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A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas

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ABSTRACT

This study formulates a model to maximize the profit of a lignocellulosic biofuel supply chain ranging from feedstock suppliers to biofuel customers. The model deals with a time-staged, multi-commodity, production/distribution system, prescribing facility locations and capacities, technologies, and material flows. A case study based on a region in Central Texas demonstrates application of the proposed model to design the most profitable biofuel supply chain under each of several scenarios. A sensitivity analysis identifies that ethanol (ETOH) price is the most significant factor in the economic viability of a lignocellulosic biofuel supply chain.

1. Introduction

As petroleum reserves are being depleted and the demand for a sustainable source of environmentally friendly fuel is increasing, a number of countries are relying upon biofuels generated from edible crops. However, these first-generation biofuels can lead to higher crop prices because they bid resources (e.g., land) as well as edible crops away from the food industry. In addition, in terms of life-cycle energy use and greenhouse gas (GHG) emissions, several studies have assessed the advantage of the second generation biofuels by using life cycle assessment methodology (Singh et al., 2010) and herbaceous lignocellulosic crops show higher advantage than the first-generation biomass (Rettenmaier et al., 2010). Thus, interest in second-generation biofuels, which are produced from energy crops as well as non-edible parts of food crops, has increased dramatically, and several pilot plants are currently studying ways to enhance conversion technologies to improve efficiency.

The biofuel industry faces unique challenges. First, biomass has low energy density and high moisture content, is geographically dispersed, and degrades during storage. Second, major feedstocks (e.g., dedicated energy crops and crop residues) can be harvested only in specific seasons but must satisfy year around demand. Third, biomass moisture content as well as the price of fuel change over time. Furthermore, alternative technologies to convert lignocellulosic biomass to biofuel, such as biochemical (e.g., enzymatic hydrolysis), thermochemical (e.g., steam explosion and pyrolysis), and bio-thermochemical (e.g., carboxylate pathway) processes, are still under development to improve conversion efficiency in the most economical way (Munasinghe and Khanal, 2010). Finally, since the biofuel industry must ultimately compete with petroleum-based fuels, determining the most profitable biofuel supply chain design is crucial to attracting the investment needed to build this emerging industry into an economically viable enterprise.

Most studies of the biofuel supply-chain have focused on upstream processes with the goal of acquiring a stable and sustainable feedstock supply. The term upstream is commonly used to refer to supply chain echelons that deal with biomass from feedstock production and biomass storage to conversion plants; and downstream, to echelons from conversion plants, which are included in both upstream and downstream, to customers, including storage and transportation of biofuel.

A major thrust of prior research has focused on estimating the cost of each process in the biofuel supply chain. Several studies (Hamelinck et al., 2005b; Tatsiopoulos and Tolis, 2003) used economic analyses to estimate logistics costs for several types of biomass (e.g., crop and forest residues). Computer simulations of biomass logistics have been used successfully to estimate relevant measures such as costs, energy consumption, and carbon emissions (De Mol et al., 1997; Sokhansanj et al., 2006). Several related studies (Constantino et al., 2008; Murray, 1999) have optimized forest harvesting schedules, maximizing profit while contributing to sustainability and observing environmental regulations. Recently,

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Gnansounou and Dauriat (2010) reviewed the economic evaluation of lignocellulosic ETOH conversion processes.

A few studies have focused on improving conversion processes. Koch et al. (2010) proposed a simulation model to study the process of generating biogas from grass silage based on the International Water Association Anaerobic Digestion Model No. 1, which can deal with highly complex chemical process.

Some prior research has addressed strategic and tactical supply chain issues simultaneously. De Mol et al. (1997) formulated a single-period Mixed Integer Program (MIP) to prescribe facility openings (for collection, transshipment, pre-processing, and conversion); and logistics for a mix of biomass types (e.g., forest prunings, waste wood, and waste paper).

Several multi-period models have been proposed to deal with the changes that parameter values may undergo over time. Gunnarsson et al. (2004) formulated a multi-period MIP with a one-year planning horizon and monthly time periods to prescribe biomass supply alternatives (self-owned forests, contracted sawmills, and foreign sources), while limiting the use of low quality biomass. Another multi-period supply chain design model (Acharya et al., 2008) prescribed facility locations and material flows, considering dry mass loss in producing ETOH from corn and corn stover. Huang et al. (2010) developed a strategic planning model to determine the locations and sizes of new refineries, additional capacities added onto existing refineries, and material flows by year, providing a case study for waste biomass resources in California with a 10-year horizon.

Several studies deal with a one-year horizon. In 2009, Ekşioğlu et al. formulated a MIP that determines the number, size and location of collection facilities, biorefineries and blending facilities, and the amount of materials (i.e., biomass and biofuel) flows during multiple time periods with a case study in the State of Mississippi. Ekşioğlu et al. (2010) considered the transportation mode additionally. Zhu et al. (2010) proposed a MIP to prescribe locations of biomass storage and conversion facilities, modes of transportation from farms to refineries, and flows of biomass over a one-year planning horizon.

The biofuel industry is subject to uncertainty; for example, biomass yield and moisture content change as functions of weather conditions, and biofuel demand and price depend on the market environment. Cundiff et al. (1997) formulated a two-stage stochastic program to prescribe logistics for herbaceous biomass, considering the uncertainty of biomass yield due to weather conditions during growing and harvesting seasons. The first stage prescribes storage capacity; and the second, biomass transportation quantities. However, they dealt with neither the moisture content of biomass nor strategic-level decisions other than storage capacity.

To date, only Cundiff et al. (1997) have formulated a stochastic model to prescribe biofuel logistics; other researchers have focused on deterministic models. Even though a stochastic model is required to address the uncertainties that the biofuel industry faces, a comprehensive and accurate, multi-period deterministic model is a necessary first step and can lead to important insights about system operation and interactions among its components.

Each previous model has assumed that the technologies are predetermined, rather than incorporating decision variables to prescribe an optimal combination and did not consider the moisture content of biomass even though it comprises a large portion of biomass (e.g., 20–60% on a wet basis) and is a significant factor in planning transportation and preprocessing. In addition, while all previous models have held the objective of minimizing total cost while meeting all demands, in practice, unmet demands could be satisfied using compatible (i.e., petroleum-based) fuels.

This study enhances prior models by incorporating decision variables to select facility technology from among alternatives, practical features (e.g., effects of moisture content and dry matter loss), and intra facility structure (i.e., storage facility before and after process and processing facility) in preprocessing and conversion facilities. To our knowledge, only a few studies, even in generic supply chain studies, have considered such intra facility issues (Goetschalckx et al., 2002). Moreover, rather than using the assumption that any unmet demand must assessed a penalty cost, this paper proposes an objective of maximizing profit because petroleum-based fuels could fill biofuel shortfalls in the coming several decades while biofuel supply is being ramped up. A solution that maximizes profit can be much different from one that minimizes cost.

We formulate a deterministic, time-staged model to maximize total system profit by prescribing strategic-level decisions (e.g., facility locations, capacities, and technology types) as well as a strategic plan for material flows, including production, transportation, and storage levels. This study deals with biomass in the upstream and biofuels in the downstream as different (i.e., multiple) commodities, integrating feedstock suppliers, preprocessors, refineries, distributors, and customers. Our model can also be used at the tactical level for which the supply chain design has been fixed and short-term and, thus, more accurate-forecasts of demands, weather conditions, and other features are available to plan specific processing, transporting, and storage quantities, for example, in each month over a year-long planning horizon.

This study holds two primary research objectives. The first is to formulate a mathematical model to prescribe an optimal biofuel supply chain that allows use of various types of lignocellulosic biomass and deals with upstream and downstream material flows. The second is to apply the model in a case study to demonstrate its use in providing decision support for industry managers and government officials.

The body of this paper comprises three sections. Section 2 describes our mathematical model and discusses a case study based on a region in Central Texas. Section 3 analyzes impacts of several economic factors based on computational results and gives recommendation of future research. Finally, Section 4 gives conclusions.

2. Methods

2.1. System description

The biofuel supply chain system considered comprises five echelons: feedstock production, preprocessing, production in conversion plants, distribution, and consumption by customers, and including possible storage locations. Each facility can use one of several technology alternatives. For example, biomass can be stored using outdoor-uncovered, outdoor-covered, indoor-aerobic, or indoor-anaerobic technologies. Preprocessing technology could include size reduction, drying moisture content, or both. Moreover, conversion technology may involve a biochemical, a thermochemical, or a bio-thermochemical process. Even though improving technologies and efficiencies in each echelon is important, integrating technologies and coordinating echelons is necessary for the system to be most successful economically.

Materials flowing in the supply chain must be stored before being processed either at preprocessing or conversion facilities, and again stored as they wait to be transported after processing. While it is being stored at upstream locations, biomass degrades over time, losing some portion of its mass due to chemical reactions (e.g., fermentation and breakdown of carbohydrates) (Sokhansanj et al., 2006). The rate of dry matter loss in storage depends on the type of biomass, moisture content, and storage conditions.

Some feedstocks contain high moisture content and must be dried on the field immediately after harvesting and/or in a prepro-