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Simultaneous Design and Operation Decisions for Biorefinery Supply Chain Networks: Centralized vs. Distributed System

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Abstract: We propose an optimization model that enables the selection of biofuel conversion technologies, processing capacities and locations, and the logistics of transportation from the locations of forestry resources to the conversion sites and then to the final markets. A mixed integer linear program (MILP) model is built to solve for (1) the optimal number, locations, and sizes of various types of processing plants, and (2) the amounts of biomass, intermediate products, and final products to be transported between the selected locations, with the goal of maximizing the overall profit under present constraints. It also outputs the cost and profit data associated the selected network in a convenient form for further analysis. The model is tested in the context of designing both distributed and centralized processing system networks based on an industry-representative data set covering the South-eastern region of the United States. We investigate: 1) Which parameters have major effect on the overall economics, and 2) benefits of going to more distributed types of processing networks, in terms of the overall economics and the robustness to demand variations.

Keywords: biomass, biofuel, optimization, supply network, MILP, economics, robustness

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1. INTRODUCTION

Biofuels are renewable fuels derived from biomass, organic material from plants and animals. The energy in biomass can be accessed by conversion of the raw feedstock material, such as starch and cellulose, using biochemical or thermochemical processes and resulting in such bio-based fuels as ethanol, methanol, diesel, gasoline, crude, and methane (U.S. EPA: Energy, Biofuels & Climate Change). Biofuels will play an important role in the U.S. clean energy portfolio and also contribute to the U.S. economy by creating jobs to handle the harvesting, collection, preprocessing, transport, and storage of sufficient volumes of sustainably produced feedstocks. Feedstocks or combinations of feedstocks that were considered include: agricultural residues, energy crops, forest resources (e.g., forest thinnings, wood chips, wood wastes, small diameter trees), and urban wood wastes (U.S. DOE: Selects Biofuels Projects). This study focuses on bio-gasoline and bio-diesel from forestry resources (logging residuals, thinnings, prunings, grasses, and chips/shavings). The value of forest biomass currently used as pine pulpwood has trended downward for the past several years. Pulpwood can also be competitive as a raw material for many energy systems at the current price.

Supply chain modeling and supply chain optimization for biomass and biofuel system have received a lot of attention among companies and research groups in recent years. A model and solution that can be used as a decision support tool for strategic analysis as well as tactical planning of the supply of forest fuel have been proposed in Gunnarsson et al. (2004). The authors present the problem of deciding when and where forest residues are to be converted into forest fuel, and how the residues are to be transported and stored in order to satisfy demand at heating plants. The issue of combining multiple biomass supply chains, aiming at reducing the storage space requirements, has been introduced (Rentizelas et al., 2009). The optimal configuration of multiple plant systems in the lignocellulosic bioethanol supply chain was presented in Alex et al. (2008). A dynamic integrated biomass supply analysis and logistics model were described to simulate the collection, storage, and transport operations for supplying agricultural biomass to a biorefinery (Sokhansanj et al. 2006). Sylvain et al. (2008) presented a mixed integer linear programming (MILP) model that determines the optimal geographic locations and sizes of methanol plants with heat recovery and gas stations in Austria.

Recently a geographical information system (GIS) has been introduced to biomass supply chains in order to compute more accurately the expected supply of biomass in a certain region and to calculate more accurately the transportation distances and related costs and to assess the spatial impacts of the feedstock subtraction of different chain designs (Geijzendorffer et al. 2008). An approach to configure a wood biomass supply network for a certain region, a federal state of Austria, was described in Manfred et al. (2007). A decision support system for forest biomass exploitation for energy production purposes based on GIS techniques was also presented (Davide et al. 2004). In the proposed approach, GIS is integrated with mathematical programming in order to yield a comprehensive system for decision making. A GIS-based environmental decision support system including three modules (GIS, data management system, optimization) was introduced for the optimal logistics for energy production from woody biomass (Frombo et al. 2009).

In this paper, we formulate a MILP model that enables the selection of fuel conversion technologies, capacities, biomass locations, and the logistics of transportation from forestry resources to conversion and from conversion to final markets. We use the MILP model to design and analyze optimal distributed and centralized conversion systems, using a realistic data set covering the Southeastern region of the United States and GIS.

2. PROBLEM DESCRIPTION

In this work, we will consider a simple supply chain network including the following elements:

A set of biomass sites where five biomass types (logging residuals, thinnings, prunings, grasses, and chips/shavings) are harvested to be used as a feedstock to conversion 1 plant.

A set of candidate sites for conversion1 plants of various capacity options where three kinds of intermediate products (bio-oil, char and fuel gas) are manufactured to be used as feedstock or utility at conversion2 plants or as a utility locally.

A set of candidate sites for conversion2 plants of various capacity options where final products (gasoline and biodiesel) are manufactured and transported to the final markets or the intermediate products from the conversion1 plants can be used as a utility without producing to the final products.

A set of markets, where the final products are sold, with certain maximum demands;

The objective is to determine the number, location, and size of the two types of processing units and the amount of materials to be transported between the various nodes of the designed network so that the overall profit is maximized while respecting the constraints associated with product demands.

3. MILP MODEL

3.1 Mass balance constraints

The mass balance must be satisfied at each node of the SC system. Equations 1 and 2 are the flow balances at the nodes of locations l and of nodes at locations l', respectively. Equation 2 states that at each conversion1 plant location l and for each intermediate product type h, the sum of the inward flows of all biomass types (indexed by k) multiplied by their corresponding yield factor α_{ikh} must be equal to the sum of all the outward flows of h plus the total amount of h consumed locally for utility energy. Here i is the index for processing type. Also, r is the index for the biomass locations and c is for capacity options. Equation 3 states that, at each conversion2 plant location l' and for each product type h', the sum of the inward flows of all the intermediate product types multiplied by the corresponding yield factor $\alpha_{i'hh'}$ must be equal to the sum of all the outward flows of product h' plus the total amount of h' consumed locally for utility energy. As before, i' here is the index for the processing type and c' is for capacity options in the second conversion step. Also, m is the index for the final market location and p is for the final products sold. To keep the equation static, we assumed no inventory for either the intermediates or the final products.

$$\sum_{i}\sum_{c}\sum_{r}\sum_{k}\alpha_{ikh}\, f_{icrkl} = \sum_{i'}\sum_{c'}\sum_{l'} f_{i'c'lhl'} + \sum_{i} f_{ilhl} \quad \forall\, l,h \tag{1}$$

$$\sum_{i'}\sum_{c'}\sum_{l}\sum_{h}\alpha_{i'hh'}\, f_{i'c'lhl'} = \sum_{p}\sum_{m} f_{pl'h'm} + \sum_{i'}\sum_{h} f_{i'l'hl'} \quad \forall\, l',h' \tag{2}$$

3.2 Availability / Capacity constraints

The sum of the flows of each biomass type k from each biomass site r to all the conversion 1 plants cannot exceed the total amount of kth type of biomass that can be harvested from the site r. This biomass availability constraint is expressed by

$$\sum_{i}\sum_{c}\sum_{l} f_{icrkl} \le \overline{rm}_{rk} \quad \forall\, r,k \tag{3}$$

We must also ensure that the sum of the biomass types coming from the different sources to each conversion1 plant location does not exceed the chosen processing capacity at that location. This is also true for each conversion 2 plant location. These constraints are represented by

$$\sum_{r}\sum_{k}\gamma_{ik}\, f_{icrkl} \le \sum_{i}\bar{\theta}_{ic}\, X_{ilc} \quad \forall\, c,l \tag{4}$$

$$\sum_{l}\sum_{h}\gamma_{i'h} f_{i'c'lhl'} \le \sum_{i'}\bar{\theta}_{i'c'}\, X_{i'l'c'} \quad \forall\, c',l' \tag{5}$$

We assumed that there exist both lower and upper bounds on the demand (the minimum demand level that must be satisfied and the maximum supply level that can be sold). These are expressed as constraints on the production quantity for each final product at each sink location.

$$\sum_{l'}\sum_{h'} f_{pl'h'm} \ge \mathrm{D}_{pm}\,(min) \quad \forall\, p,\mathrm{m} \tag{6}$$

$$\sum_{l'}\sum_{h'} f_{pl'h'm} \le \mathrm{D}_{pm}\,(max) \quad \forall\, p,\mathrm{m} \tag{7}$$

Finally, we assume that we are allowed to build only a single plant of each processing type although one can choose from multiple capacity options. This constraint is given by

$$\sum_{c} X_{ilc} \leq 1 \qquad \forall\, i, l \tag{8}$$

$$\sum_{c'} X_{i'l'c'} \leq 1 \qquad \forall\, i', l' \tag{9}$$

3.3 Objective function

The objective function to be maximized is the overall *Profit*, which is *Revenue – Cost:*

$$Revenue = \sum_{p}\sum_{m} \mathrm{SC}_{pm} + \sum_{h}\sum_{l} \mathrm{SC}_{hl} + \sum_{h}\sum_{l'} \mathrm{SC}_{hl'} \tag{10}$$

$$Cost = \sum_{l}\sum_{i} (\, O_{il} + \, C_{il} \,) + \sum_{l'}\sum_{i'} (\, O_{i'l'} + \, C_{i'l'} \,) + \sum_{\mathrm{k}} CT_k + \sum_{h} CT_h + \sum_{h'} CT_{h'} + \sum_{r}\sum_{k} \mathrm{O_{rk}} \tag{11}$$

The *Revenue* includes those from selling various products in the final market plus the credits for the utility energy produced at each plant location. It is the sum of the following three terms:

$$\mathrm{SC}_{pm} = \sum_{l'}\sum_{h'} \mathrm{C}_{pm}\, f_{pl'h'm} \tag{12}$$

$$\mathrm{SC}_{hl} = \sum_{i} \mathrm{C}_{hl} f_{ilhl} \tag{13}$$

$$\mathrm{SC}_{hl'} = \sum_{i'} \mathrm{C}_{hl'} f_{i'l'hl'} \tag{14}$$

The *Cost* has four main components. First is the operating cost. Equations 15 and 16 are the operating costs for processing types *i* and *i'* at locations *l* and *l'*, respectively.

$$O_{il} = \sum_{c}\sum_{r}\sum_{k} O_{lick}\, f_{icrkl} \tag{15}$$

$$O_{i'l'} = \sum_{c'}\sum_{l}\sum_{h} O_{l'i'c'h}\, f_{i'c'lhl'} \tag{16}$$

Next is the annualized capital cost. Equations 17 and 18 are the total annualized fixed cost of the chosen capacity options for processing types *i* and *i'* at locations *l* and *l'*, respectively.

$$C_{il} = \sum_{c} C_{ic}\, X_{ilc} \tag{17}$$

$$C_{i'l'} = \sum_{c'} C_{i'c'}\, X_{i'l'c'} \tag{18}$$

The third component is the transportation cost. Equations 19, 20 and 21 describe the three transportation cost elements related to the flows from all raw material sites to the conversion 1 sites for each feed type *k*, between all conversion 1 sites to conversion 2 sites for each intermediate type *h*, and between all conversion 2 sites to final market locations for each product type *h'* respectively:

$$CT_k = \sum_{l}\sum_{r} C_{rlk} \sum_{i}\sum_{c} f_{icrkl} \tag{19}$$

$$CT_h = \sum_{l}\sum_{l'} C_{ll'h} \sum_{i'}\sum_{c'} f_{i'c'lhl'} \tag{20}$$

$$CT_{h'} = \sum_{m}\sum_{l'}\sum_{p} C_{l'mh'}\, f_{pl'h'm} \tag{21}$$

Finally, Equation 22 represents the biomass acquisition cost for biomass type *l* at raw material site *k*:

$$\mathrm{O}_{rk} = \sum_{c}\sum_{i}\sum_{l} \mathrm{C}_{rk}\, f_{icrkl} \tag{22}$$

The maximization of the objective function subject to the previously discussed constraints is a mixed integer linear program (MILP). There are efficient commercial solvers for MILPs such as GAMS$^{\mathrm{TM}}$ with CPLEX solver, which we used in our case study.

4. CASE STUDY

Optimization models, such as the one presented in the previous section can support decision-making by answering important questions such as:

What are the bottom-line economics?

Which processing option or a combination of options is most attractive from the financial viewpoint?

What factors drive the costs and what is their relative impact? What should be improved to gain biggest improvement in the economics? What is the optimal combination of material movement, capital investment, processing cost, processing location, and access to markets?

In this case study, we examine a fairly large SC network design problem for thermochemical conversion of biomass into biofuel within the Southeastern part of the States. The data used are developed with an industrial collaborator (Weyerhaeuser NR) and represent realistic estimates of various costs involved. We examine a particular processing option where the first step (‘conversion1’) is Fast Pyrolysis and the second step (‘conversion2’) is Fischer Tropsch. The problem is described next.

In terms of designing the processing network, one can take a *distributed* approach or a *centralized* approach. Within the context of this case study, the centralized approach will refer to the approach of performing both Fast Pyrolysis and Fisher Tropsch at same locations, whereas the distributed approach considers the option of putting the two steps at separate locations. Advantages of the centralized approach include lower operating / capital cost and easier management. On the other hand, the distributed approach can offer significant savings in transportation costs as the biomass can be converted into a more easily transportable form of bio-oil at a nearby location before it is transported to the main processing facility. We examine the trade-off in our case studies.

Table 1. Acquisition cost of biomass [$/tons]

	Logging residuals	Thinning	Pruning	Grasses	Chip/ Shavings
biomass sites	25.0 ~ 30.0	25.0 ~ 30.0	20.0 ~ 24.0	35.0 ~ 42.0	50.0 ~ 60.0

Table 2. Capacity volume and fixed cost of conversion1

19 conversion1 location (C1(1) ~ C1(19))				
	plantation	reference plant	large co-op	scale
Capacity [Ton]	1225000	2450000	3675000	4900000
Fixed cost [$/year]	7728000	12768000	17808000	22848000
10 conversion1 location (C1(20) ~ C1(21))				
	plantation	reference plant	large co-op	scale
Capacity [Ton]	1750000	3500000	5250000	7000000
Fixed cost [$/year]	7100000	12255000	18097000	23068000

Table 3. Capacity volume and fixed cost of conversion2

10 conversion2 location (C2(1) ~ C2(10))				
	small	medium	large	scale
Capacity [Ton]	1750000	3500000	5250000	7000000
Fixed cost [$/year]	54637000	82019000	102548000	121107000

Table 4. Transportation cost [$/ton/mile]

Logging Residuals	Thinnings	Prunings	Grasses	Chips/Shavings
0.20	0.20	0.22	0.25	0.15

Bio Oil	Char	Fuel Gas
0.10	0.00	0.00

Gasoline	Biodiesel
0.05	0.05

Table 5. Yield parameters [dimensionless]

Biomass types to intermediate products at conversion1			
	Bio Oil	Char	Fuel Gas
Logging Residuals	0.70	0.15	0.15
Thinnings	0.65	0.25	0.10
Prunings	0.65	0.25	0.10
Grasses	0.80	0.10	0.10
Chips/Shavings	0.75	0.20	0.05
Intermediate products to final products at conversion2			
	Bio-diesel	Bio-gasoline	
Bio Oil	0.40	0.20	
Char	0.00	0.00	
Fuel Gas	0.00	0.00	

4.1 Distributed system

The regions of interest in this case study are ten states (Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Georgia, Florida, South Carolina, and North Carolina). Five different biomass types (logging residuals, thinnings, prunings, grasses and chips/shavings) are harvested at 30 biomass source locations. These biomass materials can be converted into three intermediate products (bio-oil, char, and fuel gas) at any number of 29 possible locations for conversion1 plants. Only bio-oil is transported to and converted into two final products (gasoline and biodiesel) at any number of 10 possible conversion2 plant locations. Char and fuel gas are to be consumed locally as a utility energy source at both conversion1 and conversion2 plants locations. The final products are transferred to 10 final markets for sale. Each plant, for both conversions, has four different capacity options. Latitude and longitude of each location are provided to us and we converted them into distance matrices using the GIS. Key parameters are summarized in Table 1-7.

Table 6. Capacity volume and fixed cost of centralized system model

	small	medium	large	scale
Capacity [Ton]	1750000	3500000	5250000	7000000
Fixed cost [$/year]	61737000	94274000	120645000	144175000

Table 7. Value of final and intermediate products [$/ton]

	Bio-diesel	Bio-gasoline
Final market	441.10 ~ 504.58	514.36 ~ 568.22
	Char	Fuel-gas
Conversion1	40.0 ~ 64.0	20.0 ~ 32.0
Conversion2	40.0 ~ 48.0	20.0 ~ 24.0

4.2 Centralized system

As an alternative, we consider only the 10 candidate locations, i.e., the candidate locations for conversion2 in the distributed system study, for performing the both types of conversions. We allow bigger capacity options for the conversion1 process as there is now less number of candidate locations for it than in the previous case. Operating costs are also adjusted to reflect the fact that the combined operation should cost less than the individual operations of conversion1 and conversion2 as in the distributed system.

5. RESULTS

5.1 Optimized supply network design results for distributed vs. centralized system

The proposed optimization MILP model is tested for designing both distributed and centralized processing network systems. In the optimally designed distributed system, biomass resources are transferred to 13 selected conversion1 processing locations from 27 biomass sites. 13 selected conversion1 locations include two of the conversion2 processing locations. Bio-oil converted at conversion1 processing plants is fed to three conversion2 processing locations. Two final products, bio-gasoline and biodiesel, are delivered to 10 final markets. Supply chain networks from forestry resources to conversion1, from conversion1 to conversion2 and from conversion2 to final markets are shown in Fig. 1.

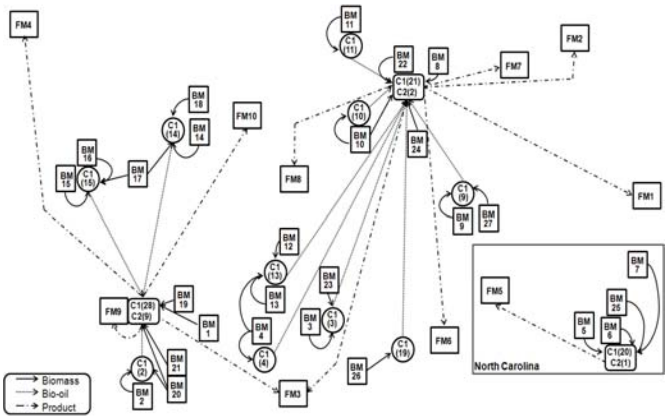

Fig. 1. Flow networks from biomass to biofuels in the optimal distributed network system (Maximum Demand: 100%)

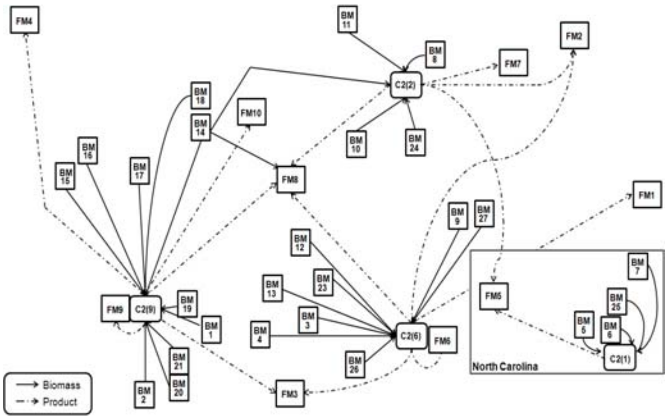

Fig. 2. Flow networks from biomass to biofuels in the optimal centralized network system (Maximum Demand: 100%)

In the optimally designed centralized network, biomass materials at 27 biomass sites are transported to four selected conversion processing locations (small size C2(1), large size C2(2), scale size C2(6) and C2(9)). Transferred biomass materials are directly converted into the final products at the conversion processing plants. The final products are delivered to the 10 final markets. Supply chain networks from biomass resources to conversion2 and from conversion2 to final markets are shown in Fig. 2.

Fig. 3 shows the total profits on demand basis comparing the two types of design. Here we lowered the maximum demand from 100% (of the previously used maximum demands) to 60% by an increment of 10% and designed optimal processing networks for each demand scenario. The total profit of distributed system is around $187.6 million more than that of the centralized design in case of maximum demand and the total profit gap between both systems is sharply decreased until 60% where the gap is just $46.4 million. The main reason is that the annualized fixed cost of the centralized system is remarkably decreased when the demand decreases. The fixed cost of the centralized system is even smaller than that of the distributed system at 60% of the maximum demand. The flow networks of the distributed system become centralized at the low demand. The transportation cost of the distributed system is generally smaller than that of centralized system in all -the demand scenarios.

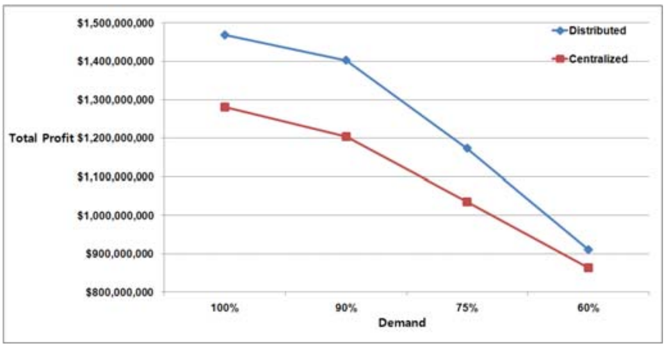

Fig. 3. Total annualized profit for the optimization on demand basis (distributed system vs. centralized system)

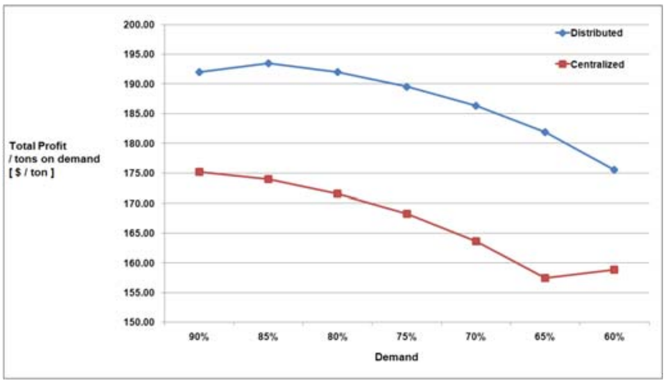

Fig. 4. Total profit per ton for the robustness to demand variation (distributed system vs. centralized system)

5.2 The robustness analysis to demand variations for distributed vs. centralized system

This is another case study intended to examine the robustness of a fixed flow network design with respect to the final market demand. We study the optimal design obtained with the 90% maximum demand. One change from the previous case study is that the operating costs are separated into fixed operating costs and variable operating costs. The fixed operating costs, which are chosen approximately 25% of the costs for the maximum volume, are incurred as long as the plant operates at any capacity. The fixed operating cost is not incurred when the plant is shut down completely. The variable operating costs increase linearly as the processing volume increase. Although the network design is fixed, we adjust the flow rates between the nodes as the demands are varied for the analysis of the robustness. The profits, the costs, the values and their elements are also recalculated optimally by decreasing with 5% intervals from the 90% of maximum demand.

Table 7. Used percentage of the capacity at conversion1 and conversion2 locations in the distributed system

Demand [%]		90	85	80	75	70	65	60
Location	Capacity option	Percentages of used [%]						
C1(3)	scale	96.8	96.8	80.9	62.4	42.3	31.0	31.0
C1(5)	plantation	41.4	0.0	0.0	0.0	0.0	0.0	0.0
C1(9)	plantation	67.0	67.0	67.0	67.0	67.0	49.0	0.0
C1(15)	reference plant	94.9	76.6	74.2	69.1	67.4	63.5	59.5
C1(21)	scale	67.8	67.8	67.8	67.8	67.8	67.8	69.4
C1(28)	scale	70.0	70.0	70.0	70.0	70.0	69.5	65.7
C2(2)	scale	98.2	94.2	85.6	77.6	68.9	61.3	56.2
C2(9)	scale	63.6	58.8	58.2	57.2	56.9	55.5	51.6

Table 8. Used percentage of capacity at conversion2 locations in the centralized system

Demand[%]		90	85	80	75	70	65	60
Location	Capacity option	Percentages of used [%]						
C2(2)	large	100.0	94.3	90.4	90.4	90.4	90.4	100.0
C2(6)	large	100.0	100.0	84.4	71.8	58.8	53.7	0.0
C2(9)	scale	100.0	97.4	97.4	94.7	90.7	80.9	98.5

The total profit per ton versus the demand is shown in Fig. 4. The optimized design of the distributed system is more robust than that of the centralized system. The difference increases as the demand decrease until the 60% maximum demand scenario, where the difference becomes much smaller. Table 7 and 8 show the processing volume and the used percentages of capacity at the conversion processing centers for each demand scenario. In the case of distributed system, one small-sized conversion1 processing center (C1(5)) shuts down at 85% demand and another small plant (C1(9)) shuts down at 60% demand. On the other hand, in the centralized system, selected all 3 conversion processing plants are operating until the demand drops down to 60% where then one of large plant (C2(6)) shuts down. This is the main reason that the profit difference between the two systems becomes smaller at 60% demand in Fig. 4.

6. CONCLUSIONS

The objective of the study is to develop optimization models that enable the decision making for the infrastructure of biofuel conversion processing including processing locations, volumes, supply networks, and the logistics of transportation from forestry resources to conversion and from conversion to final markets. Based on a realistic data set provided by our industrial partner, we developed the optimally designed networks for the maximum profit by considering acquisition cost of biomass, operating cost, capital cost, transportation cost, and sale price for various market demands. We considered the design of both the distributed system and the centralized system and compared them in terms of their profits and robustness to demand variations. This study highlighted the internal economies of size and scale and the external economies of market density and diffusion that will help to shape the supply chain network into the most cost-effective, feasible, and robust biofuels production system for the infrastructure.

REFERENCES

Alex J. D, Claire S. A, Nilay S. (2008). A spatially explicit whole-system model of the lignocellulosic bioethanol supply chain: an assessment of decentralized processing potential. *Biotechnology for Biofuels*, 1-13.

Davide F, Riccardo M, Michela R, Mauro R. Roberto S, Angela T. (2004). Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass and Bioenergy*, 26, 15-25.

Frombo F, Minciardi R, Robba M, Rosso F, Sacile R. (2009). Planning woody biomass logistics for energy production: A strategic decision model. *Biomass and Bioenergy*, 33, 372-383.

Geijzendorffer R, Annevelink E, Elbersen B, Smidt R, de Mol R. M. (2008). Application of a GIS-Bioloco tool for the design and assessment of biomass delivery chains. *16th European Biomass Conference & Exhibition*.

Gunnarsson H, Ronnqvist M, Lundgren J. T. (2004). Supply chain modeling of forest fuel. *European Journal of Operational Research*, 158, 103-123.

Manfred G, Peter R. (2007). Designing a regional forest fuel supply network. *Biomass and Bioenergy*, 31, 393-402.

Rentizelas A.A, Tolis A, Tatsiopoulos I. P. (2009). Logistics issues of biomass: The storage problem and the multi-biomass supply chain. *Renewable and Sustainable Energy Reviews*, 12, 887-894.

Sokhansanj S, Kumar A, Turhollow A.F. (2006). Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass and Bioenergy*, 30, 838-847.

Sylvain L, Dagmar S, Erik D, Erwin S, Michael O. (2008). Optimal location of wood gasification plants for methanol production with heat recovery. *International Journal of Energy Research*, 32, 1080-1091.

U.S. Department of Energy: DOE Selects Biofuels Projects to Receive up to $21 Million in Funding. [http://www.energy.gov/7848.htm]

U.S. Environmental Protection Agency: Energy, Biofuels & Climate Change. [http://www.epa.gov/Sustainability/energy.htm]