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Analyzing the design and management of biomass-to-biorefinery supply chain

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ABSTRACT

Bioenergy has been recognized as an important source of energy that will reduce nation's dependency on petroleum, and have a positive impact on the economy, environment, and society. Production of bioenergy is expected to increase. As a result, we foresee an increase in the number of biorefineries in the near future. This paper analyzes logistical challenges with supplying biomass to a biorefinery. We also propose a mathematical model that can be used to design the supply chain and manage the logistics of a biorefinery. Supply chain-design decisions are long-term type of decisions; while logistics management involves medium to short-term decisions. The proposed model coordinates these decisions. The model determines the number, size and location of biorefineries needed to produce biofuel using the available biomass. The model also determines the amount of biomass shipped, processed and inventoried during a time period. Inputs to the model are the availability of biomass feedstock, as well as biomass transportation, inventory and processing costs. We use the State of Mississippi as the testing ground of this model.

1. Introduction

Bioenergy has been recognized as one of the future power sources in the USA that will reduce nation's dependency on petroleum, thereby having a positive impact on the economy, environment, and society (United States Department of Energy, 2006). Production of bioenergy is expected to increase in the near future. According to the Renewable Fuels Standard (RFS), a provision of the US Energy Policy Act of 2005, the supply of renewable energy is expected to increase from 4 billion gallons in 2006 to 7.5 billion gallons by 2012 (Environmental Protection Agency, 2008).

Fig. 1 presents a summary of biomass feedstock sources and conversion methods that can be used to produce biofuels. Traditionally, the biomass feedstock used for producing ethanol is corn, and for biodiesel is soybean. Supply and costs of these biomass feedstock sources are uncertain for a number of reasons. First, corn and soybean are agricultural products and as such, their production yield and supply are subject to weather conditions, insect populations, plant disease, and farmers planting decisions for the next season. Second, production of corn and soybean is limited by the amount of land available. These agricultural products are commodities for which a market already exists, therefore, the increase in their demand, while supply remains about the same, will increase their market price. Third, the logistics costs of supplying corn or soybean are high as these products have high inventory holding costs because of their seasonality (fuels are used all year around, but corn or soybean are harvested once a year); high transportation costs because they are bulky and difficult to transport; high harvesting and collection costs because their supply is widely dispersed geographically.

The challenges with using these traditional biomass feedstock sources have been a motivation for identifying other viable options. Recent studies are considering the use of lignocellulosic biomass, which includes agricultural residues, forest residues, municipal solid waste (MSW), and perennial grasses, to produce bioenergy (Aden et al., 2002). As a result, biomass feedstock needed would be secured by cultivating less productive land, and using materials that would ordinarily be considered waste, such as waste from wood products and crop residues. It is a fact that the technology for producing biofuels from lignocellulosic biomass is not well established. However, using lignocellulosic biomass offers a number of advantages in terms of costs and supply reliability for the following reasons: (a) a portfolio of biomass feedstock options will be used instead. That implies lower biomass supply uncertainties; (b) harvesting windows differ across species, allowing the use of specialized harvest and collection machinery all year around and reducing the fixed costs of harvesting and collecting biomass. Less inventory of biomass will be carried due to the fact that biomass is supplied all year around; (c) perennial grasses can grow on land that is not suitable for grain production; (d) using a variety of perennial species enables a diversified landscape and reduces the potential for insect and disease risk inherent with

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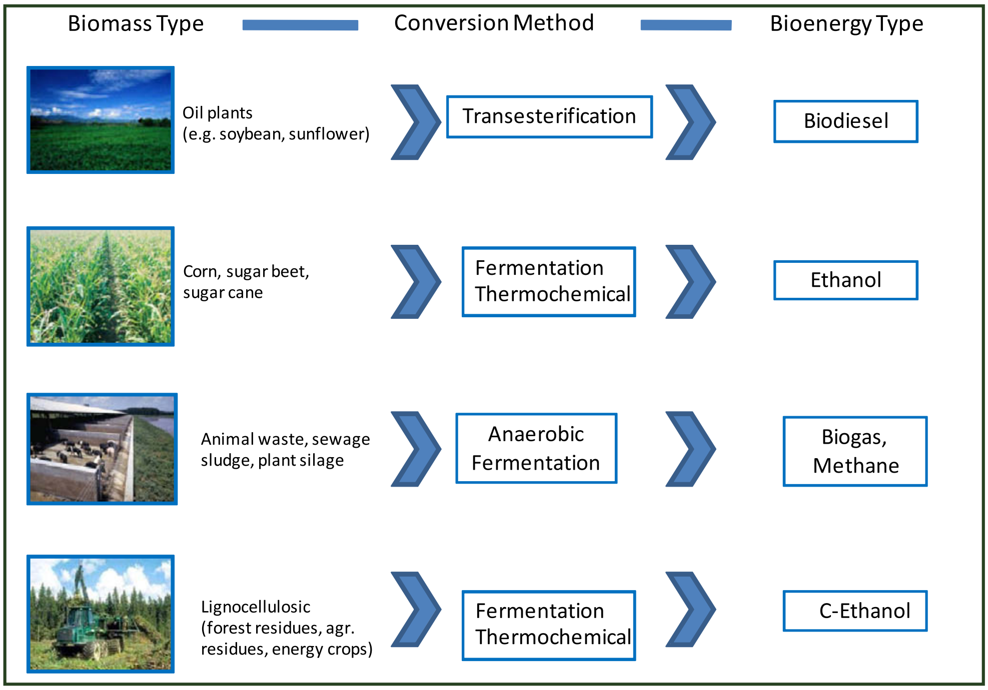


Fig. 1. Summary of processes used for producing biofuels.

monocultures; and (e) MSW avoid collection issues, is available at no, or very low cost, and is not seasonal in nature.

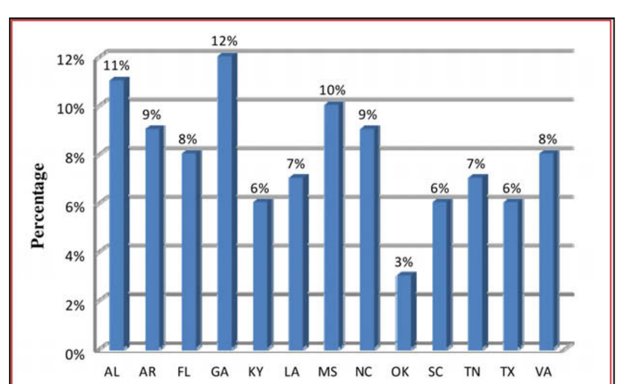
This study considers that lignocellulosic biomass will be used to produce cellulosic ethanol (c-ethanol). Although c-ethanol is a clean-burning, renewable and biodegradable fuel, its production has been very limited. Studies have indicated that fear of unreliable feedstock costs and supply, and high logistics costs of supplying biomass, have been major barriers for the start-up of biorefineries (Reynolds, 2002). It is estimated that about 20–40% of the cost of ethanol is due to biomass supply, and about 90% of the costs of supplying biomass are logistics related costs. That is why ethanol, which although a highly demanded biofuel, has a world-wide production that counts only for 3% of total gasoline consumption. In the USA, ethanol covers only 3% of the needs for gasoline.

We demonstrate through a case study about Mississippi the relevance and efficiency of the mathematical model we propose to design and manage the biomass-to-biorefinery supply chain. The economy of Mississippi relies mainly on agriculture. The two main agricultural products cultivated in the state are cotton and soybean. Traditionally, the state is known to have a corn deficit as its production does not satisfy the needs for food and animal feed. However, in 2007 the number of acres planted with corn tripled, going from 300,000 to 950,000 acres. This was motivated by the increase in the price of corn because of the increase in demand for ethanol (see Table 1). In 2007, the first corn-to-ethanol biorefinery in the state stared its production. The biorefinery is located in the city of Vicksburg, Delta region. The plant of Vicksburg will produce 60 million gallons of ethanol (MGY) and will use 22 million bushels of corn per year. Due to the increased production of corn, the amount of corn stover (another source of biomass feedstock) available will increased. Additionally, Mississippi is reach in forest residues (see Fig. 2), agricultural residues and animal waste. A recent article published on July 15, 2008 in Forbes Magazine named Iowa, North Dakota, Georgia, Mississippi and North Carolina the most important state sources of biomass. Mississippi was named for its 3.6 million tons of logging waste. To make use of the increased supply of corn and corn stover, and make use of lignocellulosic biomass that is abounding in the state, we anticipate that other biorefineries will open in the near future. Therefore, identifying potential locations for such plants; and designing cost efficient supply chains is very important. We anticipate that providing investors with well designed supply chains will attract them to Mississippi. This in turn will positively impact the economy of the state and open new jobs for rural Mississippians.

Table 1
Corn production in Mississippi.

	1000 Bushels
2003	71,550
2004	59,840
2005	47,085
2006	35,750
2007	141,000
2008	106,400

Source: NASS provided by USDA.



Source: Forest Inventory & Analysis

Fig. 2. Percentage of forest land contribution in Southern US.

2. Problem description

The in-bound and out-bound parts of the supply chain of a biorefinery are different from those of traditional refineries that use crude oil. Fig. 3 presents a typical supply chain structure for ethanol. Biomass is harvested at farms, collected at facilities near the farms and then shipped to biorefineries mainly by trucks. Ethanol is then shipped by truck or rail to blending facilities. These are facilities where biofuel is blended with gas. All vehicles can use ethanol blends such as E-10 (gasoline blended with 10% ethanol), and only a small number of vehicles (called flex fuel vehicles) can use higher blends such as E-85.

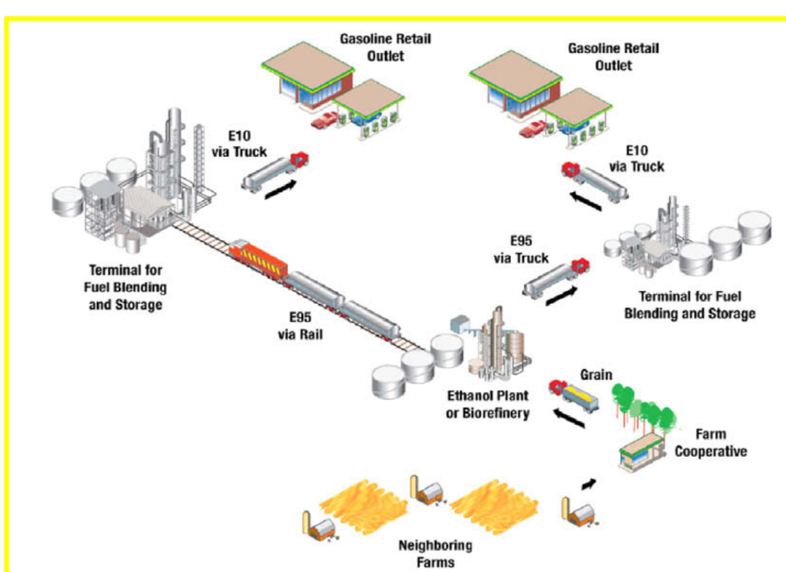
As shown in the figure above, depending on the distance traveled, rail or truck can be used to ship ethanol. Due to the high transportation costs, biorefineries prefer to get their supply of biomass from within 50 miles of radius. This is the reason why 76% of ethanol produced in the USA comes from small sized biorefineries located in four major corn producing states in the Midwest.

The design and management of efficient supply chains in today's competitive environment is a big challenge for managers (Chopra & Meindl, 2003; Simchi-Levi, 2003). Well designed and well managed supply chains contribute in reducing the cost of supplying biomass to a biorefinery which impacts the cost of producing biofuels. *Designing the supply chain* of a biorefinery means identifying: (a) the number, capacity and location of biorefineries needed to make use of the biomass available in the region; (b) the number and location of biomass collection facilities; (c) harvesting sites that serve a particular collection facility; (d) collection facilities that serve a particular biorefinery; and (e) blending facilities used by a particular biorefinery. Decisions about supply-chain design are long-term decisions which are made every 5–10 years, or even longer.

On the other side, *managing the logistics* of a biorefinery consists of mid-term to short-term decisions. These decisions relate to identifying: (a) the amount of biomass collected in a time period; (b) the amount of biomass shipped in a time period to a collection facility (or directly to a biorefinery) from each harvesting site; (c) the amount of biomass shipped to a biorefinery in a time period; (d) the amount of biofuel shipped in a time period from a biorefinery to a blending facility; (e) the amount biomass processed in a time period in a biorefinery; and (f) the amount of inventory of biomass in a facility, etc.

Long-term and mid-term decisions in a supply chain are related and impact one-another. Coordinating decisions, while a challenging problem, has the potential of creating value for the members of the supply chain. For example, coordinated harvest and transportation schedules minimize losses of biomass due to on-field storage; coordinated planting and harvesting schedules for multiple biomass feedstock sources allow a better utilization of equipment; etc. The model we use in this study integrates the long-term supply-chain design with mid-term logistics management decisions. This is achieved by using mathematical models that integrate location, with production, transportation and inventory management decisions. The objective of the mathematical models used in this study is to minimize the cost of delivering biofuel by coordinating long- and mid-term decisions related to the supply chain and logistics management of a biorefinery.

There is a vast literature on the area of supply-chain design and supply-chain management for industrial products. However, due to the nature of biomass, these models do not directly apply. For example, biomass supply is uncertain, seasonal, and constrained by land availability. Supply-chain design and management models for industrial products consider mainly demand (rather than supply) uncertainties, consider demand (rather than supply) seasonality, and focus on satisfying demand (rather than making good use of the supply). The literature related to supply-chain management for biomass supply provides models that estimate the cost of collecting, handling and hauling biomass to biorefineries (Atchison & Hettenhaus, 2004; Hamelinck, Suurs, & Faaij, 2005; Perlack & Turhollow, 2002; Sims & Venturi, 2004), compare different modes of delivering biomass (Kumar, Cameron, & Flynn, 2004; Mahmudi & Flynn, 2005), and identify supply-chain options for biobased businesses (Lummus, 2004). This literature pays little attention to the logistics associated with feedstock production, field losses, transportation, storage, storage losses, and feedstock inventory management. To our knowledge, the work of Tembo, Epplin, and Hunke (2003) is the only study that takes an integrated view of biomass harvesting, inventory, transportation processes and biorefinery location. However, the structure of the supply chain considered is different.



Source: US Department of Agriculture, 2007.

Fig. 3. Ethanol supply chain structure. (See above-mentioned reference for further information.)

The literature and practice have shown that in order to achieve significant cost savings, the supply chain should be optimized as a whole (Fine, 1996). That is, major cost factors that impact the performance of the supply chain should be considered jointly as they are highly related. The existing literature offers a number of models that deal with designing and managing efficient supply chains for industrial products. These models study the coordination of strategic with tactical and operational decisions in supply chains, such as location and transportation decisions (Eskigun et al., 2005; Francis, McGinnis, & White, 1992; Shen, 2005), production and distribution decisions (Chandra & Fisher, 1994; Cohen & Lee, 1988; van Hoesel, Romeijn, Morales, & Wagelmans, 2005), and production, inventory and transportation decisions (Ekşioğlu, Romeijn, & Pardalos, 2006). Research has also been conducted on integrated production and distribution decisions in supply chains for perishable products (Ekşioğlu & Jin, 2006).

In summary, the contribution of this paper to the current literature is twofold. On one side, this paper contributes by identifying an interesting application of supply-chain design and management models. This study is in accord with the nationwide efforts in developing sustainable and renewable sources of energy. This effort is a reaction of the rising awareness on the consequences of climate change; the desire to improve energy sustainability; and the need to create new jobs in rural areas. On the other side, the models proposed add to the body of literature on *integrated supply chains* by taking an overall view to the location, inventory, and transportation issues of the biomass-to-biorefinery supply chain. These models capture the following characteristics of biomass: deterioration, supply seasonality, and supply availability.

3. Problem formulation

We model this supply chain problem as a network design problem with additional constraints. Fig. 4 gives a network representation of a supply chain that consists of two harvesting sites, two potential locations for collection facilities, two potential locations for biorefineries, and two blending facilities. One can think of this network as consisting of a number of layers, where each layer represents a time period. Within each layer, nodes represent locations where one could potentially locate a facility, or represent harvesting sites that supply biomass feedstock. Arcs that connect harvesting sites with collection facilities and biorefineries; and collection facilities with biorefineries represent biomass transportation arcs. Arcs that connect biorefineries with blending facilities represent the transportation of biofuels. Arcs that connect the same facility in two consecutive time periods are the inventory arcs. Our model assumes no inventory of biomass is held in the field side.

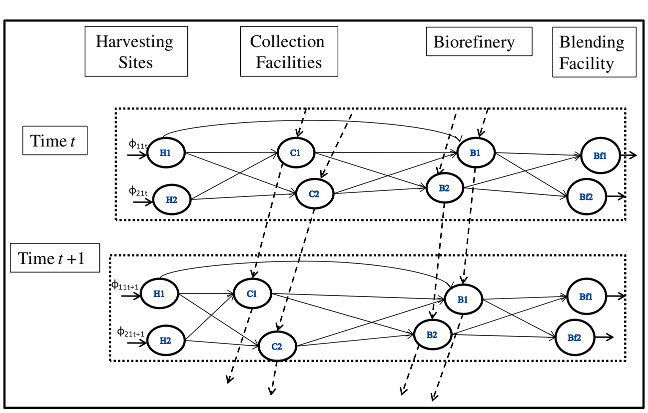


Fig. 4. Network representation of the supply chain model.

This network representation allows us to model the dynamic nature of decisions related to supply-chain design and logistics management of a biorefinery. In this network, a time period t could be as long as a day, a week, or a month. The length of the whole horizon T could be as long as one year. Decreasing the length of a time period t increases the size of the problem. Due to the availability of the data, the length of a time period used in our computational analyses is one week, and the planning horizon is one year.

The objective of this study is to identify the number, size and location of collection facilities and biorefineries needed to process the biomass available in a particular region. The selection of collection facilities and biorefineries is done in such a way that the total of harvesting, inventory, transportation and investment costs are minimized. A mixed integer programming (MIP) formulation of this problem is presented next.

The parameters used in this formulation are: ψ_{il} is amortized annual cost of constructing and operating a biorefinery of size l in location i; p_b is unit cost of planting, growing and harvesting biomass feedstock type b; h_b is unit inventory holding cost for biomass feedstock type b; h^e is unit inventory holding cost for biofuel; c^1_{kj} is unit transportation cost from harvesting site k to collection facility j; c^2_{ki} is unit transportation cost from harvesting site k to biorefinery i; c^3_{ji} is unit transportation cost from collection facility j to biorefinery i; w_b is unit cost of processing biomass feedstock of type b; λ_{kbt} is the amount of biomass b available at the harvesting site k in period t; α is deterioration rate; ω_b is the unit cost of processing biomass feedstock type b; β_b is conversion rate of biomass feedstock type b; $d_{\kappa t}$ is the demand of customer κ in period t; C_l is production capacity of a biorefinery of size l; S_f is storage capacity of a collection facility of size f; S_l is storage capacity of a biorefinery of size l.

The decision variables used in the MIP formulation are: x_{il} is a binary variable that equals to 1 if a biorefinery of size l is located in site i, and 0 o/w; x_{jf} is a binary variable that equals to 1 if a collection facility of size f is located in site j, and 0 o/w; ϕ_{kbt} is the amount of biomass type b harvested at site k in period t; z^1_{jbt} the amount of biomass type b stored at the storing facility at site j in period t; z^2_{ibt} is amount of biomass type b stored at biorefinery i in period t; z_{it} is amount of biofuel stored at biorefinery i in period t; y^1_{kjbt} is the amount of biomass type b shipped from harvesting site k to collection facility j in period t; y^2_{kibt} is the amount of biomass type b shipped from harvesting site k to a biorefinery i in period t; y^3_{jibt} is the amount of biomass type b shipped from collection facility j to biorefinery i in period t; $y_{i\kappa t}$ is amount of biofuel shipped from biorefinery i to blending facility κ in period t; w_{ibt} is amount of biomass type b processed at biorefinery i in period t; e_{it} is amount of biofuel produced at biorefinery i in period t.

The objective function minimizes the annual costs of: harvesting, storing, transporting and processing biomass; storing and transporting ethanol; and locating and operating biorefineries.

$$
\begin{aligned}
\text{minimize} \quad & \Bigg[\sum_{k=1}^{K}\sum_{b=1}^{B}\sum_{t=1}^{T} p_b\phi_{kbt} + \sum_{b=1}^{B} h_b\left(\sum_{t=1}^{T}\left(\sum_{j=1}^{J} z^1_{jbt} + \sum_{i=1}^{I} z^2_{ibt}\right)\right) \\
& + h^e\sum_{i=1}^{I}\sum_{t=1}^{T} z_{it} + \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{t=1}^{T}\omega_b w_{ibt} + \sum_{b=1}^{B}\sum_{t=1}^{T} \\
& \times\left(\sum_{k=1}^{K}\sum_{j=1}^{J} c^1_{kj}y^1_{kjbt} + \sum_{k=1}^{K}\sum_{i=1}^{I} c^2_{ki}y^2_{kibt} + \sum_{j=1}^{J}\sum_{i=1}^{I} c^3_{ji}y^3_{jibt}\right) \\
& + \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{\kappa=1}^{K} c_{i\kappa}y_{i\kappa t} + \sum_{i=1}^{I}\sum_{l=1}^{L}\psi_{il}x_{il}\Bigg]
\end{aligned}
$$

$$
\text{Subject to :} \quad \phi_{kbt} \leqslant \lambda_{kbt} \quad k = 1,\ldots,K;\; b = 1,\ldots,B;\quad t = 1,\ldots,T \tag{1}
$$

$$\phi_{kbt} \leqslant \sum_{j=1}^{J} y_{kjbt}^{1} + \sum_{i=1}^{I} y_{kibt}^{2} \quad k = 1, \ldots, K; \;\; b = 1, \ldots, B; \;\; t = 1, \ldots, T \tag{2}$$

$$\sum_{k=1}^{K} y_{kjbt}^{1} + (1-\alpha) z_{jb,t-1}^{1} = \sum_{i=1}^{I} y_{jibt}^{3} + z_{jbt}^{1} \quad j = 1, \ldots, J; \;\; b = 1, \ldots, B; \;\; t = 1, \ldots, T \tag{3}$$

$$\sum_{k=1}^{K} y_{kibt}^{2} + \sum_{j=1}^{J} y_{jibt}^{3} + (1-\alpha) z_{ib,t-1}^{2} = w_{ibt} + z_{ibt}^{2} \quad j = 1, \ldots, J; \;\; b = 1, \ldots, B; \;\; t = 1, \ldots, T \tag{4}$$

$$e_{it} \leqslant \sum_{b=1}^{B} \beta_b w_{ibt} \quad i = 1, \ldots, I; \;\; t = 1, \ldots, T \tag{5}$$

$$e_{it} + z_{i,t-1} = \sum_{\kappa=1}^{K} y_{i\kappa t} + z_{it} \quad i = 1, \ldots, I; \;\; t = 1, \ldots, T \tag{6}$$

$$\sum_{b=1}^{B} z_{jbt}^{1} \leqslant \sum_{f=1}^{F} S_f x_{jf} \quad j = 1, \ldots, J; \;\; t = 1, \ldots, T \tag{7}$$

$$\sum_{b=1}^{B} z_{ibt}^{2} \leqslant \sum_{l=1}^{L} S_l x_{jl} \quad i = 1, \ldots, I; \;\; t = 1, \ldots, T \tag{8}$$

$$e_{it} \leqslant \sum_{l=1}^{L} C_l x_{il} \quad i = 1, \ldots, I; \;\; t = 1, \ldots, T \tag{9}$$

$$\sum_{i=1}^{I} \sum_{\kappa=1}^{K} y_{i\kappa t} = d_t \quad t = 1, \ldots, T \tag{10}$$

$$\sum_{l=1}^{L} x_{il} \leqslant 1 \quad i = 1, \ldots, I \tag{11}$$

$$\sum_{f=1}^{F} x_{jf} \leqslant 1 \quad j = 1, \ldots, J \tag{12}$$

$$z_{jb0}^{1}, z_{ib0}^{2}, z_{i0} = 0 \quad k = 1, \ldots, K; \;\; j = 1, \ldots, J; \;\; i = 1, \ldots, I; \;\; b = 1, \ldots, B \tag{13}$$

$$\phi, z, y, \omega, e \geqslant 0 \tag{14}$$

$$x \in \{0, 1\} \tag{15}$$

Note that, in order to calculate the amortized annual cost of constructing and operating a biorefinery of size l (ψ_{il}), we first identified the investment costs (INV_{il}) for building such a facility. Next, we calculated the corresponding annuity for a discount factor equal to r and project lifetime equal to T using the factor $\frac{r(1+r)^T}{(1+r)^T-1}$. Finally, to the discounted investment costs we add the annual operating costs $\left(\psi_{il} = INV_{il} * \frac{r(1+r)^T}{(1+r)^T-1} + operating\ cost_{il}\right)$.

Constraint (1) shows that the amount of biomass b harvested at site k in a particular time period is limited by the amount of biomass available in that period (λ_{kbt}). The amount of biomass available depends on the amount of land suitable at harvesting site k for production of biomass feedstock b, the proportion of land at site k that can be cultivated with biomass feedstock b; and the yield of biomass feedstock b per acre of land at harvesting site k. Constraints (2)–(4) are the flow conservation constraints that ensure no more biomass is shipped/processed from a location than what is actually available at the time of shipment/processing. Constraint (5) determines the amount of biofuel produced in a period. Constraint (6) is the flow conservation constraints for biofuel at a biorefinery which ensure that no more biofuel is shipped to a blending facility than what is available at the time of shipment. Constraints (7) and (8) are capacity constraints that ensure the amount of inventory of biomass feedstock in a storage facility/biorefinery in a given time period does not surpass the available capacity. Constraint (9) is the production capacity constraints. Constraint (10) ensures that the demand for in each time period is met. Constraints (11) and (12) force that at most one storage facility/biorefinery of one particular size is open in a given location. Constraint (13) shows that initial inventory level is zero. Constraint (14) is the non-negativity constraints. Constraint (15) is the binary constraints.

Characteristics that make this model adequate for the biomass-to-biorefinery supply chain are the following: (a) the flow conservation constraints for biomass (Constraints (3) and (4)) consider the fact that biomass deteriorate with time. Therefore, inventories at collection facilities and biorefineries are reduced by α% each time period; (b) the supply of biomass is seasonal and constraint by land availability. Constraint (1) captures the seasonality and availability of biomass supply through the coefficient λ_{kbt}; (c) the biomass harvested is immediately (within 1 week) shipped to either a collection facility or a biorefinery. Therefore, there are no inventory variables in the flow conservation constraints at a harvesting site (Constraint (2)); and (d) the amount of biofuel produced using a particular type of biomass is calculated using Constraint (5).

4. Case study

The two main biomass supply sources that we consider in this case study are corn stover and woody biomass (forest residues, pulpwood and sawtimber). We choose these biomass feedstock sources because of their availability in Mississippi. We consider that the type of biofuel produced is c-ethanol.

4.1. Demands for ethanol in Mississippi

Mississippi's gasoline consumption in 2005 was about 1.7 BGY (Mississippi Institute for Forest Inventory, 2009). Assuming that E10 would be consumed, the potential ethanol use in Mississippi would be 1.7 MGY. This figure is reported by the American Coalition for Ethanol (ACE) handbook for 2005 (ACE, 2006).

4.2. Biomass supply

The data about *corn stover* supply in Mississippi came from the National Agricultural Statistics Service (NASS) provided by USDA (2009). NASS conducts hundreds of surveys every year and prepares reports covering virtually e aspect of US agriculture. NASS publishes the following data related to corn and other crops: harvested area, production yield, total production, planting and harvesting periods, crop price during the current harvesting period, historical crop prices, etc. This information is given at the county and state level. The study considers only 45 of the 84 counties in Mississippi. The amount of corn produced in a county is used as a threshold. Only the counties that have more than 1000 acres of land dedicated to corn production are considered. As in Petrolia (2008), we assume a 1:1 ratio of corn to corn stover. Feedstock deterioration rate is estimated to be 0.5% and 0.1% for in-field and on-site storage correspondingly. Harvesting of corn stover happens only during a few weeks in a year. The harvesting season for stover follows the harvesting of corn which starts early September and ends in November.

Petrolia (2008) provides estimates of harvesting and transportation costs for corn stover. Wallace, Ibsen, McAloon, and Yee (2005) study the feasibility of co-locating and integrating ethanol production plants from corn and lignocellulosic biomass and give estimates of investment costs for such plants. This report also provides data about processing cost of ethanol and conversion rates of corn stover to ethanol. USDA's Economic Research Service

(2006) provides historical data and forecasts of the production cost for corn. Table 2 provides a summary of the input data used. Note that the biomass yields provided in Table 2 are an average over all counties in Mississippi. In the model, we have used the actual yield for each county.

The data about woody biomass supply in Mississippi came from the Mississippi Institute for Forest Inventory (MIFI, 2009). MIFI's report provides information about the volume of pulpwood and sawtimber by county in Mississippi. So far, MIFI has made available on line reports about the forest inventory in the Southwest, Southeast and Central regions of the state. Therefore, in our model we consider that the supply of woody biomass come from these regions only. In Mississippi, woody biomass is collected all year around other than during 3 months of winter.

4.3. Investment costs

In order to estimate investment costs for building a biorefinery, we used data provided by a study completed by MIFI (2007). MIFI's report presents estimates about investment costs to build a biorefinery in Wiggins, Mississippi. The report estimates investment costs to build a biorefinery that produces 58 MGY of ethanol is $310,102,000.

Wallace et al. (2005) in his study about the feasibility of co-locating and integrating ethanol production plants from corn and lignocellulosic biomass, estimates that doubling the size of the plant (from 50 to 100 MGY), increases the investment costs by a factor of 1.6. We used this factor and interpolated investments costs to calculate estimates of investment costs for biorefineries of different sizes. We use a 20 years project life; and a 15% interest rate. The project life and interest rate are used to calculate the equivalent annual investment costs (ψ_{il}). We consider 5 different biorefinery sizes (l = 10 MGY, 20 MGY, 30 MGY, 50 MGY, and 60 MGY).

4.4. Transportation costs

In this model we assume that stover is collected and then baled into large rectangular shape. The bales are staged at the field edge and then loaded onto flatbeds pulled by semi trucks to storage facilities. Semi trucks are also used to transport bales from storage to biorefinery. The cost per mile per ton is estimated $0.195 if distance travelled is less than 25 miles; $0.143 if distance traveled is between 26 and 100 miles; and $0.078 if distance traveled is more than 100 miles (USDA Agricultural Marketing Service, 2005). The transportation costs represent costs for round trips. The cargo weight for a load is estimated 44,736 lbs or 952 bushels. In order to estimate the total transportation costs for woody biomass we consider $0.125 is paid per ton, per mile traveled. In order to calculate the total transportation cost of ethanol we consider a price of $0.001 per mile/per gallon.

To calculate the distance traveled, we identified the coordinates of each harvesting site; potential storage facilities, biorefineries and blending facilities. The data used in this paper is given at the county level, therefore the coordinates of the center point of a county are used to calculated the geographical distances between locations. Transportation costs are calculated by multiplying the transportation unit costs with the distance traveled.

Table 2
Input data.

	Stover	Woody biomass	Unit
Feedstock cost	88.33	543.00	$/acre
Inventory cost	4.90	8.05	$/dt
Processing cost	44.30	29.17	$/dt
Biomass yield	3.33	18.46	dt/acre
Deterioration rate	0.1–0.5	0.1–0.5	%
Conversion rate	73.71	71.49	Gallons/dt

5. Output analyses

5.1. Biomass supply

Considering the amount of woody biomass and corn stover available in the state, we estimate the potential c-ethanol production in Mississippi. Table 3 summarizes our findings for forest residues, pulpwood, sawtimber and corn stover.

For each biomass feedstock options, we consider an optimistic and a pessimistic scenario. In the optimistic scenario, the conversion rate of biomass feedstock to c-ethanol is 80 gallons/dt. In addition, if biomass feedstock used is pulpwood or sawtimber, we expect that 10% of the available annual volume in Mississippi to be used for c-ethanol. For corn stover, we expect 30% of the available annual volume to be used for c-ethanol.

In the pessimistic scenario, the conversion rate of biomass feedstock to ethanol is 50 gallons/dt. In addition, if biomass feedstock used is pulpwood or sawtimber, we expect that 1% of the available annual volume in Mississippi to be used for c-ethanol. For corn stover, we expect 10% of the available annual volume is used. Based on these assumptions, the potential c-ethanol production would be anywhere between 43 MGY (assuming only forest residues are used) and 642 MGY.

Considering the available biomass options, we analyze 3 different scenarios. In scenario 1, we consider that the only biomass feedstock used is forest residues and the total amount of c-ethanol expected to be produced is 40 MGY. In scenario 2, we consider that the biomass feedstock sources are forest residues and pulpwood (10% availability). The total amount of c-ethanol expected to be produced is 150 MGY. Finally, in scenario 3, we consider that the biomass feedstock sources are forest residues, pulpwood (10% availability) and sawtimber (10% availability). The total amount of c-ethanol expected to be produced is 170 MGY.

The results presented in the following subsection were collected when using CPLEX 9.0 callable libraries to solve MIP formulation presented above.

5.2. Computational results

Table 4 presents the changes in the delivery cost of c-ethanol for different values of construction costs and conversion rate. Delivery cost of c-ethanol includes all costs incurred from the moment biomass is collected, to the moment when c-ethanol is delivered to a blending facility. Note that, as the conversion rate increases from

Table 3
Potential c-ethanol production in Mississippi.

	Annual volume (AV) (dt)	Conversion rate	
		50 gallons/dt	80 gallons/dt
		c-Ethanol (MGY)	
Forest residues (FR)	864,894	43	69
Pulpwood (P)	27,738,096		
High: 10% AV	2,773,810	139	222
Low: 1% AV	277,381	14	22
Sawtimber (S)	37,439,257		
High: 10% AV	3743,926	187	300
Low: 1% AV	374,393	19	30
Corn stover (CS)	2,151,000		
High: 30% AV	645,300	32	51
Low: 10% AV	215,100	11	17

50 gallons/dt to 80 gallons/dt, the cost of producing one unit of c-ethanol decreases. This is due to decrease in transportation and processing costs. As conversion rate increases, a smaller amount of biomass feedstock is needed to produce the same amount of c-ethanol. Decreasing the amount of biomass feedstock used decreases the cost of transporting and processing biomass.

Fig. 5 presents the distance traveled as biomass conversion rate changes. For smaller conversion rates, the average distance traveled is higher, as in order to produce the same amount of c-ethanol, a plant would use more biomass. In order to obtain the additional biomass, shipments from harvesting sites located further away of the biorefinery are needed.

Table 5 presents the running time of CPLEX. It is interesting to note that as conversion rate decreases, the running time of CPLEX increases. As conversion rate decreases, the amount of biomass required to produce 40 MGY of c-ethanol is larger. In this case, more suppliers will be used, and more biomass will be transported and processed. As a result, in an optimal solution a larger number of variables will take a non-zero value, and a larger number of solutions in this case need to be investigated. This is why we observe an increase in the running time of CPLEX.

Table 6 presents the impact of transportation costs on the delivery cost of c-ethanol. The increase in transportation costs we investigate is rather drastic (0–400%). This is motivated by the increase in gas prices we have seen in the last few years. Transportation costs count anywhere from 17% (when conversion rate is 80 gallons/dt) to 30% (when conversion rate is 80 gallons/dt) of the delivery cost of c-ethanol. Results show that with the increase in transportation costs, the cost of delivering c-ethanol will increase; however, this increase is not as high as the increase in transportation costs.

Table 7 presents the running time of CPLEX as transportation costs and conversion rate change. Table 8 presents the facility locations identified by our model for these problems. It is interesting to note that as transportation costs increase and conversion rates decrease, the model decides to open two or three smaller size facilities instead of one centrally located, large-sized facility. Savings due to investment costs and other economies of scale when operating large-sized facilities are undermined by the increase in transportation costs. For the rest of the problems generated in scenario 1, the model identified as the best location for a biorefinery the Covington County. Production capacity of this plant is 50 MGY. Covington County is surrounded by dense forested areas. Facility location decisions were not affected by changes in investment costs, biomass collection costs and biomass processing costs at the biorefinery.

Fig. 6 presents the facility locations identified in scenario 1. In this scenario, forest residues only are considered as biomass feedstock for the biorefinery. Biomass supply region for this scenario consist of Central, Southeast and Southwest regions of Mississippi which are rich in forest. Covington County has a central location with respect to biomass supply. For problems (see Table 8) with high transportation costs, two or three smaller size facilities are open instead. In these problems, biorefineries are located as follows: on in the south, on in the center, and one in the north part of the biomass supply region. Each facility is supplied with biomass from forest farms located nearby.

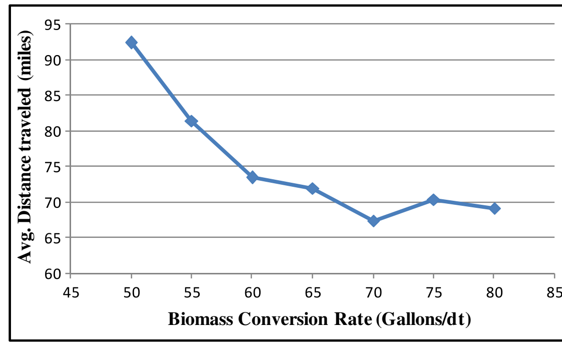


Fig. 5. Scenario 1. Average distance traveled versus biomass conversion rate.

Table 9 presents the impact of transportation and biomass processing costs on the delivery cost of c-ethanol. Results indicate that the increase in processing costs has a bigger impact on the delivery cost of c-ethanol as compared to transportation costs. This is due to the fact that 24% of the delivery cost of c-ethanol is due to processing costs (see Fig. 7), and 17% of the delivery cost of c-ethanol (for 80 gallons/dt conversion rate) is due to transportation costs.

Tables 10 and 11 present the impact of biomass collection costs in the delivery cost of c-ethanol and running time of CPLEX. Increase of biomass collection costs has a direct impact on the delivery cost of c-ethanol.

Fig. 8 compares the delivery cost of c-ethanol in all three scenarios with respect to increase in transportation costs. For each scenario, we present results for only two levels of conversion rate, low (50 gallons/ton) and high (80 gallons/ton). The impact of increasing transportation costs on the delivery cost of c-ethanol is higher for scenario 1 as compared to scenarios 2 and 3. This is due to the fact that in scenario 1 distance traveled is high, therefore the impact of increase in transportation costs as we go from a low to high conversion rates, is higher. Fig. 9 presents potential locations for birefineries under scenario 3.

Finally, trends similar to the ones depicted in scenario 1 (Tables 4–11) were observed in scenarios 2 and 3 when investment costs, biomass conversion rate, biomass collection costs, biomass transportation and biomass processing costs changed. However, the delivery cost of c-ethanol for scenarios 2 and 3 were smaller and facility size and locations were different. In scenarios 2 and 3, transportation costs are smaller due to the fact that more biomass is available. Increase in biomass availability decreases transportation costs as biorefineries can get larger shipments from forest farms located nearby. Reduced transportation costs have a direct

Table 4
Scenario 1: construction costs versus conversion rate.

Gallons/dt	Investment cost per annual gallon								
	$1.00	$1.50	$2.00	$2.50	$3.00	$3.50	$4.00	$4.50	$5.00
	Price per gallon of c-ethanol produced (in $)								
80	2.00	2.62	3.24	3.86	4.48	5.10	5.71	6.33	6.95
75	2.06	2.68	3.30	3.92	4.54	5.16	5.78	6.40	7.01
70	2.13	2.75	3.37	3.99	4.61	5.23	5.85	6.47	7.09
65	2.21	2.83	3.46	4.08	4.70	5.32	5.94	6.55	7.17
60	2.30	2.93	3.56	4.18	4.80	5.42	6.04	6.66	7.28
55	2.42	3.05	3.68	4.30	4.93	5.55	6.17	6.79	7.41
50	2.58	3.21	3.83	4.46	5.09	5.71	6.34	6.96	7.58

Table 5
Scenario 1: investment costs: CPLEX running time.

Gallons/dt	Investment cost per annual gallon								
	$1.00	$1.50	$2.00	$2.50	$3.00	$3.50	$4.00	$4.50	$5.00
	Running time of CPLEX (in CPU s)								
80	88	75	75	69	72	67	71	74	79
75	103	81	72	79	72	82	85	82	78
70	127	128	98	81	91	87	92	95	90
65	193	170	118	96	86	92	103	119	98
60	244	221	121	110	101	102	109	104	107
55	328	260	252	151	125	125	125	133	132
50	480	325	318	213	197	192	176	177	160

Table 6
Scenario 1: transportation costs versus conversion rate.

Gallons/dt	Increase in transportation costs								
	0%	50%	100%	150%	200%	250%	300%	350%	400%
	Delivery cost of c-ethanol (in $/gallons)								
80	2.00	2.11	2.22	2.33	2.44	2.55	2.66	2.77	2.88
75	2.06	2.19	2.31	2.43	2.55	2.68	2.80	2.92	3.04
70	2.13	2.28	2.41	2.55	2.69	2.83	2.97	3.11	3.24
65	2.21	2.39	2.54	2.70	2.86	3.02	3.18	3.31	3.44
60	2.30	2.52	2.70	2.89	3.06	3.21	3.35	3.50	3.64
55	2.42	2.68	2.90	3.08	3.24	3.41	3.57	3.74	3.86
50	2.58	2.90	3.11	3.30	3.49	3.68	3.87	4.06	4.22

Table 7
Scenario 1: transportation costs: CPLEX running time.

Gallons/dt	Increase in transportation costs								
	0%	50%	100%	150%	200%	250%	300%	350%	400%
	Running time of CPLEX (in CPU s)								
80	88	101	111	116	134	174	178	235	291
75	103	126	139	174	170	206	277	309	394
70	127	161	189	217	241	294	469	570	1042
65	193	223	270	349	516	739	954	1278	1625
60	244	280	421	607	1024	1159	1610	1625	2194
55	328	480	803	1163	1235	1648	2004	3272	3445
50	480	806	1273	1368	1748	2441	3757	4761	4877

impact on the delivery cost of c-ethanol. In scenarios 2 and 3 the amount of c-ethanol produced is higher. Since the largest biorefinery size is 60 MGY, at least 3 biorefineries should be operating to produce 150 MGY or 160 MGY.

6. Summary of results and conclusions

This paper presents issues related to designing and managing the biomass-to-biorefinery supply chain. We propose a mathematical model that can be used to design and manage this supply chain. We use the State of Mississippi as a case study to show how this model can be used to identify potential location for biorefineries, and give insights about the factors that impact the delivery cost of c-ethanol.

The data used to validate the model and perform the computational analyses presented above is collected from a number of sources such as USDA and MIFI's reports as well as research articles. Due to the availability of data, we consider only two major sources of biomass feedstock corn stover and woody biomass (forest residues, pulpwood and sawtimber). The same model can be used to design the supply chain of a biorefinery if other biomass feedstock is being used.

Figs. 5–9 and Tables 4–11 summarize the results of the output analyses. Based on these results, *supply chain-design decisions* for biorefineries are affected by transportation costs and biomass availability. When biomass availability is low and transportation

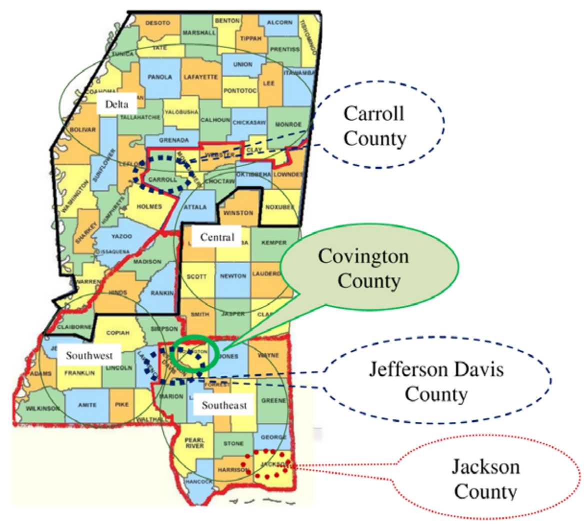


Fig. 6. Biorefinery location for scenario 1.

Table 8
Scenario 1: transportation costs: facility locations.

Gallons/dt	Increase in transportation costs								
	0%	50%	100%	150%	200%	250%	300%	350%	400%
	Facility locations								
80	1	1	1	1	1	1	1	1	1
75	1	1	1	1	1	1	1	1	1
70	1	1	1	1	1	1	1	1	1
65	1	1	1	1	1	1	1	2 and 3	2 and 3
60	1	1	1	1	2 and 3	2 and 3	2 and 3	2 and 3	2 and 3
55	1	1	1	2 and 3	2 and 3	2 and 3	2 and 3	2 and 3	2 and 3
50	1	1	2 and 3	2 and 3	2 and 3	2 and 3	2 and 3	2, 3 and 4	2, 3 and 4

Note: 1 – Covington County; 2 – Carroll County; 3 – Jefferson Davis County; 4 – Jackson County.

Table 9
Scenario 1: transportation costs versus processing costs.

Increase in processing costs (%)	Increase in transportation costs								
	0%	50%	100%	150%	200%	250%	300%	350%	400%
	Price per gallon of c-ethanol produced (in $)								
0	2.00	2.09	2.18	2.28	2.37	2.46	2.56	2.65	2.74
50	2.18	2.27	2.37	2.46	2.55	2.65	2.74	2.83	2.92
100	2.36	2.45	2.55	2.64	2.73	2.83	2.92	3.01	3.11
150	2.54	2.64	2.73	2.82	2.92	3.01	3.10	3.20	3.29
200	2.73	2.82	2.91	3.01	3.10	3.19	3.28	3.38	3.47
250	2.91	3.00	3.09	3.19	3.28	3.37	3.47	3.56	3.65
300	3.09	3.18	3.28	3.37	3.46	3.56	3.65	3.74	3.83
350	3.27	3.37	3.46	3.55	3.65	3.74	3.83	3.92	4.02
400	3.45	3.55	3.64	3.73	3.83	3.92	4.01	4.11	4.20

costs are high, smaller size biorefineries become economical. Results indicate that constructing two or three smaller size biorefineries – instead of one centrally located biorefinery of large size – will decrease the overall supply chain costs by decreasing transportation distances and corresponding costs. The economies of scale due to operating large-sized facilities are overcome by the increase in transportation costs. Results indicate that the supply chain-design decisions are not impacted by changes in biomass collection costs and biomass processing costs.

Experimental results also indicate that one of the major factors affecting the delivery cost of ethanol is *biomass availability*. Higher biomass availability implies that the biorefinery would be supplied from harvesting sites which are located nearby; therefore transportation costs would be low. Additionally, higher the availability of biomass allows for increase in the production capacity of the biorefinery. Due to economies of scale in production, the unit cost of c-ethanol would be lower.

Based on the input data (see Fig. 7) and our experimentations (see Tables 4–11) we can say that about 49% of the delivery cost of c-ethanol is due to investment costs, about 21% is due to operating costs, about 10% is due to feedstock collection costs, about 3% is due to inventory costs, and about 17% is due to transportation costs (for a 80 gallons/dt conversion rate). It is then understandable why our computational results indicate that changes in investment costs impact the most the delivery cost of c-ethanol. For smaller conversion rates, such as 50 gallons/dt, transportation costs count for about 30% of the delivery cost of c-ethanol, due to the fact that more biomass is shipped in the facility to produce the same amount of biofuel. When biomass needed is not available nearby, long haul shipments are required.

Improvements in the technology of converting biomass feedstock to ethanol have a high impact on the unit cost of c-ethanol. This is due to the fact that less biomass will be required to produce the same amount of c-ethanol. As a result, less biomass will need to be harvested and transported. This in turn will decrease the cost of producing a gallon of c-ethanol. Results indicate that improvements on the technology for converting woody biomass to c-ethanol have a higher impact on costs than improvements on the technology for converting corn stover to ethanol.

Table 10
Scenario 1: biomass collection costs versus conversion rate.

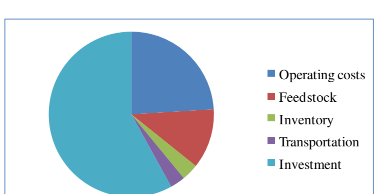
Gallons/dt	Increase in biomass collection costs								
	0%	50%	100%	150%	200%	250%	300%	350%	400%
	Delivery cost of c-ethanol (in $/gallons)								
80	2.00	2.09	2.18	2.27	2.37	2.46	2.55	2.64	2.73
75	2.06	2.16	2.26	2.36	2.45	2.55	2.65	2.74	2.84
70	2.13	2.24	2.35	2.45	2.55	2.66	2.76	2.86	2.97
65	2.21	2.34	2.45	2.56	2.67	2.79	2.90	3.01	3.12
60	2.30	2.46	2.58	2.70	2.82	2.94	3.06	3.18	3.30
55	2.42	2.60	2.73	2.86	2.99	3.13	3.26	3.39	3.52
50	2.58	2.78	2.93	3.07	3.22	3.37	3.51	3.66	3.80

Because of its availability in Mississippi, production of c-ethanol relies mainly on woody biomass. Therefore, improvements on the conversion technology of woody biomass have a higher impact on costs.

Other factors that impact the cost of producing c-ethanol are planting and harvesting costs, transportation costs. Due to the increase of the price of gas, it is expected that the cost of planting, harvesting biomass (due to the cost of using equipments) and transportation costs will increase. Increases in these costs impact

Table 11
Scenario 1: biomass collection costs: CPLEX running time.

Gallons/dt	Increase in biomass collection costs								
	0%	50%	100%	150%	200%	250%	300%	350%	400%
	Running time of CPLEX (in CPU s)								
80	88	91	89	93	90	91	85	90	87
75	103	117	113	112	106	108	121	108	101
70	127	142	152	137	132	142	133	138	150
65	193	211	209	237	201	197	190	172	179
60	244	213	181	245	208	208	224	230	227
55	328	302	322	303	306	317	284	255	236
50	480	442	383	382	392	363	384	382	414



Forest Residues

Costs	$/gallon
Operating costs	0.41
Feedstock	0.20
Inventory	0.06
Transportation	0.05
Investment	0.99
Total	1.71

Source: MIFI's Report

Fig. 7. Distribution of costs per gallon of c-ethanol.

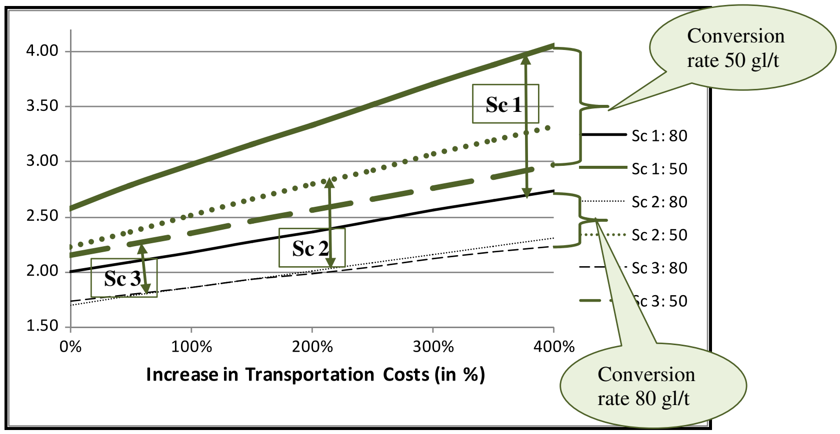


Fig. 8. Delivery cost of c-ethanol.

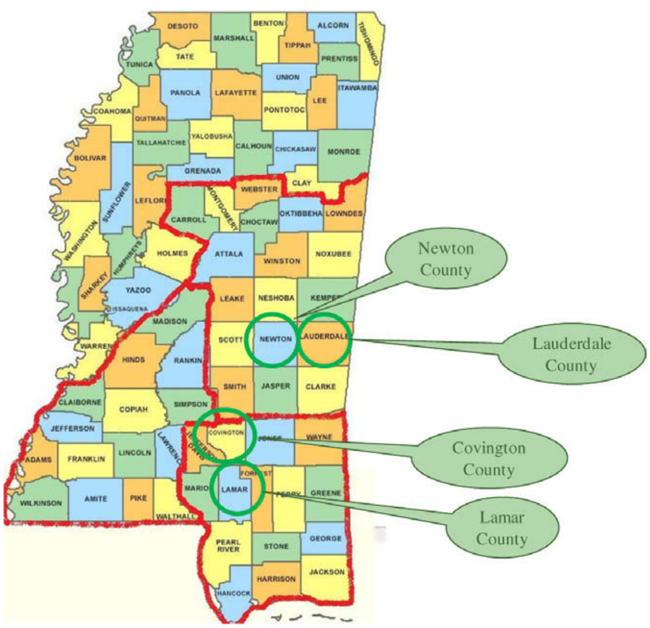


Fig. 9. Biorefinery location for scenario 3.

the cost of ethanol. The cost of c-ethanol is also impacted by factors such as the project life and interest rates.

Experimental results indicate that the running time of CPLEX for these problems is relatively small. The minimum running time is 87 CPU s and the maximum 4877 CPU s. Increasing the problem size (which would be the case when one uses this model to design and manage larger supply chains that consider a larger number of biomass feedstock options, larger number of biomass supply sources, etc.) may result in longer running times for CPLEX, or failure of CPLEX to read the problem created. Therefore, our future work includes designing solution approaches that would provide good quality solutions to these problems in a reasonable amount of time.

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