OPTIMIZATION OF SUPPLY CHAINS FOR PRODUCTION OF BIOFUEL USING MILP (CASE STUDY: UPPER PENINSULA OF MICHIGAN)

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Abstract— With growing concern over the decline of non-renewable energy, production of biofuel from biomass is gaining momentum. Critical to the financial success of producing biofuel is identifying the optimal location for the facility. The location decision is especially important for woody biomass and corn stover feedstock owing to the distributed nature of biomass and the significant costs associated with transportation. In this study first the model was created to simulate a similar one which was published in 2006. The Upper Peninsula of Michigan was used for the case study to locate the optimal farming sites. The model was made multi-period with multi-feedstock and multiple biorefineries from being a single period and single feedstock model. Depots and railway lines were added to the model. Many parameters contributed in finding the solution which includes fuel price, transportation distance, and pulpwood and corn stover availability.

Keywords— Linear Programming, Optimization Model, Corn Stover, Pulp Wood.

I. INTRODUCTION

While the energy history of the United States is one of significant change, three fossil fuel sources—petroleum, natural gas, and coal—have made up at least 80% of total U.S. energy consumption for more than 100 years.[1]In 2015, 24 percent of the oil consumed in the US was imported from foreign countries. Between 2013 and 2040, natural gas consumption is expected to increase by 13.4 percent and coal consumption by 5.6 percent. With such trends in place, it won't take more than half a century for the resources to run out.[2]In 2015, renewable energy sources accounted for about 10% of total U.S. energy consumption and about 13% of electricity generation.

In addition to heat and power generation, cellulosic biomass can be converted into biofuels (e.g., ethanol, biodiesel, "drop-in" fuels, etc.) via various technologies. According to the U.S. Energy Information Administration / Monthly Energy Review June 2016, a total of 2,103 billion Btu of energy was produced from biofuel and 9,678 billion btu of renewable energy was produced in year the 2015.[3]Lignocellulosic biomass is generally sent for pretreatment to reduce the moisture content and size of biomass particles, remove lignin, convert hemicellulose into fermentable sugar, etc.[4]Pretreatment of biomass generally can be divided into physical (e.g., mechanical comminution, drying, and densification), physicochemical (e.g., ammonia fiber explosion, liquid hot water, and steam explosion with SO2), and chemical (e.g., dilute acid, alkaline, and organosolv) pretreatments.

In the biochemical platform, pretreated biomass is sent to enzymatic hydrolysis to convert cellulose and hemicellulose into sugar monomers. It is then followed by microbial fermentation for the production of the ethanol-containing fermentation broth.[5]In the thermo chemical platform, biomass can be converted into syngas via indirect[6]or direct[7]gasification. Raw syngas produced from gasification is conditioned to meet downstream requirements. The concept of integrated biorefinery emerges as an integration of several biomass conversion technologies to maximize the economic potential.[8]

A number of studies focusing on the design of the entire cellulosic biofuel supply chains (SCs) have also appeared in the literature. Comprehensive reviews have been provided by An et al., Awudu and Zhang, Sharma et al., Yue et al., and Garcia and You.[9][10][11][12][13]The objective is the maximization of profit, or minimization of cost, of the entire biofuel SC. On the other hand, the concept of a collection facility or regional biomass processing depot(referred to in this study as "depot") has been introduced to improve the handling efficiency of biomass as well as reduce transportation cost and CO2 emissions.[14]

II. PROPOSED MODEL

2.1. Variables Definition

An overview of the model equations (without depots) have been given below. We introduce the following binary decision variable:

W_l/W_k	=1 if a biorefinery *l*/depot *k* is selected

And the following non-negative continuous decision variables:

$H_{i,j,l,t}$	Amount of compound $i \in \mathbf{I}^F$ harvested at site *j* sent to biorefinery *l* during time period *t* (kt/season)
$F_{i,j,l,t}/F_{i,j,k,t}/F_{i,k,l,t}$	Amount of compound $i \in \mathbf{I}^F / i \in \mathbf{I}^F / i \in \mathbf{I}^{ID}$ shipped along the arc $j \rightarrow l/j$

	$\rightarrow k/k \rightarrow l$ during time period t (kt/season)
$G_{i,l,m,t}$	Consumption level of compound $i \in \mathbf{I}^{\text{ID}}$ at biorefinery l using technology $m \in \mathbf{M}^{\text{CB}}$during time period t (kt/season)
$G'_{i,k,m,t}$	Consumption level of compound $i \in \mathbf{I}^{\text{F}}$ at depot k using technology $m \in \mathbf{M}^{\text{DD}}$during time period t (kt/season)
$L_{i,l,t}$	Total quarterly sales of compound $i \in \mathbf{I}^{\text{P}}$ from biorefinery l during time period t(kt/season)
$P_{i,l,m,t}$	Production level of compound $i \in \mathbf{I}^{\text{P}}$ by technology $m \in \mathbf{M}^{\text{CB}}$ at biorefinery l during time period t (kt/season)
$P'_{i,k,m,t}$	Production level of compound $i \in \mathbf{I}^{\text{ID}}$ by technology $m \in \mathbf{M}^{\text{DD}}$ at depot k during time period t (kt/season)
$S_{i,j,t}/S_{i,l,t}/S_{i,k,t}$	Inventory level of compound i at supply chain node $j/l/k$ at the end of time period t(kt/season)
$Q_{l,m/}\ Q_{k,m,}$	Daily operating capacity of the technology m at biorefinery l/depot k (kt/d)
$C_t^{\text{F/P/I/T}}$	Total feedstock cost; total production cost; total inventory cost; total transportation cost (10^3 \$/season)
$C^{\text{Total/C}}$	Total annual cost; annualized capital cost (10^3 \$/y)

2.2. Model Equations

The amount of biomass that is harvested, $H_{i,j,l,t}$, is subjected to the constrain,

$$H_{i,j,l,t} \leq \alpha_{i,j,t} \qquad i \in \mathbf{I}^{\text{F}}, j, t \qquad (1)$$

The biomass inventory at the harvesting site is,

$$S_{i,j,t} = S_{i,j,t=|\text{T}|}(1-\theta_{i,t}) + H_{i,j,t} - \sum_l F_{i,j,l,t} - \sum_k F_{i,j,k,t} \qquad i \in \mathbf{I}^{\text{F}}, j, t = 1 \qquad (2a)$$

$$S_{i,j,t} = S_{i,j,t-1}(1-\theta_{i,t}) + H_{i,j,t} - \sum_l F_{i,j,l,t} - \sum_k F_{i,j,k,t} \qquad i \in \mathbf{I}^{\text{F}}, j, t \geq 2 \qquad (2b)$$

The inventory of biomass at the depot, $S_{i,k,t}$, is,

$$S_{i,k,t} = S_{i,k,t=|\text{T}|}(1-\theta_{i,t}) + \sum_{m \in \mathbf{M}^{\text{DD}}} P'_{i,k,m,t} - \sum_l F_{i,k,l,t} \qquad i \in \mathbf{I}^{\text{ID}}, k, t = 1 \qquad (3a)$$

$$S_{i,k,t} = S_{i,k,t-1}(1-\theta_{i,t}) + \sum_{m \in \mathbf{M}^{\text{DD}}} P'_{i,k,m,t} - \sum_l F_{i,k,l,t} \qquad i \in \mathbf{I}^{\text{ID}}, k, t \geq 2 \qquad (3b)$$

And the production of pulpwood and cornstover pellets is given by,

$$\sum_j F_{i,j,k,t} = \sum_{m \in \mathbf{M}^{\text{DD}}} G'_{i,k,m,t} \qquad i \in \mathbf{I}^{\text{F}}, k, t \qquad (4)$$

$$P'_{i',k,m,t} = \sum_{i \in \mathbf{I}^{\text{F}}} \eta_{i,m} G'_{i,k,m,t} \quad i' \in \mathbf{I}^{\text{ID}}, l, m \in \mathbf{M}^{\text{DD}}, t \qquad (5)$$

Similarly, there is no biomass/intermediate inventory at the biorefinery (see assumptions in Section 3), which means that the mass balance of biomass can be written as follows:

$$\sum_j F_{i,j,l,t} = \sum_{m \in \mathbf{M}^{\text{CB}}} G_{i,l,m,t} \qquad i \in \mathbf{I}^{\text{F}}, l, t \qquad (6a)$$

$$\sum_k F_{i,j,l,t} = \sum_{m \in \mathbf{M}^{\text{CB}}} G_{i,l,m,t} \qquad i \in \mathbf{I}^{\text{ID}}, l, t \qquad (6b)$$

And the inventory balance for the product is given by,

$$S_{i,l,t} = S_{i,l,t=|\text{T}|} + \sum_{m \in \mathbf{M}^{\text{CB}}} P_{i,l,m,t} - L_{i,l,t} \qquad i \in \mathbf{I}^{\text{P}}, l, t = 1 \qquad (7a)$$

$$S_{i,l,t} = S_{i,l,t-1} + \sum_{m \in \mathbf{M}^{\text{CB}}} P_{i,l,m,t} - L_{i,l,t} \qquad i \in \mathbf{I}^{\text{P}}, l, t \geq 2 \qquad (7b)$$

Hence the production level of ethanol $P_{i,l,m,t}$, is given by,

$$P_{i,l,m,t} = \sum_{i' \in \mathbf{I}^{\text{IB}}} \eta_{i,m} G_{i,l,m,t} \qquad i \in \mathbf{I}^{\text{P}}, l, m \in \mathbf{M}^{\text{CB}}, t \qquad (8)$$

The total sales are bounded within lower and upper and lower targets by the equation,

$$\beta_{i,t}^{\text{L}} \leq \sum_l L_{i,l,t} \leq \beta_{i,t}^{\text{U}} \qquad i \in \mathbf{I}^{\text{P}}, t \qquad (9)$$

The operating capacity of the technology m at the biorefinery and the depotare constrained as follows:

$$W_l \gamma_m^{\text{L}} \leq Q_{l,m} \leq W_l \gamma_m^{\text{U}} \qquad l, m \in \mathbf{M}^{\text{CB}} \qquad (10)$$

$$W_k \gamma_m^{\text{L}} \leq Q_{k,m} \leq W_k \gamma_m^{\text{U}} \qquad k, m \in \mathbf{M}^{\text{DD}} \qquad (11)$$

The consumption level of biomass at the depot and the biorefinery, $G_{i,l,m,t}$ and $G'_{i,k,m,t}$is also constrained by the operating capacity of the technology as follows:

$$\sum_{i \in \mathbf{I}^{\text{IB}}} G_{i,l,m,t}/\nu \geq Q_{l,m} \qquad l, m \in \mathbf{M}^{\text{CB}}, t \qquad (12)$$

$$\sum_{i \in \mathbf{I}^{\text{F}}} G'_{i,k,m,t}/\nu \geq Q_{k,m} \qquad k, m \in \mathbf{M}^{\text{DD}}, t \qquad (13)$$

The concept of "cyclic" inventory balance is adopted to ensure the operations can be carried out in the next year and to avoid the underestimation of inventory cost. The inventory level at the beginning (t = 0) and end (t = |T|) of the horizon should be the same: $S_{i,j,t=0} = S_{i,j,t=|T|}$, $S_{i,k,t=0} = S_{i,k,t=|T|}$ and $S_{i,l,t=0} = S_{i,l,t=|T|}$.

The total annual cost, is given by:

$$C^{\text{Total}} = \sum_t (C_t^{\text{F}} + C_t^{\text{P}} + C_t^{\text{I}} + C_t^{\text{T}}) + C^{\text{C}} \qquad t \qquad (14)$$

The detailed formulations of each of the cost factors are given below:

$$C_t^{\text{F}} = \sum_{i \in \mathbf{I}^{\text{F}}, j, l} H_{i,j,l,t} \lambda_i \qquad t \qquad (15)$$

$$C_t^{\text{P}} = \sum_{i \in \mathbf{I}^{\text{IB}}, l, m} G_{i,l,m,t} + \sum_{i \in \mathbf{I}^{\text{F}}, k, m} G'_{i,k,m,t} \qquad t \qquad (16)$$

$$C_t^{\text{I}} = \sum_{i \in \mathbf{I}^{\text{F}}, j} (\iota_i S_{i,j,t}) + \sum_{i \in \mathbf{I}^{\text{P}}, l} (\iota_i S_{i,l,t}) \qquad t \qquad (17)$$

$$C_t^{\text{T}} = \sum_{i \in \mathbf{I}^{\text{F}}, j, l, o} (k_{i,o}^F F_{i,j,l,t} + k_{i,o}^V F_{i,j,l,t} D_{j,l}) + \sum_{i \in \mathbf{I}^{\text{F}}, j, k, o} (k_{i,o}^F F_{i,j,k,t} + k_{i,o}^V F_{i,j,k,t} D_{j,k}) + \sum_{i \in \mathbf{I}^{\text{F}}, k, l, o} (k_{i,o}^F F_{i,k,l,t} + k_{i,o}^V F_{i,k,l,t} D_{k,l}) \qquad t \qquad (18)$$

$$C^{C} = \sum_{l,m\epsilon \mathbf{M}^{CB}} (\Omega_m / \Gamma_m) Q_{l,m} + \sum_{l,m\epsilon \mathbf{M}^{DD}} (\Omega_m / \Gamma_m) Q_{k,m} \quad (19)$$

III. RESULTS AND DISCUSSION

3.1. Case Study

To check the viability of the model it was applied to the Upper Peninsula of Michigan. Forest resources, a widely available source of sustainable biomass, hold promise for energy production in Michigan[21], since more than half of State's land area is classified as forestland. A study of growth/removal ratios, calculated for the Great Lakes States from the national forest inventory, suggests significant opportunities for forest biomass as a biofuel feedstock[22]. Since 80% of the land area of Upper Peninsula of Michigan is forested it was selected as the region of interest to apply the methodology established above.

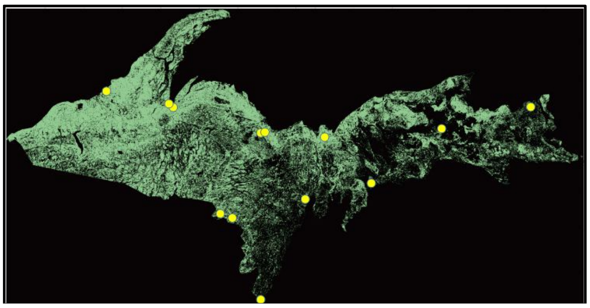

Figure 1 Map of UP of Michigan displaying the density of pulpwood in terms of the contrast (yellow spots: potential biorefineries)

The initial model was written in GAMS to check the efficiency by comparing the results with the results obtained in a 2006 research paper where upper peninsula of Michigan was considered.[24]

The availability data as well the location of the potential biorefinery has been taken from the previous paper and all the parameters were tailored according to it. The final result was obtained in the form of the distribution of harvesting sites selected from where pulpwood was sent to the biorefinery to produce Ethanol. As can be seen in Figure 2a and 2b, the results compare well except for the selection of the top corner region (Keewenaw county) in the current model. This can be explained with the fact that in the previous paper the availability was taken to be homogenous over every county disregarding the exclusion infeasible sites. However in the current model availability has been taken for every square mile separately and hence the infeasible regions have also been considered. The extra area selected hence compensates for the infeasibility regions in the map which can be seen in Figure 1.

3.2. Thermal Fatigue behaviours of TBCs systems

Square specimen were selected to consider the effect in practical application of thermal barrier coating (TBC) system, such as edges and corners in internal combustion (IC) engine piston. It can be seen from Fig. 1 compressive loads and more frequent thermal shock than their aircraft counterparts. In addition, many of these TBCs must cope with the contaminates found in lower-grade fuels. The difference between aircraft TBCs and diesel TBCs are often ignored by coating applicators. Thermal barrier coatings can be applied on gas turbines, automotive engines and diesel equipment. The use of TBC on diesel components such as valves, pistons and fire decks insulates the metal substrates from high-temperature oxidation and corrosive environments. As a thermal barrier, it reduces metal temperatures not occur. After 52 cycles, gradual weight loss was observed indicating thermal degradation of coated specimens. After 97 cycles, the sudden weight loss of samples was observed, which implied the coating damage via the cracking mode.

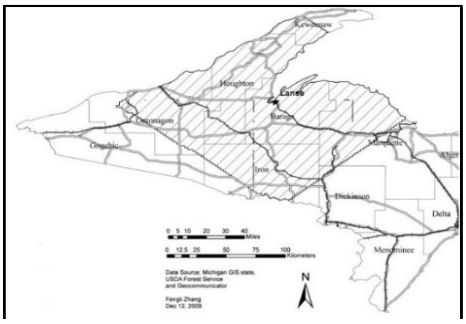

Figure 2aData obtained from previous paper

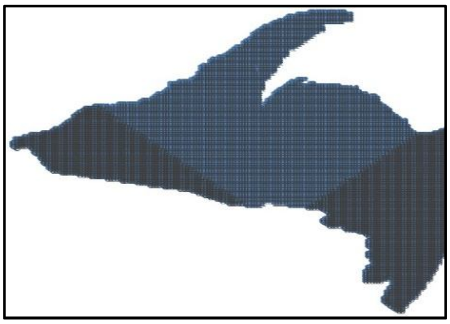

Figure 2a Data obtained from previous paper

For the sake of testing the model, it was assumed that the availability of Corn-stover at every site was half as that of Pulpwood. Although this was a deviation from the actual value since Corn-stover is not a popular crop of the Upper Peninsula, it will not affect the logistics of the model.[30]

The next step was to include more biorefineries since the Upper Peninsula had 13 potential ones. Hence apart from L'anse, Ishpeming, Munising and Norway were also taken as potential sites as they covered a good area of the map. Railway lines were also added to the map for cheaper transportation of biomass over longer distances. Till then trucks were assumed to transport the goods which had a greater variable price compared to trains. Finally, depots were installed at certain Railway Stations (every 20 mile radius) to convert the biomass feedstock into pellets before sending them to the biorefinery/biorefineries.

The map of distribution of selected regions for pulpwood and corn-stover has been shown in Figure 3a and 3b. It can be seen that a greater percentage of corn stover is transported while switching from without railway lines to with. This is justified by the fact that the variable cost of transportation is much higher for a truck than a train for corn stover.

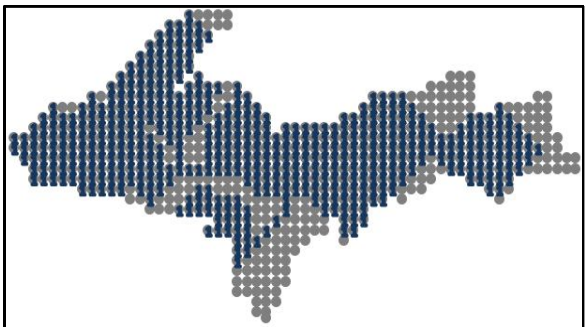

Figure 3a Distribution of selected areas (Corn Stover)

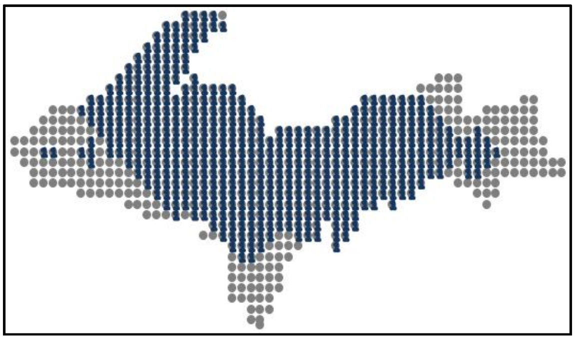

Figure 3b Distribution of selected areas (Pulpwood)

Table 1a. Summary of results

Model Type	Total Cost (in million $/y)	Total Cost* (in million $/y)	% of pulpwood
Type 1	224.7	227.4	65
Type 2	222.65	223.1	43.3
Type 3	223.7	225.9	42.1

Table 1b. Summary of results

% of corn stover	Fixed Cost (in million $/y)			Variable Cost (in million $/y)		
	PW	CS	T	PW	CS	T
35	4.29	10.7	2.94	0.07	0.31	0.007
56.6	4.29	10.7	2.94	0.07	0.31	0.007
57.9	4.29	10.7	2.94	0.07	0.31	0.007

Total cost while fixing a biorefinery L'anse

Type 1: Without railway lines; Type 2: With railway lines; Type 3: With railway depots

PW: Pulpwood via truck; CS: Cornstover via truck; T: Both feedstock via Train

The results have been compiled in Table 1(a&b). It can be observed that the total cost reduces by 2 million $ and 1 million $ approximately with the help of railway lines and depots respectively. This was because of the trade-off between availability and the transportation cost, especially the variable transportation cost.

CONCLUSIONS

A general optimization model was presented for the transportation of pulpwood and cornstover from the harvesting sites in the Upper Peninsula of Michigan to the potential biorefineries. Although Michigan has been studied before, only a single period model was developed on it. The present model has converted the single period model into a multi-period, multi-feedstock model with multiple biorefineries and railway depots. It was also observed that the total cost reduced by 2 million $ after adding the railway lines and by 1 million $ after the regional depots. The model accounts for selection of the harvesting site based on a variety of real time parameters such as the availability, distance and transportation cost. Furthermore, the proposed model has a lot of scope for improvement in terms of obtaining real time data for the railway co-ordinates as well as the corn stover availability. By adding these advancements and if fed with the necessary data, it can prove to be helpful for the biorefineries in the Upper Peninsula in terms of their decision-making process.

The Supporting Information is available in the following link: http://goo.gl/AUDGMr

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