-periphery model is the most fundamental framework of new economic geography (NEG), developed by Krugman (1991). The core-periphery model "illustrates how the interaction among increasing returns at the level of the firm, transport cost and factor mobility can cause spatial economic structure to emerge and change" (Fujita, and Mori, 2005). Specifically it focused on the rationale of why manufacturing is usually concentrated in "core" regions, while the "peripheral" regions are suppliers of agricultural products for the core (Krugman, 1991; Fujita, and Mori, 2005).

In the model there are two regions core, and periphery regions, and two types of production: agriculture and manufacturing. The manufacturing sector produces under scale economies, therefore, when each firm produce is heterogeneous, and labor is considered the only input factor, the cost to transport product is of "iceberg"[2] form. Workers in the manufacturing sector are mobile—in essence, they will move to the region with the higher real wages. In the agricultural sector, farmers produce homogeneous product under a constant return, labor is only input considered, and the transportation of produce is costless.

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[2] Iceberg form – a portion of the good "melts away" during the time of transit.

Farmers are immobile, therefore, it is assumed that they are equally distributed in the two regions (Krugman 1991).

In this model, there are two forces: centripetal and centrifugal. The first promotes geographical concentration, while the second opposes such an occurrence. Table 1 is the identification of forces that affect the geographical concentration of economic activity.

Table 1: Factors Affecting Geographical Concentration

Centripetal Forces	Centrifugal Forces
Market-Size Effect	Immobile Factors
Thick Labor Markets	Land Rents
Pure External Economies	Pure External Diseconomies

Source: Krugman (1998)

Centripetal forces favor the idea of agglomeration of firms because they possess the concentration of economic activity. The extent of the market size determines the scale of the input and output markets. A large local market is a desirable location for production of both final and intermediate goods, and manufacturers also get to benefit from economies of scale through mass production in this circumstance. A thick labor market provides incentive to both the employees and employers because employees are able to easily identify potential employers, and employers have a larger pool of potential employees to choose from. The pure concentration of firms refers to the potential of information spillover due to the local concentration of industries (Krugman, 1998).

Centrifugal forces favor a wide spatial distribution of firms over space. In certain circumstances, various factors of production are immobile. For example, land and some natural resources such as gold and oil deposits are immobile, therefore extraction and/or production must take place at a specific location. In addition, individuals at the international level are immobile due to international laws and regulations. Land rent can also be very influential in determining the concentration and location of industries. As industries concentrate, demand for land becomes a crucial issue, which consequently causes the rent on land to rise in that specific area. Pure external diseconomies—for example congestion—are likely to come into existence as firms concentrate their activities (Krugman, 1998).

The relative strength of centripetal or centrifugal forces will determine whether industries will agglomerate or deglomerate. Thus, the drive toward geographical concentration is dependent on the economy in the region. A highly urbanized region is ideal for manufacturing to take place because there will be a large local market in combination with the presence of various goods and services (Krugman, 1991). Urban firms are more productive than rural firms due to the effects of agglomeration (Venables 1996; Koo and Lall 2007). Concentration of firms in urban regions will attract population from other regions; therefore, the majority of population will be located in this urban region (Krugman, 1998; Venables 1996; Koo and Lall 2007). In essence, a large market provides scale economies to manufacturing firms, due to the concentration of production of each variety in a single location. Due to transport cost, it is rational to produce in this large market and ship to other regions.

In this model, core-periphery market patterns will likely be present in the region where there is "…low transportation cost, a large manufacturing sector, strong economies of scale, and when circular causation[3] sets in" (Krugman, 1991).

Presently, Krugman's NEG model of 1991 is still the only general model that exists in determining location of agglomeration. However, over the years the model has undergone numerous modifications and extensions. A few of these modifications are summarized as follows: Koo and Lȧll (2007) identified that there is an upward bias in the estimation of the contribution of economic geography on performance when firm location is not taken into account. Mori and Turini (2005) established that workers are heterogeneous in skills level; they found that workers will sort themselves across regions, high skilled workers will tend to locate where the consensus of similar skilled workers are present, and the income level in high, while lower skilled workers will settle in other regions. Murata (2003) hypothesized that heterogeneity in individual preference on their desired residential location could be a potential centrifugal force in NEG, and concluded that non-market activity as previously mentioned, along with market must both be taken into account in the spatial distribution model. Fan, Treyz, and Treyz (2000) presented a model with multiple regions, multiple industries, and where labor and capital mobility are built in a monopolistic competition framework. Their results have concluded that "… the economic-geography equilibrium reached by the economy depends not only on initial

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[3] Circular causation refers to circularity process—in this case, "manufactures production will tend to concentrate where there is a large market, but the market will be large where manufactures production is concentrated" (Myrdal, 1957; as mentioned in Krugman, 1991).

condition, but also the speed of adjustment of the firm's location changes based on nonnegative profits" (Fan, Treyz, and Treyz, 2000).

Krugman's model has undergone many more extensive approaches, however his models remains dominant to date in the field of economic geography. The majority of the work done in extension of Krugman's core-periphery model can be categorized into five broad topics: multi-regions models, heterogeneity within workers and locations, labor mobility, additional centripetal and centrifugal forces, and agglomeration and growth.

Mixed Integer Programming (MIP) and Facility Location

Identifying the optimal facility location is a recurring problem faced by investors because of the fixed investment associated with such a decision. Agricultural economists have utilized mathematical programming methods thoroughly to solve spatial market equilibria and facility location problems. Mixed-integer programming has appeared to be extensive throughout the literature as an analytical tool in determining the optimal number, size and location of facilities. Due to the flexibility and adoptability in mathematical program models, each model is developed for the specific purpose at hand in respect to its specific objective function and specific constraints.

The objective of MIP is either cost minimization or profit maximization. The MIP model can either be capacitated or un-capacitated. Capacitated models are said to have an upper limit on the output that a facility can produce at a profit. However, most of the time the upper limit is not fixed and if additional input is added, higher additional output can be obtained. However, the cost of this additional input is higher than the benefit obtained from the additional output. On the other hand, in un-capacitated models there is simply a set of demand and supply regions. The idea is to determine the number of facilities that would satisfy the demand and incur the minimal cost. In un-capacitated models, the demand and supply in a specific region can take on any positive integer (Harkness, and ReVelle, 2003).

A few examples of the relevant literature that utilizes mathematical programming to solve for the optimal location, size, and number are as follows: Faminow and Sarhan (1983), Moseley, Spreen, and Pheasant (1986), Broek et al (2006), and Hsieh and Chiang (2001).

In the late 1970's and the 1980's development of the extensive production of feed grain in the Southwest Plains of the United States (US) showed viability for the production of fed cattle in the region. The Midwest region has always been the undisputed area for cattle fed production, slaughtering, and processing in the US. However, Faminow and Sarhan (1983) saw the possibility that the Southwest region could become the dominant center. Nevertheless, they developed a mixed integer plant location model for fed cattle slaughtering and processing in the US. The model objective was to determine the optimal number, location, and size of large scale feed cattle slaughtering and processing facilities given spatially dispersed and separated patterns of fed cattle supply and beef demand. The MIP model used the cost minimization approach. The cost to transport the fed cattle, the slaughtering and processing cost, and the transportation cost of beef shipment to the final market were all minimized.

Supply and demand regions were identified throughout the US. Binary variables were used to select or not select sites where the slaughtering and processing facilities should be built throughout those regions. Fixed cost was established through the binary variable when a site was selected. The fixed cost was a constant and was determined by the annual capacity of the facility. The transportation, slaughtering, and processing costs were all linear variable costs. The model was restricted by capacities of the facilities built and the amount of input supplies (fed cattle) available.

Moseley, Spreen, and Pheasant (1986) developed a mixed integer plant location model with a temporal and spatial dimension to address the following problem. Florida has historically been one of the top producers of fed cattle throughout the US. However, there were minimal slaughter and processing of beef in the state. Boxed beef was imported from other regions to meet the demand of the state. Increase in transportation over years had caused the Florida cattle industry to receive considerably lower prices for their feeder calves than other producing regions nearer to the central market (in this case that would be the Midwest region). In addition, consumers paid a higher price for imported beef from other states due to the cost of transportation.

The objective of Moseley et al model was to determine the optimal location for back-grounding weaned calves, as well as the optimal location, size, and number of feedlots and slaughtering plants in Florida. The MIP model used the cost minimization approach. This model minimizes the aggregate cost of weaned calf assembly, back-grounding, and slaughtering cost of the calves. Time is important in this model because fed calves were only allowed a certain length of time (which was defined as quarters) which they were to move through the process—from calves weaning to the finish product of boxed beef.

The supply and demand regions were known and fixed. Seasonal patterns in past supplies of fed calves were identified; thus the scheduling of animals through the system was necessary to minimize slack capacity at plants. The temporal dimension of the MIP model addresses this problem by varying the length of time that animals can remain in the back-grounding and in feedlots in an attempt to maintain the availability of boxed beef. An annual fixed cost was incurred with the decision to build a plant in a specific region. The unit cost of slaughter was a linear function of the plant volume. Transportation had a fixed unit cost per loaded mile; therefore, total transportation was a function of the distance travel and the unit cost per loaded mile. The model was constrained by the capacities of both the feedlots and slaughtering plants (Moseley, Spreen, and Pheasant, 1986).

In an effort to improve the economies of scale of the Norwegian Meat Cooperative (NMC) Broek et al (2006) developed a mixed integer linear programming model based on linearization of facility cost and Lagrangean relaxation. Greedy heuristics algorithm was also used to discover optimal solutions. The aim of this study was to investigate cost savings from reducing the number of plants currently employed by the cooperative and increase the size of the remainder of the plant. The objectives of the model are to identify the optimal location and size of slaughterhouses in respect to the allocation of animals, given the spatial distribution of these animals. Minimizing the cost of transportation and slaughterhouse cost were the specific function of this MIP program.

The MIP model developed in this paper is similar to that of an un-capacitated facility location problem. The difference is that the facility cost used is this model employs the staircase cost form. The facility cost is modeled using special ordered sets of continuous variables. The Lagrangean relaxation was used to find the lower bound at all iteration of the problem. This was accomplished by relaxing the constraints of the model. The optimal solutions from the Lagrangean relaxation are not feasible solutions for the model. The greedy heuristic algorithm was then used to determine the upper limit (Broek et al, 2006).

The fuel oil refinery industry in China has always been a monopolistic business for the Chinese Petroleum Corporation (CPC) until January 1999 when the government opened the market to competitors. An open market introduced numerous uncertainties to the industry production planning model in CPC. Hsieh and Chiang (2001) developed a Possibilistic mathematical linear programming model that would be responsive and flexible to uncertainties of the market and that would establish a sound manufacturing to sale process. The model was to maximize the company profit.

The Possibilistic model extends the range of the parameters of the triangular possibility function in the model to include fluctuation in resources and cost coefficients due to uncertainties. These new parameters then form new objective functions along with Possibilistic constraints. A multiple objective function model is then formed. The pessimistic/optimistic value of the objective function is defined and the membership function of the objective function is estimated. The multiple objective linear programming model is then transformed to single objective programming model and solves for the optimal solution. In short, the Possiblistic linear programming model introduced additional parameters that are somewhat like ranges which allow the model to be flexible and to change in cost and demand, so that whenever cost changes, the model does not need to be changed (Hsieh and Chiang, 2001).

Cellulosic Ethanol Production

Cellulosic ethanol and other bio-based product show potential of economic feasibility in the near future. As the world supply of crude oil seems to be dwindling and while the United States (US) continues to be the world's largest consumer of petroleum energy, there are concerns about the country's energy security. There is also a global need to reduce carbon emissions into the atmosphere which are produced by the burning of fossil fuels in an attempt to avoid the potentially catastrophic repercussions of global warming. Thus, the US has developed numerous renewable energy mandates in order avoid a crisis of this nature and magnitude. Presently, there are 180 ethanol plants operating throughout the in the US (the majority are corn-based, approximately 82%, and the other 18% are from other field crops and baggasse) producing some 11,051 million gallons of ethanol per year (MGY). And another 21 refineries are under construction that is projected to produce another 1,580 MGY (Renewable Fuel Association, 2008). With the increasing number of corn based ethanol plants, demand for corn grain escalates, causing the price of the grain to become inflated, which, in turn, causes the economic feasibility of the plants to be marginal. Nevertheless, numerous pilot projects and research have been implemented to developed technology that will use biomass resources in the production of ethanol. A number of different feedstock has been indentified and several conversion technologies have been developed, however, none of these options are currently available at commercial scale.

Potential Feedstock

The ability to establish a constant flow of biomass at a low cost to a cellulosic ethanol plant is vital for commercial success (Carolan et al, 2007; Mapemba et al, 2007; Mapemba et al, 2008). Numerous feedstocks have been asserted to be economically feasible in producing cellulosic ethanol, such as: herbaceous crop residues (HCR), dedicated energy crop, municipal waste, and forest residues. The US is the world's largest agricultural field crop producer, therefore herbaceous crop residues such as wheat straw, corn stover, barley straw, among others, are the largest supplies of biomass available for production of ethanol. Switchgrass and hybrid poplar are categorized as dedicated energy crops and are commonly grown on land enlisted under Conservation Reserve Program and require minimal energy to produce.

"…The characteristics of the ideal energy crop are: (1) high yield (maximum production of dry matter per hectare), (2) low energy input to produce, (3) low cost, (4) composition with the least contaminants, and (5) low nutrients requirement" (McKendry, 2002a). However, the desired energy output will determine the potential biomass. Transportation fuels, electricity or heat, and chemical feedstock are the main products of biomass.

In addition, the moisture content of feedstock is critical in determining the energy conversion process. HCR and dedicated energy crop, and forest residues are considered to have low moisture and content, and they are also considered to be more economically viable in commercialization of ethanol production (McKendry, 2002a).

Cellulosic Ethanol Conversion Process

A common characteristic of biomass is that it contains three main components, which are cellulose, hemicellulose, and lignin. "Cellulose is a glucose polymer …, hemicelluluose is a mixture of polysaccharides, composed entirely of sugars …, and lignin can be regarded as a group of amorphous high molecular-weight compounds. Cellulose, hemicellulose, and lignin contribute 40-50%, 20-40%, and 15-20% respectively to weight of biomass. "The relative proportions of cellulose and lignin are one of the determining factors in identifying the suitability of plant species for subsequent preprocessing as energy crop". Herbaceous crops usually contain minimal lignin and therefore are a useful crop in the production of cellulosic ethanol (McKendry, 2002b).

The chemical breakdown of biomass in the process of energy production can be accomplished through two technological processes known as thermo-chemical or biochemical conversion. Thermo-chemical conversion consists of four different processes, which are referred to as combustion, pyrolysis, liquefaction, and gasification. Bio-chemical conversion consists of two processes, which are fermentation and digestion. Fermentation of cellulosic biomass requires some form of acid or enzymatic pretreatment to extract the sugar from the biomass before one can proceed to the process of fermenting the pentose sugar to ethanol.

Figure 1 below demonstrates a simplified process flow for a biorefinery where ethanol is the primary product. The configuration involves the potential of producing animal feed and electricity as co-products of ethanol production. The process is as follows: biomass feedstock is brought into the plant, the feedstock is then pretreated and ready for biological conversion. Protein for animal feed may be recovered at this stage. The pretreated biomass is converted to ethanol by means of enzymatic hydrolysis and fermentation. Ethanol is recovered through distillation. The lignin in the residual is separated and undergoes processing that generates steam or electricity that can be used in the plant or exported (Lynd et al, 2002; Wyman 2007). Appendix 1 provides a detailed configuration of the process flow for a cellulosic ethanol plant using AFEX treatment and Simultaneous Saccharification and Fermentation (SSF)[4] technologies (Lynd et al, 2002).

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[4] Simultaneous Saccharification and Fermentation systems can hydrolyze and ferment both pentose sugars and hexose sugars in the same vessel (Carolan et al, 2007). According the US Department of Energy National Renewable Energy Labatory as mentioned in Borgwardt (1999), SSF is the least cost option for processing cellulosic biomass to ethanol.

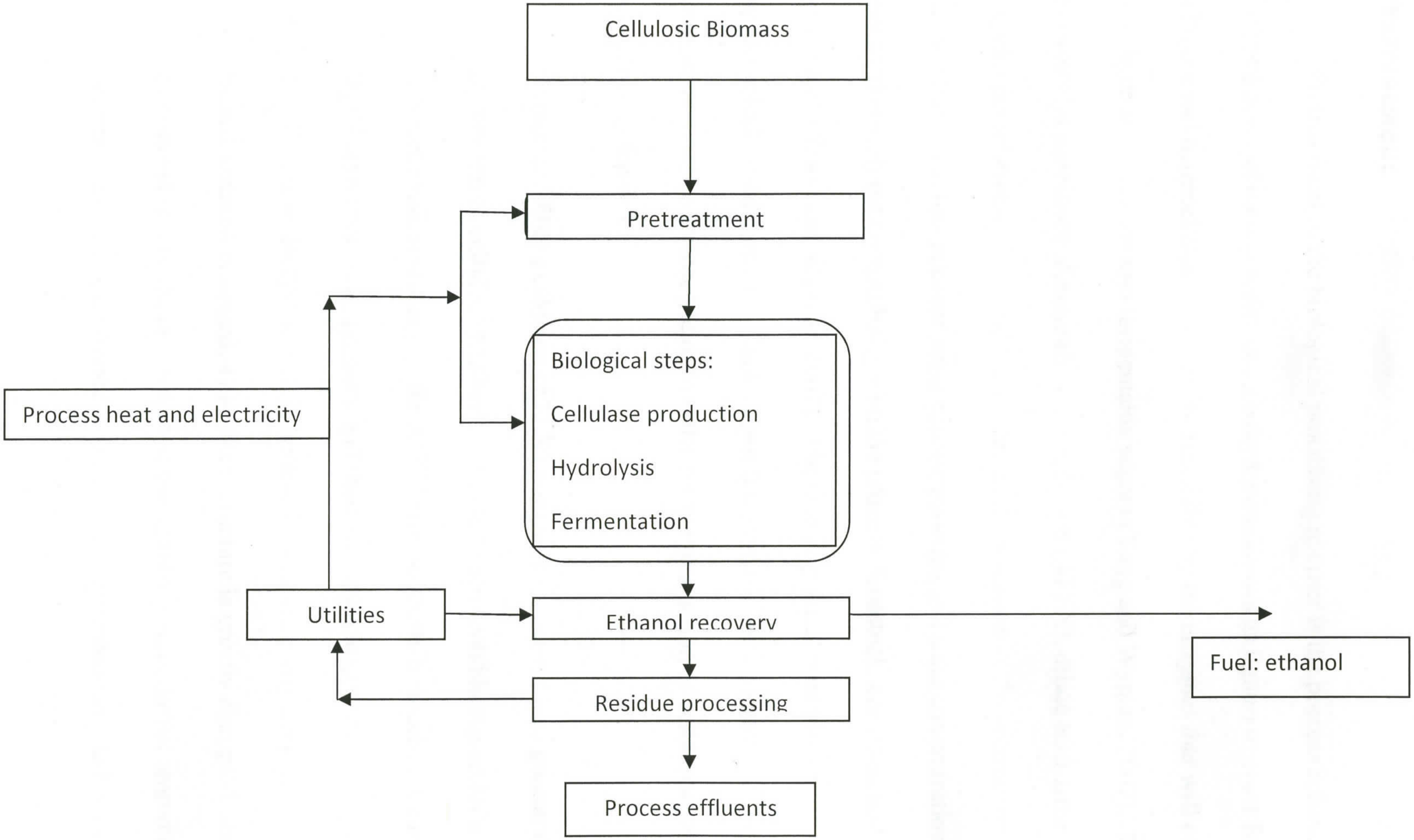

Figure 1: Simplified Process Flow for Biological Conversion of Biomass to Ethanol.

Source: Wyman (2007)

Pretreatment

Pretreatment in the biological processing manner is the process referred to during the breakdown of natural resistant carbohydrates (known as lignin) in order for the cellulose and hemicellulose to be easily accessible by the enzymes that will convert the carbohydrates polymers into fermentable sugars (Yang and Wyman, 2007). There are five pretreatment processes: Ammonia fiber explosion (AFEX), dilute acid, lime, Ammonia recycles percolation (ARP), and hot water. In the selection of the pretreatment technology, "... one must take into account sugar-release patterns, and solid concentration in conjunction with the compatibility with the process, feedstock, enzymes, and organism to be applied" (Yang, and Wyman, 2007). The cost of pretreatment alone accounts for 18% the biological production of ethanol. Thus, the required pretreatment should provide high hemicellulose and cellulose yields in order for the production of cellulosic ethanol to be economically feasible.

> "Ammonia fiber explosion (AFEX) pretreatment can achieve greater than 90% conversion of cellulose and hemicellulose to fermentable sugars for a variety of lignocellulosic materials ... the AFEX process treats lignocellulosic materials with liquid ammonia under pressure and them rapidly releases pressure, with result that 1) cellulose is decrystallized, 2) hemicelluloses are prehydrolyze, 3)lignin in the treated material is altered, 4)the fiber structure is greatly disrupted, and 5) the small amounts (1-2% of the dry weight of the cellulosic material) of ammonia left behind can serve as a nitrogen source in subsequent fermentations. AFEX can employ low

cost materials than for dilute sulfuric acid and the hydrolyzate is compatible with fermentation organisms without conditioning" (Yang, and Wyman, 2007).

Table 2 below compares the capital cost associated with the five pretreatment processes. The first column compares the fixed capital associated with the different types of pretreatment plants. Of the five processes hot water pretreatment cost is considerably lower than the others; the cost involved with the other four processes are approximately the same. However, considering the total fixed cost of each of the processes show, the costs are similar, with the exception of the lime pretreatment, which is significantly lower. However, the idealistic factor in this table is the capital requirements per annual gallon of capacity, since that's where the tradeoff between cost and revenue comes in play. Again, lime pretreatment is dominant because it requires the lowest capital cost per annual gallon capacity. The downfall of this process is that the existence of a value-added co-product is limited (Eggeman, and Elander, 2005).

Overall AFEX and dilute acid seem to be the preferred pretreatment processes because the capital cost per gallon capacity is competitive with that of lime pretreatment. Furthermore, there are numerous co- products to ethanol such as electricity, chemicals, etc. that can generate additional revenue and offset capital requirement per gallon of ethanol.

Table 2: Capital Cost for Different Pretreatment Processes

Pretreatment process	Pretreatment direct fixed capital, $M	Total fixed capital, $MM	Ethanol production, MM gal/yr	Total fixed Capital, $/gal annual capacity
Dilute acid	25	208.9	56.1	3.72
Hot water	4.5	200.9	44	4.57
AFEX	**25.7**	**211.5**	**56.8**	**3.72**
ARP	28.3	210.9	46.5	4.56
Lime	22.3	163.6	48.9	3.35
No pretreatment	0	200.3	9	22.26
Ideal pretreatment	0	162.6	64.7	2.51

Source: Eggeman, and Elander (2005)

Besides being economically and technically feasible AFEX pretreatment provides two other significant advantages. The first advantage is that the pretreated biomass at the end of the pretreatment process is dry and inert, as compared to other processes which are usually wet and require drying at some cost. The dry biomass improves the bulk density from 4-6 $1b/ft^3$ to 8-12 lb/ft^3 (These figures take into consideration that the biomass was chopped and ground before being pretreated.). Thus, this particular process makes the biomass easy to transport and/or store, which, in turns, provides a critical advantage in supply chain logistics. The second advantage of AFEX pretreatment is that the pretreated biomass that is created through the AFEX process can be used as feed for ruminant animals without further processing. In fact, the ammonia (about 3%) that is left in the pretreated biomass improves nutrient value. Table 3 below presents the nutrient analysis of animal feed for seven different AFEX pretreated biomasses. Oats and whey seem to provide the highest Crude Protein (% DM). Wheat provides the highest net energy (Mcal/lb). Overall, the nutrients provided by the different biomasses are similar (Carolan et al, 2007).

Table 3: Nutrient Analysis of Animal Feeds

Animal Feed	Crude Protein (%DM)	Net Energy (NEL)(Mcal/lb)	Dry Matter (%)
Corn stover	**10**	**0.86**	**85**
Sorghum or milo	10.4	0.84	89
Wheat	**11.3**	**0.89**	**89**
Switchgrass	12	0.87	85
Barley	**12.8**	**0.87**	**89**
Oats	13	0.8	89
Whey, dried	13	0.85	93

Source: Carolan et al (2007)

Decentralizing the pretreatment process from the bio-refinery plant can improve the techno-economic feasibility of producing ethanol from biomass. A proposed system of a series of pretreatment plants located near feedstock supplies can alter the transportation and reduce cost associated with transporting low bulk density feedstock over long distances, which can be very costly. Also, with the decentralization of the pretreatment process, the same capital can be used to build larger biorefinery facilities, which in turn will increase production, and thereby facilities could benefit from larger economies of scale. The economic feasibility of decentralized pretreatment is embedded within the trade-off between the cost of transporting low density feedstock over long distances and the fixed cost associated with building the regional pretreatment plants (Carolan et al, 2007).

The production of ethanol from cellulosic biomass requires a smooth configuration of key elements of the supply chains— from a continuous and stable supply of feedstock, to choosing the right pretreatment process, the right conversion technology, and most of all the optimal size of the plant so that the maximum return is achieved due to larger economies of scale. In addition, a high value co-product of ethanol will definitely lower the cost of ethanol and make it competitive in the market with crude oil (Leistritz et al, 2006). AFEX pretreatment along with Simultaneous Saccharification and Fermentation process seem to be the favored combination that shows potential for the next generation of renewable energy.

CHAPTER 3

EMPIRICAL MODEL

Introduction

To determine the optimal number, size and location of pretreatment plants and bio-refinery facilities the mixed integer programming approach is utilized. The mixed integer programming in this particular fixed charge facilities location maximizes total returns over total cost. The costs included in this model can be placed in four categories: fixed capital cost, variable operating cost, storage cost and transportation cost. The fixed capital cost is the cost incurred when a plant (either a biorefinery or pretreatment plant) is built. The total fixed capital cost is spread throughout the plant life to derive annual fixed cost, but the annual fixed cost for plants of different sizes varies. The operating variable cost includes the cost for pretreatment, processing cost, and harvesting cost. These variable operating costs are linear functions of the volume of feedstock fed into them. In the case of harvesting, it is the number of bales produced. Harvesting cost includes baling and wrapping of straw or stovers.

Storage can either take place in a field (in bales) or at a pretreatment facility where the material can be stored as bales of straw or as pretreated biomass. The storage cost is on a per unit basis; thus, the total storage cost is a function of the number of units stored multiplied by the per unit storage cost. There is no ending inventory.

Transportation cost is the cost associated with transporting feedstock from the field to the pretreatment plant and from the pretreatment to the bio-refinery facility. Total transportation cost is calculated as a function of the cost per ton per loaded mile multiplied by the distance traveled. The model only allows for straw/stovers to be transported in loads of 17 tons.

The supply region is located in the northeastern region of North Dakota. The seven northeastern counties of North Dakota (Towner, Cavalier, Pembina, Ramsey, Walsh, Nelson, and Grand Forks) and portions of three northwestern Minnesota counties (Kittson, Marshall, Polk) served as the study area for the plant location model. A grid of 24-mile squares was imposed over the area, creating 17 equal sized cells (see Figure 2 below). It was necessary to calculate distances in the model from (a) farm to storage and/or pretreatment site, (b) from storage to pretreatment site, and (c) from pretreatment site to the ethanol processing plant.

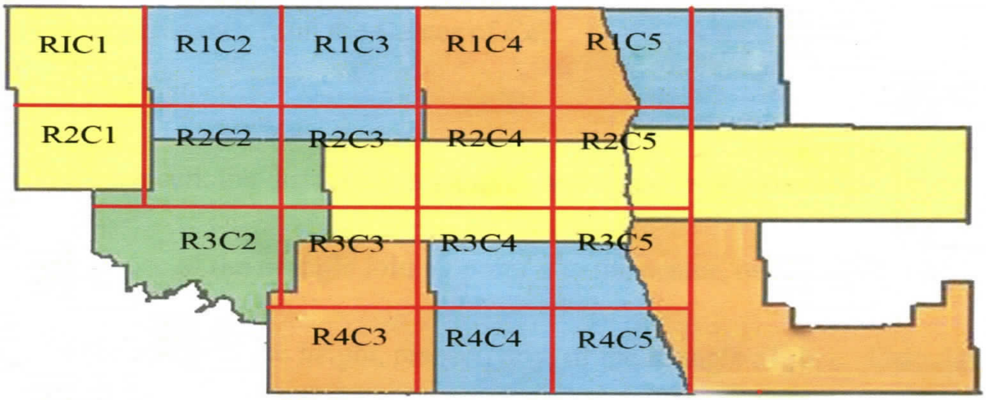

Figure 2: Counties Divided into Cells

It was assumed that farms would be uniformly distributed over each cell. Pretreatment facilities were located at the center of each cell. Ethanol plants were also assumed to be located at the center at each cell, but roughly related to the following towns due to their connections to transportation facilities: Cavalier, Cando, Lakota, Edmore, Devils Lake, Park River, and Larimore.

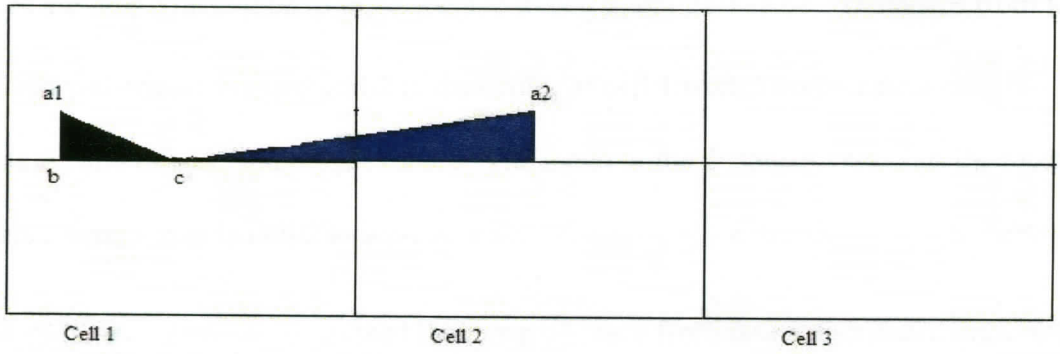

Figure 3: Average Distance from the Center of Cell

Within each cell, the distance from a farm to the center of the cell can be calculated along the hypotenuse of the triangle joining point *a* to the center, or $\overline{ac} = \sqrt{b_{ac}^2 + h_{ac}^2}$, where b_{ac} and h_{ac} are the base and the height, respectively, of the triangle a1, b, c. Calculating all possible distances from the center to farms within cell 1 was based on 100,000 random draws of $0 < b_{ac} \leq 12$ and $0 < h_{ac} \leq 12$ (based on the distance *ec* and *ed* equaling twelve miles).

Distance from farms distributed in the cell adjoining grid 1 are also based on straight-line travel from the farm to point c. The height of the triangle remains unchanged, $0 < h_{ac} \leq 12$, where a now refers to farms within cell 2. The base changes to reflect two attributes of the distance from farms in cell 2 to the center of cell 1. First, $0 \leq b_{ac} \leq 36$, since the longest distance from the furthermost point in cell 2 from the center of cell 1(c) is 12 miles from c to the edge of cell 1 plus the 24 mile width of cell 2. The second adjustment eliminates the problem of double-counting farms in the first cell. Triangle base values are thus constrained to those located in cell 2, or $12 < b_{ac} \leq 36$. Distances from farms uniformly distributed across cell 2 to the center of cell 1 were thereby calculated for 100,000 pairs of base and height values. The mean of the distances served as the mean distance from farms in cell 2 to a pretreatment plant located in the center of adjacent cell 1.

Similar calculations determined the mean distance from farms distributed uniformly across all cells in the northeastern North Dakota study area to the centers of the seventeen grids.

Empirical Model

Model Assumption

Several assumptions were made to simplify the complexities of the cellulosic ethanol process. The following simplifying assumptions were made: (1) straw/stovers supply may be separated into a finite number of regions in space and represented by single discrete points; (2) straw/stovers supplies are fixed and known, (3) all straw/stovers are of the same quality in terms of the composition levels of cellulose, hemicelluloses, and lignin; (4) both pretreatment and biorefinery plants are built at the center of each cell and fields are uniformly distributed around them; (5) transportation costs and bale costs are assumed to be the same over the region, and (6) storage does not affect the quality of the biomass.

Table 4: Empirical Model Notations

	Notations	Description
Subscripts:		
	i	Straw nodes & pretreatment plant
	k	refinery plant locations
	t	time period (t=1, 2 ,3)
	a	size of pretreatment plant
	b	size of ethanol processing plant
	Sites	location of cells (i and k)
	Crop	crops grown
Scalar:		
	Haulcost	cost per ton per loaded mile to haul straw bales
	Harvest	per ton costs of baling straw
	SoilVal	nutrient value of straw left on field
	FeedVal	value of preprocessed straw as animal feed
	Eprice	Ethanol price per gallon
Parameter:		
	SSupply	straw supply by crop in each cell
	Straw	total tons of straw produce
	FC_b	fixed cost of constructing a bio-refinery plant of size b
	VC_b	variable cost per gallon of ethanol produced at a bio-refinery of size b
	$PPFC_a$	fixed cost of constructing pre-processing plant of size a
	$PPVC_a$	variable cost per ton of pre-processing plant of size a
	CAP_b	Maximum annual capacity of each ethanol plant - gallon per year
	$CAPP_a$	Maximum annual capacity of each preprocessing plant - tons of straw per year
	CSX	cost to transporting straw
	CXS	straw storage costs
	CPPS	pretreated feedstock storage costs
	CPPX	pretreated feedstock transport costs
Positive Variables:		
	X_i	quantity of biomass produced in cell
	$Leave_i$	quantity of straw left in fields
	Miles	the distance between two Sites
	$Store_i$	storage of unprocessed biomass
	$Preproc_{ak}$	quantity of biomass preprocessed
	$Feed_k$	use of preprocesses straw as animal feed
	$PPstore_k$	storage of preprocessed biomass

Table 4 (continued)

	Notations	Description
	ShipStraw_{ik}	shipments of straw
	ShipPP_{kj}	shipments of preprocessed feedstock
	Use_{jbt}	quantity of processed biomass distilled
	Raw_{jbt}	ethanol produced per period
Binary Variables:		
	Build_{jb}	build the ethanol plant in area Plant
Integer Variables:		
	BuildPP_{ka}	build the preprocessing plant in area Plant

Mathematical Programming Formulation

To derive the optimal solution for the MIP model, the objective function to be maximized is represented as equation 1.

$$
\begin{aligned}
(1)\quad Z = {} & \left(Eprice \bullet \sum_{t}\sum_{k}\sum_{b} Raw_{t,k,b} + SoilVal \bullet \sum_{i} Leave_{i} + FeedVal \bullet \sum_{t}\sum_{i} Feed_{t,i} \right) - \\
& \left[\left(Harvest \bullet \sum_{i} X_{i} \right) + \left(\sum_{t}\sum_{i}\sum_{i1} CSX_{i,i1} \bullet ShipStraw_{t,i,i1} \right) + \left(\sum_{t}\sum_{i}\sum_{i1} CPPX_{i,i1} \bullet ShiPP_{t,i,i1} \right) + \right. \\
& \left(\sum_{t}\sum_{i} CXS_{i} \bullet Store_{t,i} \right) + \left(\sum_{t}\sum_{i} CPPS_{i} \bullet PPStore_{t,i} \right) + \left(\sum_{t}\sum_{i}\sum_{a} PPVC_{a} \bullet Preproc_{t,i,a} \right) + \\
& \left. \left(\sum_{i}\sum_{a} PPFC_{a} \bullet BuildPP_{i,a} \right) + \left(\sum_{t}\sum_{k}\sum_{b} VC_{b} \bullet Raw_{t,k,b} \right) + \left(\sum_{k}\sum_{b} FC_{b} \bullet Build_{k,b} \right) \right]
\end{aligned}
$$

The returns from ethanol sales, feed sales, and soil nutrients left on the fields are maximized, when the net cost of the following is minimalized: transportation cost from farms fields to pretreatment plant and from pretreatment plant to a biorefinery; the storage cost on the field and at the pretreatment plant; the fixed and variable cost associated with each pretreatment and biorefinery plants.

Maximization of Equation 1 is constrained by the following equations in table 5 below.

Table 5: Empirical Model Constraints

Constraints:

1) $X_i + Leave_i = \sum_{crop} Straw_{crop} \bullet SSupply_{i,crop}$ $\quad\forall i$

2) $X_i = \sum_{i1} ShipStraw_{t1,i,i1}$ $\quad\forall i$

3) $\sum_{i} ShipStraw_{t,i,i1} = \sum_{a} Preproc_{t,i1,a} + Store_{t,i1}$ $\quad\forall t,i1$

4) $Store_{t,i} = Store_{t+1,i} + \sum_{i1} ShipStraw_{t+1,i,i1}$ $\quad\forall t,i$

5) $\sum_{a} Preproc_{t,i,a} = \sum_{i1} ShipPP_{t,i,i1}$ $\quad\forall t,i$

6) $\sum_{i} ShipPP_{t,i,k} = PPStore_{t,k} + Feed_{t,k} + \sum_{b} Use_{t,k,b}$ $\quad\forall t,k$

7) $PPStore_{t,k} = PPStore_{t+1,k} \sum_{k} ShipPP_{t+1,k,k1}$ $\quad\forall k, t \le 2$

8) $Raw_{t,k,b} = 55.65 \bullet Use_{t,k,b}$ $\quad\forall t,k,b$

9) $\sum_{t} Preproc_{t,i,a} \le CapPP_a \bullet BuildPP_{i,a}$ $\quad\forall i,a$

10) $\sum_{t} Raw_{t,k,b} \le Cap_b \bullet Build_{k,b}$ $\quad\forall k,b$

11) $\sum_{t} Raw_{t,k,b} \ge Cap_{b-1} \bullet Build_{k,b}$ $\quad\forall k, b > 1$

12) $Raw_{t,k,b} \ge 0.80 \bullet Raw_{t-1,k,b}$ $\quad\forall k,b,t \ge 2$

13) $Raw_{t,k,b} \le 1.2 \bullet Raw_{t-1,k,b}$ $\quad\forall k,b,t \ge 2$

14) $Preproc_{t,i,a} \ge 0.8 \bullet Preproc_{t-1,i,a}$ $\quad\forall i,a,t \ge 2$

15) $Preproc_{t,i,a} \le 1.2 \bullet Preproc_{t-1,i,a}$ $\quad\forall i,a,t \ge 2$

Constraint 1: The quantity of biomass produced plus the quantity of straw/stover left in the field in site *i* is equal to the total supply of straw/stover produced by all crops at that site, and for all straw production sites in the region.

Constraint 2: The quantity of biomass produced is equal to the sum of all straw shipped from site *i* to the pretreatment plant located at site *i*1 and/or to another site, and for all straw production sites in the region

Constraint 3: The sum of all straw shipped from site *i* to the pretreatment plant located at site *i*1 in time *t* is equal to the sum all biomass pretreated and/or stored at that pretreatment plant, and for all time periods and pretreatment plant sites.

Constraint 4: The storage of unprocessed biomass at site *i* in time *t* either continued to be stored or shipped to a pretreatment plant located at site *i*1 in time *t+1* for all time periods and straw production sites.

Constraint 5: The sum of all biomass pretreated at the pretreatment plant located at site *i*1 of size *a* in time *t* is equal to the sum of all pretreated biomass shipped from the pretreatment plant located at site *i1* to a biorefinery in time *t*, for all time periods and straw production sites.

Constraint 6: The sum of all pretreated biomass shipped from the pretreatment plant located at site *i*1 is either stored, used as animal feed, or distilled at a biorefinery plant, for all time periods and biorefinery plants

Constraint 7: Pretreated biomass at the pretreatment plant located at site $i1$ in time t either continued to be stored or shipped to a biorefinery in time $t+1$, for all pretreatment plants sites and time periods must be less than or equal to 2 periods.

Constraint 8: Ethanol produced at the biorefinery plant located at site k of size b in time t is equal to the quantity of biomass distilled at the biorefinery plant multiplied by 55.65 (the gallon yield of ethanol per ton of biomass); for all time period, and all size of biorefinery plants.

Constraint 9: The sum of all biomass pretreated at the pretreatment plant located at site $i1$ of size a in time t is greater than or equal to capacity limit of that pretreatment plant; for pretreatment plants of all sizes.

Constraint 10: The sum of all ethanol produced at the biorefinery located at site k of size b in time t is less than or equal to the capacity limit of that biorefinery plant; for all size of biorefinery.

Constraint 11: The sum of all ethanol produced at the biorefinery located at site k of size b in time t must be greater than or equal to the capacity limit of a biorefinery that is a size smaller; for all biorefinery greater in capacity than size 1. This constraint was identified in order to prohibit the model from building a larger biorefinery plant than is necessary.

Constraint 12: The sum of all ethanol produced at the biorefinery located at site k of size b in time t must be greater than or equal to 80% of the capacity limit of that biorefinery plant throughout the year; for all sizes of biorefineries in a time period greater than or equal to 2 periods.

Constraint 13: The sum of all ethanol produced at the biorefinery located at site *k* of size *b* in time *t* must be less than or equal to 120% of the capacity limit of that biorefinery plant throughout the year; for all sizes of biorefineries in a time period greater than or equal to 2 periods.

Constraint 14: The sum of biomass pretreated at the pretreatment plant located at site *i*1 of size *a* in time *t* must be greater than or equal to 80% of the capacity limit of that pretreatment plant throughout the year; for all sizes of pretreatment plants in a time period greater than or equal to 2 periods.

Constraint 15: The sum of biomass pretreated at the pretreatment plant located at site *i*1 of size *a* in time *t* must be less than or equal to 120% of the capacity limit of that pretreatment plant throughout the year; for all sizes of pretreatment plants in a time period greater than or equal to 2 periods.

Data Development

Identifying the optimal location, size, and number of pretreatment and biorefinery plants requires critical data about the region, especially on feedstock (straw/stover) production, transportation cost, and cost of harvesting crops. Data on grain harvested and yields of wheat, corn, barley, and durum was collected from USDA–National Agriculture Statistical Service for the years of 2003–2007 for the seven northeastern North Dakota counties and three northwestern Minnesota counties previously listed. Data on spring wheat and winter wheat were combined and averaged, using the weight average[5] method. Simple averages were taken on the harvested and yield of each crop, which was used for estimation purposes in this paper. The Harvest Index formula (Ottman et al 2007) was used to estimate the production of straw/stovers based on grain yield. The Formula is as follows:

$$HarvestIndex = \left(\frac{DryGrainWeight}{TotalPlantDryWeight} \right)$$

Wheat straw, barley straw, and durum straw was converted at 85.17 pounds of straw per bushels of grain, and corn stover was converted at 59 pounds of stover per bushel of corn. However, 43% of the total production of the straw had to remain on the fields in order to protect the soil from erosion and to maintain the nutrient value of the soil, according to Lundstorm (1994) and as mentioned in (Leistritz et al, 2006).

Table 6 below presents the total production of straw for wheat, barley, durum and corn stover in each county. Because we imposed the 24 mile square grids over the region, we were forced to developed estimates of the portion on each county that is part of each cell. Table 7 present the estimated percentage of the county that is part of a respective square grid(s). For example, 50% of Towner County is located in cell R1C1 and 50% of Towner County is located in R2C1, thus we assume that 50% of the total straw production in Towner is located in R1C1 and the other 50% in R2C1.

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[5] Weighted average is whereby each of the data points contributes depending of their size (weight) to the final average.

Table 6: County Straw and Stover Production

County	Wheat Straw	Barley Straw	Durum Straw	Corn Stovers
Cavalier	247063	60031	11435	1286
Grand Forks	184442	18686	632	48672
Nelson	83418	32653	1444	13421
Pembina	188051	12103	943	42739
Ramsey	81649	78901	7263	39627
Towner	127040	45513	12544	7118
Walsh	184507	21318	2379	18906
Kittson	124546	5820		3430
Marshall	182904	31639		7704
Polk	278650	14588		40280

Table 7: Percentage of County in Cell

Cell	Towner	Cavalier	Pembina	Ramsey	Walsh	Nelson	GForks	Kittson	Marshall	Polk
R1C1	0.5									
R1C2		0.375								
R1C3		0.375								
R1C4			0.525							
R1C5			0.225					0.2		
R2C1	0.5									
R2C2		0.125		0.32						
R2C3		0.125		0.08	0.24					
R2C4			0.175		0.3					
R2C5			0.075		0.06			0.05	0.06	
R3C2				0.48						
R3C3				0.12	0.16	0.3				
R3C4					0.16		0.25			
R3C5					0.08		0.2		0.01	
R4C3						0.7				
R4C4							0.35			
R4C5							0.2			0.025
Sum	1	1	1	1	1	1	1	0.25	0.07	0.025

The statewide (North Dakota) average transportation cost per loaded mile (represented in the model as haulcost) was obtained from Aakre (2007) and was estimated at $4.00 for loads of hay bales or loose hay between 10 to 20 tons. The price is projected to be the same for baled straw and stovers. A load is equal to 17 tons.

The cost of baling straw or stover in round bales, weighing more than 1,500 lbs was estimated at $8.00 (Aakre, 2007). $12.27 per ton is the estimated value that farmers received in terms of nutrient value to the soil, if they leave the straw/stover on the field (Leistritz et al, 2006). Carolan et al (2007) valued the cost of AFEX pretreated biomass at $98.47 per ton, in relation of the nutrient value it provides to ruminant animals and to the relative cost of corn and soybeans as a possible alternative feed source. The storage cost of baled biomass was estimated to be $10.00 per ton per year. Pretreated biomass storage cost at a pretreatment plant was estimated at $0.50 per ton per year.

Five different sizes of pretreatment plants and three different sizes of biorefinery plants were used in this study. Table 8 and Table 9 presents the total annual fixed and unit variable cost and total capacities associated with each size of pretreatment and biorefinery plants, respectively. These tables demonstrate that as the size of the plants increases, economies of scale become larger; therefore, less fixed and variable cost is used per output. The capital cost of a decentralized pretreatment plant was acquired from Carolan et al (2007) using a straight line depreciation. The capital cost of the biorefinery was taken from a National Renewable Energy Laboratory report prepared by Aden et al (2002). The report estimated that 30.17% of the total cost of a conventional biorefinery plant (where pretreatment is centralized) is cost associated with the capital cost for pretreatment. Thus, the capital cost was derived at by the aforementioned percentage to obtain the cost of our particular biorefinery plant. The capital cost then scaled up and down for the biorefinery to determine the capital cost of the other two biorefinery plants. The exponential scaling formula was used to estimate the scaling of the biorefinery. The formula is as follows:

$$NewCost = OriginalCost\left(\frac{NewSize}{OriginalSize}\right)^{\exp}$$

The scaling exponent used was 0.6. This is the scaling exponent suggested by Remer and Chai (1990), which they estimate is reasonable for engineering-economic studies of plants.

Table 8: Pretreatment Plant Cost

	Size				
	S1	S2	S3	S4	S5
Total Fixed Cost (per year)	650,549	806,196	1,092,678	1,839,803	2,706,502
Unit Variable Cost per ton	14.88	13.72	12.55	11.37	10.83
Total Capacity (tons per year)	243,090	324,120	486,545	973,090	1,622,060

Table 9: Biorefinery Plant Cost

	Size		
	S1	S2	S3
Total Fixed Cost (per year)	3,621,738	6,098,120	8,970,838
Unit Variable Cost per ton	0.7812	0.7058	0.6747
Total Capacity (gallon per year)	29,177,702	58,355,404	97,273,600

The price of ethanol is a very important factor to study because our model seeks to maximize total revenue over costs to the regional industry; however, a competitive price of conventional petroleum fuel and corn based ethanol needs to be feasible for this model to be effectively used. Figure 4 below presents the prices of corn based ethanol and unleaded petroleum from January to October 2008 in Nebraska, FOB Omaha. The average wholesale price of gasoline and corn-based ethanol for the past ten months was approximately \$2.50. Nevertheless, the wholesale base price of ethanol for the model is \$2.50. This price could have been lower and yet economically feasible if additional co-products of ethanol and government and state subsidies were taken into consideration.

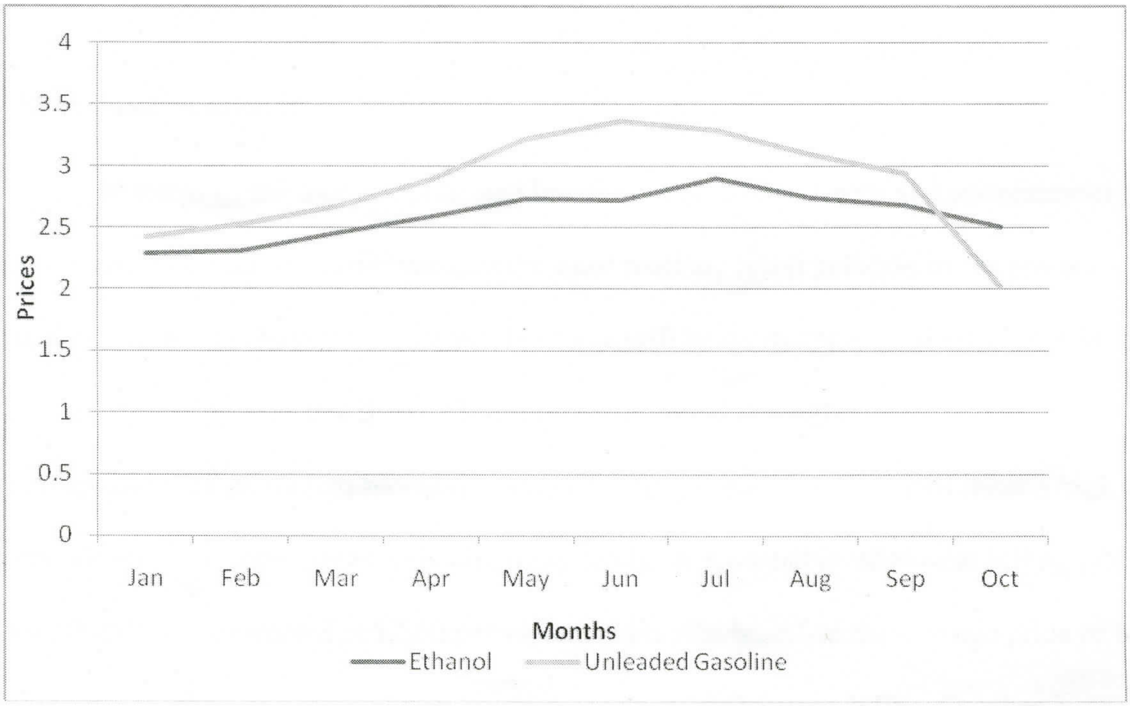

Figure 4: Monthly Ethanol and Unleaded Rack Prices F.O.B. Omaha, Nebraska 2008
Source: Nebraska State Government Energy Office

CHAPTER 4

RESULTS

Introduction

To estimate the optimal number, size, and location of biorefinery and pretreatment plants in northeastern North Dakota, a mixed integer programming model that maximizes total revenue over costs in General Algebraic Modeling System (GAMS). Initially, we ran a base scenario to determine the feasibility of cellulosic produced ethanol at different prices. Subsequently, we ran a number of sensitivity analyses on key parameters of the model.

Base Case Scenario

In terms of the number, size, and location of both biorefinery and pretreatment plants, the base case scenario provides the most realistic result solution to the present market. In this scenario it is assumed that there will be no markets for feed for ruminant animals due to the fact that livestock farming is minimal throughout this region. Transporting the pretreated biomass to regions with prolific livestock will incur a high cost that will make it non-competitive with other feeds. A reasonable wholesale selling price for ethanol was estimated at $2.50 per gallon. This was based on the average price of both unleaded gasoline and ethanol over the past ten months (January 2008 – October 2008). All other previously mentioned costs remain the same in the model.

Table 10: Base Case Scenario

Ethanol Price	$1.50	$1.75	$2.00	$2.25	**$2.50**	$2.75	$3.00	$3.25	$3.50	$3.75	$4.00
Harvest	N/A	1,750,784	1,750,784	1,750,784	**1,862,007**	1,862,007	1,750,784	1,750,784	1,750,784	1,862,007	1,862,007
Leave	1,862,007	111,222	111,222	111,222	**0**	0	111,222	111,222	111,222	0	0
PP1 - Size	N/A	R1C2 - S1	R1C2 - S1	R1C3 - S2	**R1C2 - S2**	R1C2 - S3	R1C3 - S1	R1C3 - S5	R1C2 - S3	R1C2 - S4	R1C2 - S3
PP2 - Size	N/A	R1C3 - S3	R1C3 - S2	R2C1 - S3	**R1C3 - S2**	R1C3 - S1	R3C4 - S5	R4C3 - S2	R1C2 - S4	R1C3 - S5	R1C3 - S3
PP3 - Size	N/A	R2C1 - S1	R2C1 - S1	R3C4 - S4	**R1C5 - S1**	R1C5 - S3	N/A	R4C5 - S1	R3C4 - S1	R1C5 - S2	R2C1 - S1
PP4 - Size	N/A	R2C5 - S1	R3C4 - S1	R4C3 - S1	**R2C1 - S2 (x2)**	R2C1 - S3	N/A	N/A	R3C4 - S4	R2C1 - S1	R2C5 - S4
PP5 - Size	N/A	R3C4 - S2	R3C4 - S3	N/A	**R2C5 - S3**	R2C5 - S1	N/A	N/A	N/A	R2C1 - S5	R3C4 - S4
PP6 - Size	N/A	R4C3 - S1	R4C3 - S2	N/A	**R3C4 - S3**	R3C4 - S3	N/A	N/A	N/A	R2C5 - S1	R4C3 - S2
PP7 - Size	N/A	N/A	N/A	N/A	**R3C5 - S2**	R3C5 - S3	N/A	N/A	N/A	R3C4 - S1	R4C5 - S1
PP8 - Size	N/A	N/A	N/A	N/A	**R4C3 - S3**	R4C3 - S2	N/A	N/A	N/A	R4C3 - S5	N/A
PP9 - Size	N/A	N/A	N/A	N/A	**N/A**	N/A	N/A	N/A	N/A	R4C5 - S1	N/A
E. Plant1 - Size	N/A	R2C3 - S3	R3C3 - S3	R3C3 - S3	**R3C3 - S3**	R2C3 - S1	R2C4 - S3	R2C3 - S3	R2C4 - S3	R2C2 - S3	R2C3 - S3
E. Plant2 - Size	N/A	N/A	N/A	N/A	**R4C4 - S1**	R2C4 - S3	N/A	N/A	N/A	R4C4 - S2	R4C4 - S1
E. Plant3 - Size	N/A	N/A	N/A	N/A	**N/A**	R3C3 - S1	N/A	N/A	N/A	N/A	N/A
Ethanol prod	0	97,273,600	97,273,600	97,273,600	**103,453,100**	103,453,100	97,273,600	97,273,600	97,273,600	103,453,100	103,453,100

The results from the base scenario in Table 10 above suggest that at a price of $2.50, the total available straw in the region will be used to produce ethanol. A total of nine small pretreatment plants will be built throughout the region, and they are as follows: 1 of size 1, 5 of size 2, and 2 of size 3. These pretreatment plants are randomly distributed throughout the region.

Two biorefinery plants, 1 of size 1 and 1 of size 3, producing approximately 103.5 million gallon (mg) of ethanol, was the optimal solution for the base case. Both biorefinery plants are located close to the center of the region.

Sensitivity Analyses

Ethanol Prices

The energy market is very volatile when it comes to the price of liquid fuel. Sensitivity analysis on the price of ethanol was conducted (as shown in Table 10 above) to determine the effect of price on the production of ethanol. At a price of $1.50 ethanol will not be produced, because it would not be feasible to produce at that price level. Other prices below the base case scenario demonstrate that there will be a lower level of ethanol production—about 6 mg less. For a price of $3.00 through $3.50, the ethanol production fell below that of the base scenario. This was an unexpected result because it was anticipated that as the price of ethanol increased, production would also increase. The reason for lower production is that the model utilized a diminished number of larger pretreatment plants, therefore it benefited from larger economies of scale. Also, only one large biorefinery (size 3) operating at full capacity is utilized by the model. Although the production of ethanol for prices of \$3.00 through \$3.50 is lower than that of the base case scenario, the return over the total supply chain is greater than that of the base scenario because of the lower fixed cost associated with building both pretreatment and biorefinery plants incurred, the lower average variable cost per ton of pretreated biomass from larger scale economies, and of course higher wholesale prices for the ethanol.

Overall, the level of ethanol production is not very sensitive to price change. However, the number and size of the pretreatment plants are very responsive. This could be because the model seeks to maximize returns over net cost; however, using larger pretreatment plants in regions with high straw production offset some cost.

Transportation Cost

The cost of transportation is very critical to the economic feasibility of cellulosic ethanol due to the low density of biomass. Presented in Table 11 below are the sensitivity analysis results when cost varies plus or minus (±) 15 % and 25%, assuming that the other parameters remain constant, as in the base case scenario. With a 15 % increase in the transportation cost, the production of ethanol decreases and also returns over the supply chain. This result was expected.

Conversely, one would expect that the number of biorefineries and pretreatments would increase, causing the total mileage of transportation to decrease; however, this simulation proved otherwise by drastically reducing the number of pretreatment plants and

Table 11: Sensitivity Analysis - Transportation Cost

	+ 15 % trans	+ 25 % trans	- 15 % trans	- 25 % trans
Ethanol Price	$2.50	$2.50	$2.50	$2.50
Harvest	1,750,784	1,862,007	1,862,007	1,750,784
Leave in Field	111,222	0	0	111,222
PP1 - Size	R1C2 - S3	R1C2 - S2	R1C2 - S1	R1C2 - S3
PP2 - Size	R1C3 - S3	R1C3 - S3	R1C3 - S1	R1C3 - S3
PP3 - Size	R3C4 - S3	R1C5 - S1	R2C1 - S1	R3C4 - S5
PP4 - Size	N/A	R2C5 - S1	R3C4 - S3	R3C5 - S2
PP5 - Size	N/A	R3C4 - S3 (X2)	R3C5 - S3	N/A
PP6 - Size	N/A	R3C5 - S2	R4C3 - S4	N/A
PP7 - Size	N/A	R4C3 - S1	R4C5 - S1	N/A
E. Plant1 - Size	R2C4 - S3	R2C4 - S3	R2C3 - S2	R2C4 - S3
E. Plant2 - Size	N/A	R3C3 -S1	R4C4 - S3	N/A
Ethanol prod	97,273,600	103,453,100	103,453,100	97,273,600

by using only one biorefinery plant. Nonetheless, at a 25% increase in transportation cost above the base case, the production of ethanol remains the same as the base case, but at cost of lower return over the supply chain. This result was unexpected, it was expected that as transport cost increased, a lower production of ethanol would result because a shorter distance would have been traveled to collect biomass. In addition, another unexpected result occurred when the simulation demonstrated that eight small pretreatment plants would be built to feed biomass directly to two biorefinery plants. Despite this fact, as expected, the number of pretreatment and biorefinery plants increased to offset the transportation cost.

By comparison, as the cost of transportation decreased by 15%, ethanol production remained the same as in the base case. However, the number of pretreatments decreased when the transport cost was lower, as expected. Surprisingly, at a transport cost of 25% below the base case, the production of ethanol decreased. The drastic reduction in the number and increase in the size of pretreatment plants are self-explanatory since, as mentioned earlier, the transport cost is lower. However, the profitability of producing at this lower level is higher than that of the base case. Thus, the marginal cost of incurring an additional fixed cost from the construction of another plant to produce additional ethanol is higher than that of leaving the biomass of on the field.

Overall, the effect of transportation cost on the production of ethanol was minimal. This is because the model uses the flexibility of its decentralized pretreatment plants to offset the increased cost. The return is very responsive to an increase in transportation cost, because it can incur a more fixed cost by building more pretreatment and biorefinery plants to minimize the transportation cost.

Straw Value

The value that is ascribed to leaving the biomass on the field is very critical to a cellulosic ethanol plant since it is the determining factor for farmers to decide whether or not they are willing to sell the biomass in terms replacing it with some alternative fertilizer. Results from the sensitivity analysis on the prices of soil value are presented in table 12 below. An unexpected result from this simulation is that a 25% increase in the price of the soil value derived from leaving the biomass on the ground does not alter the production of ethanol from the base case scenario. However, this is at the cost of a lower return than the base case scenario. Comparatively speaking, a 25% decrease in the cost associated with soil value shows that ethanol production will also decrease. This was an unexpected result because in this scenario the soil should reduce the cost associated with obtaining the biomass.

The reduction in the production of ethanol also causes the return to be lower than that of the base case. The probable reason could be that the economic feasibility of building additional Pretreatment and biorefinery plants will incur additional cost is not worthwhile in terms of return that will be received from the additional production of ethanol.

Table 12: Sensitivity Analysis - Soil Value

	+ 15 % Soilval	+ 25 % SoilVal	- 15 % SoilVal	- 25 % SoilVal
Ethanol Price	$2.50	$2.50	$2.50	$2.50
Harvest	1,750,784	1,862,007	1,862,007	1,750,784
Leave in Field	111,222	0	0	111,222
PP1 – Size	R1C2 - S1	R1C2 - S3	R1C2 - S2	R1C2 - S2
PP2 – Size	R1C3 - S3	R1C3 - S3	R1C3 - S1	R1C3 - S3
PP3 – Size	R2C5 - S1	R2C1 - S2	R1C5 - S1	R1C5 - S3
PP4 – Size	R3C4 - S5	R3C4 - S4	R2C1 - S2 (x2)	R3C4 - S4
PP5 – Size	N/A	R3C5 - S4	R3C4 - S2 (x2)	N/A
PP6 – Size	N/A	R4C3 - S1	R3C5 - S1	N/A
PP7 – Size	N/A	N/A	R4C3 - S3	N/A
E. Plant1 – Size	R2C3 - S3	R2C2 - S2	R3C3 - S3	R2C4 - S3
E. Plant2 – Size	N/A	R4C4 - S3	R4C4 - S1	N/A
Ethanol prod	97,273,600	103,453,100	103,453,100	97,273,600

In other words, the marginal value received from producing an additional gallon of ethanol is lower than the marginal result of not producing that additional gallon.

The overall effect of straw value on the production of ethanol was minimal. However, the value of the straw is critical to the return of the process.

Feed Value

The results that are presented in Table 13 below depict the outcome when feed was entered into the base case scenario as a co-product of ethanol. The value of pretreated biomass as feed for ruminant animals is estimated at $98.47 per ton. In the base case scenario with the existence of a feed market, no ethanol would be produced and all the pretreated biomass would be sold as animal feed.

Sensitivity analysis on the price of ethanol for a ± 15% and 25% was then simulated. Results were as expected: as the price of feed increases 15% and 25%, there will be no ethanol production. As the price of feed decreases at both 15% and 25%, a combination of both ethanol and feed is produced, with ethanol being the main product.

Table 13: Sensitivity Analysis - Feed Value

	Base Model with Feed	+ 15 % FeedVal	+ 25 % FeedVal	- 15 % FeedVal	- 25 % FeedVal
Harvest	1,862,007	1,862,007	1,862,007	1,862,007	1,862,007
Leave in Field	0	0	0	0	0
PP1 - Size	R1C2 - S1	R1C2 - S1	R1C2 - S5	R1C3 - S3	R1C3 -S1
PP2 - Size	R1C2 - S4	R1C3 - S5	R1C3 - S5	R1C5 - S1	R1C3 - S3
PP3 - Size	R1C3 - S3	R1C5 - S5	R1C5 - S1	R2C1 - S2	R2C1 - S1
PP4 - Size	R2C5 - S4	R2C1 - S5	R2C1 - S5	R3C4 - S5	R3C4 - S4
PP5 - Size	R2C5 - S1	R2C5 - S1	R2C5 - S5	N/A	N/A
PP6 - Size	R3C4 - S1	R3C4 - S5	R3C4 - S5	N/A	N/A
PP7 - Size	R4C3 - S2	R4C3 - S5	R4C3 - S5	N/A	N/A
PP8 - Size	R4C5 - S1	R4C5 - S5	R4C5 - S5	N/A	N/A
E. Plant1 - Size	N/A	N/A	N/A	R3C3 - S3	R2C4 - S3
Ethanol prod	N/A	N/A	N/A	97,273,600	97,273,600
Feed	1,862,007	1,862,007	1,862,007	112,222	112,222

CHAPTER 5

SUMMARY AND CONCLUSIONS

Summary

A highly dependent logistical supply chain system is critical to the economic feasibility of producing cellulosic ethanol. Identifying the optimal location, size, and number of pretreatment and biorefineries is critical in the cellulosic ethanol production process.

Over the past several years, the price of conventional petroleum fuel has been steadily rising. The need for an alternative liquid fuel is a high priority for most developed nations. Corn based ethanol has been successful so far, but due to the increase in energy prices, the price of corn has escalated and caused the industry to operate on marginal returns. Herbaceous crop residues have been an alternative of interest for a long time now and recent technological development and research have shown that the technology is nearing commercialization.

Carolan et al (2007) and Leistritz et al (2006) both found that the combination of AFEX pretreatment and Simultaneous Saccharification and Fermentation (SSF) distillation technologies have the potential advantage over other current technologies. Decentralizing the pretreatment plant from the biorefinery can provide possible economic value to the processes of producing ethanol because it will offset the high transportation cost associated in transporting low density biomass over long distances (Carolan et al, 2007).

Results show that producing 97,273,600 million gallons of ethanol per year at a price of $1.75 per gallon (which would be very competitive with unleaded gasoline and corn based ethanol prices) can generate some 44.3 million dollars in profit annually. Our results support Carolan's et al (2007) proposal to decentralized pretreatment plants in an attempt to offset transportation cost. The economies of scale of larger plants are very important to the feasibility of producing cellulosic ethanol. Pretreated biomass for feed for ruminant animals used as co-product for ethanol is likely to add value to the production process and improve the economic feasibility of cellulosic ethanol.

Need for further Study

Although this study includes the most important parameters, there are other parameters that could both decrease and increase the cost of producing cellulosic ethanol. Federal and State subsidies could have been included in this model as additional revenue. More focus could have been placed on storage cost, so that it could have been more influential on the overall process.

There are numerous other aspects that could be looked at in the future, such as: the impact of weather variations on the harvesting and the quality of biomass; farmer's attitude towards harvesting biomass; variation in the moisture content of biomass; and lastly, the extension of additional co-products of ethanol on a larger focus region.

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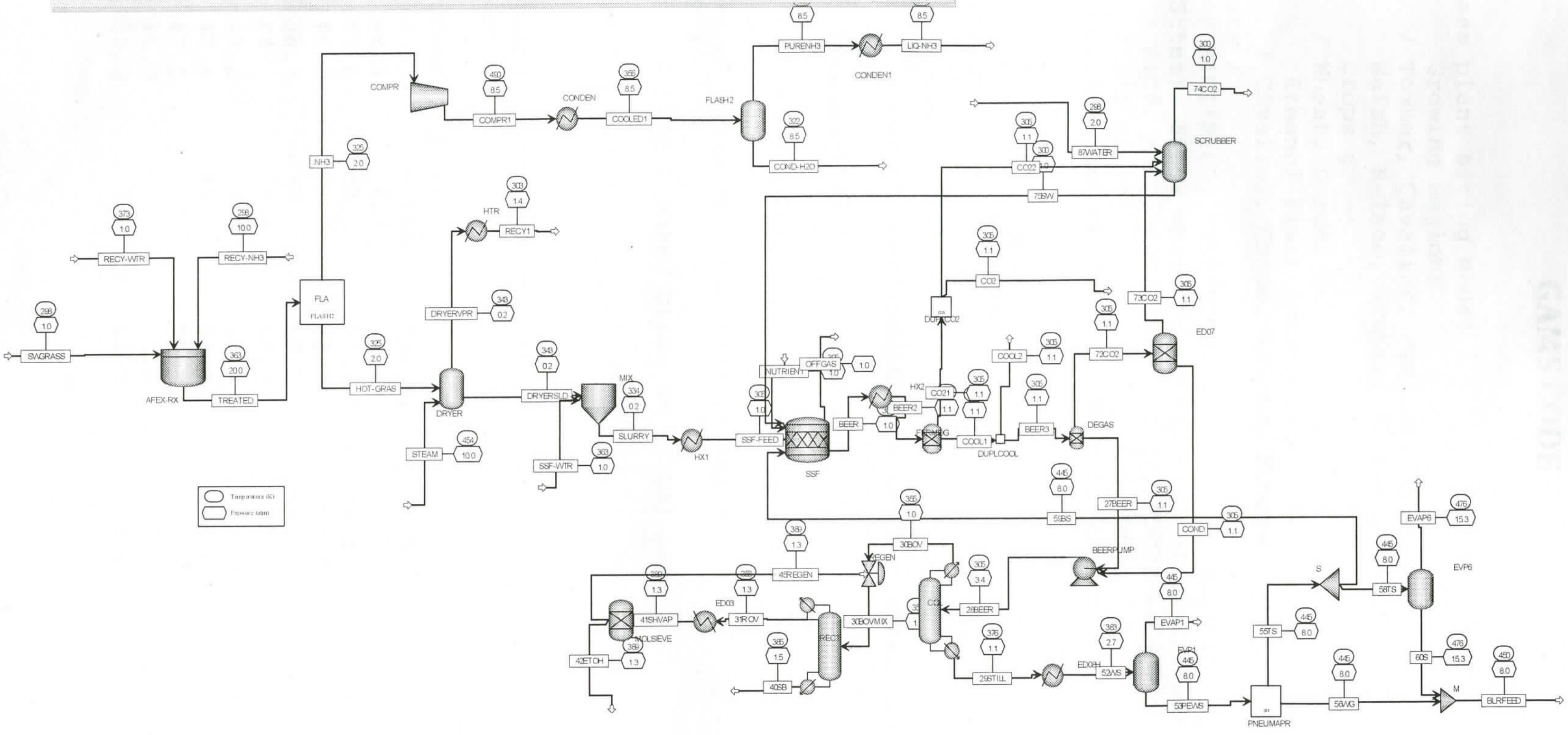
APPENDIX A

AFEX Pretreatment Process of Straw/Stovers



Source: MBI International

APPENDIX B

GAMS CODE

```
$TITLE  Biomass plant siting model
SETS  County    Growing Regions
              / Towner, Cavalier, Pembina, Ramsey,
                Walsh, Nelson, GForks, Kittson, Marshall, Polk /
      Crop      Crops grown
              / Wheat, Durum, Barley, Corn /
*      Plant     Ethanol Plant Locations
*             / Cavalier, Cando, Lakota, Edmore, Devils Lake, Park
River, Larimore /
      Sites  / R1C1*R1C5, R2C1*R2C5, R3C2*R3C5, R4C3*R4C5 /
      Plant(Sites)  Sites where potential ethanol plants can be sited
             / R1C4, R2C2, R2C3, R2C4, R3C2, R3C3, R4C4 /
      Size    Plant sizes                        / S1*S5 /
      Time    Production schedule                / T1*T3 / ;

ALIAS (Time,Time1);
ALIAS (Sites,Sites1);
ALIAS (Plant,Plant1);

SCALAR
     Haulcost Cost per ton per loaded mile to haul straw bales-Aakre
      / 4.00 /
     RFS      Renewable fuel gallon mandate
      / 1750 /
Harvest  Per ton costs of baling straw-Aakre
      / 8.00 /
SoilVal  Nutrient value of straw left in place
      / 12.27 /
FeedVal  Value of preprocessed straw as animal feed
      / 10 /
 EPrice  Ethanol price per gallon
      / 5.5 / ;

*  Adjust hauling cost for 17 ton straw loads
Haulcost = Haulcost/17;

TABLE YIELD(COUNTY, CROP)
             Wheat     Durum     Barley     Corn
Towner       38.5      38.4      58.4       84.7
Cavalier     40.6      41.3      57.9       86.3
Pembina      45.3      51.5      61.2       107.3
Ramsey       38.3      37        60.5       86.2
Walsh        44        44.3      56.9       108
Nelson       40.2      40.8      57.3       86.3
GForks       47.8      46        61.4       101.4
Kittson      47.5                60.2       102.7
Marshall     46.9                61.4       102.5
Polk         53.3                66.5       104.8
```

```
TABLE ACRES(COUNTY, CROP)
             Wheat     Durum     Barley     Corn
Towner       180200    17840     42560      6625
Cavalier     332320    15120     56620      1175
Pembina      226700    1000      10800      31400
Ramsey       116420    10720     71220      36240
Walsh        229000    2933      20460      13800
Nelson       113320    1933      31120      12260
GForks       210720    750       16620      37840
Kittson      143190              5280       2633
Marshall     212973              28140      5925
Polk         285500              11980      30300

PARAMETER
     Straw    Convert wheat yield to tons of straw
     FC(Size)   Fixed cost of constructing plant assuming PreTreat costs
30.17% of total
          / S1 = 3621738, S2 = 6098120, S3 = 8970838, S4 = 99999999, S5 =
99999999 /
     VC(Size)   Variable cost per gallon of ethanol produced
          / S1 = 0.7812, S2 = 0.7058, S3 = 0.6747, S4 = 999, S5 = 999 /
     PPFC(Size)   Fixed cost of constructing pre-processing plant
(Carolan depreciation)
          / S1 = 650549, S2 = 806196, S3 = 1092678, S4 = 1839803, S5 =
2706502 /
     PPVC(Size)   Variable cost per ton of pre-processing (Carolan)
          / S1 = 14.88, S2 = 13.72, S3 = 12.55, S4 = 11.37, S5 = 10.83 /
     CAP(Size) Maximum annual capacity of each ethanol plant GPY
          / S1 = 29177702, S2 = 58355404, S3 = 97273600, S4 = 0, S5 = 0 /
     CAPPP(Size) Maximum annual capacity of each preprocessing plant
(Carolan)
      / S1 = 243090, S2 = 324120, S3 = 486545, S4 = 973090, S5 = 1622060
/;

*   0.43 - Baling yield of wheat straw
*   85.17 - Convert small grain bushels to pounds of straw
  Straw(Crop)$(ord(crop) lt 4)  = 0.43*85.17/2000;
*   Convert corn bushels to pounds of stover - initial guess is 50 pound
bushels
  Straw("Corn")   = 59/2000;

TABLE  Miles(Sites, Sites) Miles between Cells
      R1C1 R1C2 R1C3 R1C4 R1C5 R2C1 R2C2 R2C3 R2C4 R2C5
R1C1      9   25    48    72    96        25    35    54    76    99
R1C2      25  9     25    48    72    35    25    35    54    76
R1C3      48  25    9     25    48    54    35    25    35    54
R1C4      72  48    25    9     25    76    54    35    25    35
R1C5      96  72    48    25    9     99    76    54    35    25
R2C1      25  35    54    76    99    9     25    48    72    96
R2C2      35  25    35    54    76    25    9     25    48    72
R2C3      54  35    25    35    54    48    25    9     25    48
R2C4      76  54    35    25    35    72    48    25    9     25
R2C5      99  76    54    35    25    96    72    48    25    9
```

```
R3C2     54  48   54   68   87   35   25   35   54   76
R3C3     68  54   48   54   68   54   35   25   35   54
R3C4     87  68   54   48   54   76   54   35   25   35
R3C5     108 87   68   54   48   99   76   54   35   25
R4C3     87  76   72 76      87   68   54   48   54   68
R4C4     102 87   76 72      76   87   68   54   48   54
R4C5     120 102  87   76   72   108  87   68   54   48

  +     R3C2 R3C3 R3C4 R3C5 R4C3 R4C4 R4C5
R1C1     54   68   87   108  87  102  120
R1C2     48   54   68   87   76  87   102
R1C3     54   48   54   68   72  76   87
R1C4     68   54   48   54   76  72   76
R1C5     87   68   54   25   87  76   72
R2C1     35   54   76   99   68  87   108
R2C2     25   35   54   76   54  68   87
R2C3     35   25   35   54   48  54   68
R2C4     54   35   25   35   54  48   54
R2C5     76   54   35   25   68  54   48
R3C2     9    25   48   72   35  54   76
R3C3     25   9    25   48   25  35   54
R3C4     48   25   9    25   35  25   35
R3C5     72   48   25   9    54  35   25
R4C3     35   25   35   54   9   25   48
R4C4     54   35   25   35   25  9    25
R4C5     76   54   35   25   48  25   9

TABLE  Distn(Sites, County) Proportion of county in each cell
       Towner Cavalier Pembina Ramsey Walsh Nelson GForks Kittson
Marshall Polk
R1C1     0.5
R1C2            0.375
R1C3            0.375
R1C4                    0.525
R1C5                    0.225                               0.2
R2C1     0.5
R2C2            0.125           0.32
R2C3            0.125           0.08   0.24
R2C4                    0.175          0.3
R2C5                    0.075          0.06                 0.05    0.06
R3C2                            0.48
R3C3                            0.12   0.16   0.3
R3C4                                   0.16         0.25
R3C5                                   0.08         0.2             0.01
R4C3                                          0.7
R4C4                                                0.35
R4C5                                                0.2
0.025
;

PARAMETER PRODUCE  County crop production
          SSupply  Straw supply by crop in each cell;
 PRODUCE(County, Crop) = YIELD(County, Crop)*ACRES(County, Crop);
 SSupply(Sites,Crop) = Sum(County, Distn(Sites,
County)*Produce(County,Crop));
```

```
*  Transportation costs from node to node:
Parameter CSX     Costs to haul straw
          CXS     Straw storage costs
          CPPS    Pretreated feedstock storage costs
          CPPX    Pretreated feedstock transport costs ;
  CSX(Sites,Sites1) = Haulcost*Miles(Sites,Sites1);
  CXS(Sites) = 10;
  CPPS(Sites) = 0.50;
  CPPX(Sites,Plant) = 0.5*CSX(Sites,Plant);

VARIABLES
    Z          Objective function cost ;
POSITIVE VARIABLES
    X           Quantity of Biomass produced in County
    Leave       Quantity of straw left in fields
    Store       Storage of unprocessed Biomass
    Preproc     Quantity of Biomass preprocessed
    Feed        Use of preprocessed straw as animal feed
    PPStore     Storage of preprocessed Biomass
    ShipStraw   Shipments of straw
    ShipPP      Shipments of preprocessed feedstock
    Use         Quantity of processed Biomass distilled
    Raw         Ethanol produced per period
BINARY VARIABLES
    BUILD    Build the ethanol plant in area Plant;
INTEGER VARIABLES
    BUILDPP  Build the preprocessing plant in area Plant ;

EQUATIONS
    OBJ     'Minimize transportation, investment, and operating costs'
    CON1     Produce Biomass based on area wheat yields
    CON2     Ship biomass from area County in period 1
    CON3     Shipped Biomass must be preprocessed or stored in each
period
    CON4     Stored Biomass either continued to be stored or shipped
    CON5     Shipping preprocessed feedstock
    CON6     Store or Use preprocessed feedstock in each period
    CON7     Stored Pretreatement either continued to be stored or
shipped
    CON8     Produce Raw ethanol from Use
    CON9     Capacity limits on preprocessing plant (dependent on
investment in plant)
    CON10     Capacity limits on ethanol plant (dependent on investment
in plant)
    CON11    Lower limits on Capacity
    CON12    Smooth ethanol production in built plants lower limit
    CON13    Smooth ethanol production in built plants upper limit
    CON14    Smooth pretreatment in built plants lower limit
    CON15    Smooth pretreatment in built plants upper limit ;
*   Mandate  Ethanol demand by period;

BUILD.fx(Sites,Size)$(not Plant(sites)) = 0;
ShipPP.fx(Time,Sites,Sites1)$(not Plant(sites1)) = 0;
STORE.fx('T3',Sites) = 0;
```

```
PPStore.fx('T3',Plant) = 0;
PPStore.fx(Time,Sites)$(not Plant(sites)) = 0;

OBJ .. Z =E=  Eprice*Sum((Time,Plant,Size), Raw(Time,Plant,Size))
         + Sum(Sites, SoilVal*Leave(Sites))
         + Sum((Time,Plant), FeedVal*Feed(Time,Plant)) -
       (   Sum(Sites, Harvest*X(Sites))
         +
Sum((Time,Sites,Sites1),CSX(Sites,Sites1)*ShipStraw(Time,Sites,Sites1))
         +
Sum((Time,Sites,Plant),CPPX(Sites,Plant)*ShipPP(Time,Sites,Plant))
         + Sum((Time,Sites),CXS(Sites)*Store(Time,Sites))
         + Sum((Time,Plant),CPPS(Plant)*PPStore(Time,Plant))
         + SUM((Time,Plant,Size), PPVC(Size)*Preproc(Time,Plant,Size))
         + SUM((Sites,Size), PPFC(Size)*BuildPP(Sites,Size))
         + SUM((Time,Plant,Size), VC(Size)*Raw(Time,Plant,Size))
         + SUM((Plant,Size), FC(Size)*Build(Plant,Size)) ) ;

*  Con1: Determine straw and stover (S&S) production at each Site.
*  Straw and stover can enter the ethanol channel through X, or remain on
the
*  ground for soil nutrient enhancement
CON1(Sites) .. X(Sites) + Leave(Sites) =E= sum(Crop, Straw(Crop) *
SSupply(Sites,Crop));

*  In period T1, S&S is shipped from Sites to Sites1.  Total supply X
(determined from Con1)
*  is upper limit on shipments.

CON2(Sites) .. X(Sites) =E=
              Sum(Sites1,ShipStraw("T1",Sites,Sites1));

*  Total quantity shipped from Sites to Sites1 in time period Time is
either preprocessed
*  or stored at sites1.

CON3(Time,Sites1) ..  Sum(Sites,ShipStraw(Time,Sites,Sites1)) =E=
        Sum(Size,Preproc(Time,Sites1,Size)) + Store(Time,Sites1);

*  S&S stored at Sites in period T either continues to be stored at T+1
or is shipped to another Sites1.

CON4(Time,Sites)$(ord(time) le 2) .. Store(Time,Sites) =E=
*        Store(Time+1,Sites) +
  Sum(Sites1,ShipStraw(Time+1,Sites,Sites1)) ;

*  Total S&S pre-treated at time T at Sites in a plant of size Size is
shipped to Sites1.
*  ShipPP is the weight of the pre-treated feedstock.

CON5(Time,Sites) .. Sum(Size,Preproc(Time,Sites,Size)) =E=
         Sum(Sites1,ShipPP(Time,Sites,Sites1));

*  Pre-treated feedstock from Sites is either stored, used for feed, used
in an ethanol plant at Sites1.
```

```
*  Potential ethanol plants are only available at select Sites.

CON6(Time,Plant) .. Sum(Sites,ShipPP(Time,Sites,Plant)) =E=
         PPStore(Time,Plant) + Feed(Time,Plant) +
         Sum(Size,Use(Time,Plant,Size));

*  Pretreated feedstock stored at Plants in period T either continues to
be stored at T+1 or
*  is shipped to another Plant1.

CON7(Time,Plant)$(ord(time) le 2) .. PPStore(Time,Plant) =E=
        PPStore(Time+1,Plant) + Sum(Plant1,ShipPP(Time+1,Plant,Plant1)) ;

*  Feedstock used at Sites is converted to raw ethanol with a yiled of
55.56 gallons per ton of feedstock.

CON8(Time,Plant,Size) ..
    Raw(Time,Plant,Size) =E= 55.56 * Use(Time,Plant,Size);

*  Total pre-treatment at Sites cannot exceed plant capacity.

CON9(Sites,Size) .. Sum(Time,Preproc(Time,Sites,Size))
         =L= Cappp(Size)*BuildPP(Sites,Size);

* Total ethanol production at Sites1 cannot exceed ethanol plant capacity

CON10(Sites1,Size)$Plant(Sites1) .. Sum(Time,Raw(Time,Sites1,Size))
         =L= Cap(Size)*Build(Sites1,Size);

CON11(Plant,Size)$(Ord(Size) gt 1) .. Sum(Time,Raw(Time,Plant,Size))
         =G= Cap(Size-1)*Build(Plant,Size);
*  Once an ethanol plant is built, operations are continuous through the
year by not being less than
*  80% (CON10) or greater than 120% (CON11) of the initial time period's
production

CON12(Time,Plant,Size)$(Ord(Time) ge 2) .. Raw(Time,Plant,Size)
         =G= 0.80*Raw(Time-1,Plant,Size);

CON13(Time,Plant,Size)$(Ord(Time) ge 2) .. Raw(Time,Plant,Size)
         =L= 1.2*Raw(Time-1,Plant,Size);

CON14(Time,Sites,Size)$(Ord(Time) ge 2) .. Preproc(Time,Sites,Size)
         =G= 0.80* Preproc(Time-1,Sites,Size);

CON15(Time,Sites,Size)$(Ord(Time) ge 2) .. Preproc(Time,Sites,Size)
         =L= 1.20* Preproc(Time-1,Sites,Size);

* Not used, but places a minimum mandate on each period's ethanol
production.
* Mandate(Time) ..  SUM((Sites1,Size), Raw(Time,Sites1,Size)) =G=
(1/Card(Time))*RFS;

MODEL Ethanol /ALL/;
SOLVE Ethanol using MIP maximizing Z;
```

```
Parameter Result,Results,Result1;
  Result("Ethanol") = Sum((Time,Plant,Size),Raw.L(Time,Plant,Size));
  Result("Use") = Sum((Time,Sites,Size),Use.L(Time,Sites,Size));
  Result("Pretreat") = Sum((Time,Sites,Size),Preproc.L(Time,Sites,Size));
  Result("Leave") = Sum(Sites, Leave.L(Sites));
  Result("Harvest") = Sum(Sites, X.L(Sites));
  Result("TotalStraw") = sum((Sites,Crop), Straw(Crop) *
SSupply(Sites,Crop));
  Results(Plant,Size,"Ethanol") = Sum(Time,Raw.L(Time,Plant,Size));
  Results(Sites,Size,"PreTreat") = Sum(Time,Preproc.L(Time,Sites,Size));

Result1(Time,"Ship")=Sum((Sites,Sites1),ShipStraw.L(Time,Sites,Sites1));
  Result1(Time,"ShipPP")=Sum((Sites,Sites1),ShipPP.L(Time,Sites,Sites1));

DISPLAY     X.L, Leave.L, ShipStraw.L, ShipPP.L, Store.L, Preproc.L,
Feed.L, PPStore.L, Use.L, Raw.L, BUILD.L, BuildPP.L, Result, Results,
Result1, Z.L  ;
```