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Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty

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ABSTRACT

Bio-fuels represent promising candidates for renewable liquid fuels. One of the challenges for the emerging industry is the high level of uncertainty in supply amounts, market demands, market prices, and processing technologies. These uncertainties complicate the assessment of investment decisions. This paper presents a model for the optimal design of biomass supply chain networks under uncertainty. The uncertainties manifest themselves as a large number of stochastic model parameters that could impact the overall profitability and design. The supply chain network we study covers the Southeastern region of the United States and includes biomass supply locations and amounts, candidate sites and capacities for two kinds of fuel conversion processing, and the logistics of transportation from the locations of forestry resources to the conversion sites and then to the final markets.

To reduce the design problem to a manageable size the impact of each uncertain parameter on the objective function is computed for each end of the parameter's range. The parameters that cause the most change in the profit over their range are then combined into scenarios that are used to find a design through a two stage mixed integer stochastic program. The first stage decisions are the capital investment decisions including the size and location of the processing plants. The second stage recourse decisions are the biomass and product flows in each scenario. The objective is the maximization of the expected profit over the different scenarios. The robustness and global sensitivity analysis of the nominal design (for a single nominal scenario) vs. the robust design (for multiple scenarios) are analyzed using Monte Carlo simulation over the hypercube formed from the parameter ranges.

1. Introduction

Lignocellulosic biomass is one of the most promising resources for biofuels. Among potential biofuels feedstocks, forestry sources have some of the best attributes in terms of feasibility and environmental sustainability, but the economic supply, transportation and processing of woody biomass source feedstocks to new biofuels processing infrastructure depends on many assumptions. Forecasts are currently very preliminary and understanding how uncertainties in price, technology, supply, and demand impact design decisions is important to reducing risk and uncertainty that limit investment.

Estimating supply and inventory of biomass feedstocks for biofuels is complex, and the quality of estimates varies by feedstock type. Inventory, technical and environmental constraints are spatially very variable and not consistently available at spatial scales finer than the county level. Estimating feedstock price is more complicated than gross potential supply and cost. This is because, although production and harvest cost components can be estimated, the interactions of a competitive market for fiber and other products from forestry with increased demands for feedstock from biofuels are opaque. This uncertainty mirrors how food prices react to increased demand for starch feedstocks for first generation ethanol production. Price and demand estimates for final fuel markets are uncertain because little current market data exists, significant policy intervention has been undertaken but future regulation is uncertain, and competing technologies such as increased fuel efficiency, hybrid and electric vehicles may reduce the overall demand for liquid fuels.

Overall, this creates a dauntingly complex landscape for decision-makers that wish to invest in emerging technologies in lignocellulosic biofuels. The complexity creates a need for tools to help assess which uncertainties will have the biggest impacts on technology and system design, and to help synthesize solutions that are robust to them. This study presents possible future directions of biofuel production, transportation, and logistics of the infrastructure for the lignocellulosic biofuel industry in the SE region of the US. To do this, we identify the key parameters which impact the infrastructure decisions, find optimized supply chain network designs under the key uncertainties, and verify that the

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uncertainties that are not considered in the design do not have a significant influence on the overall outcome.

Supply chain modeling and optimization for biomass and biofuel systems has been studied by companies and academic research groups alike in recent years. Supply chain design decisions influence the overall structure of the biofuel production network through capital investment, production technology and location choices. Logistics management involves medium to short-term decisions on the procurement of biomass and distribution of products. Decision models of increasing scope and sophistication have been devised, including an emphasis on the environmental performance and incorporating uncertainty. One type of model focuses on the supply element of the biomass processing chain. For decision support, a dynamic integrated biomass supply analysis and logistics model was developed to simulate the collection, storage, and transport operations of supplying agricultural biomass in Sokhansanj, Kumar, & Turhollow (2006). The issue of combining multiple biomass supply chains, aimed at reducing the storage space requirements, is introduced in Rentizelas, Tolis, & Tatsiopoulos (2009).

Geographical information systems (GIS) have been introduced to biomass supply chain studies in order to compute more accurately the expected supply of biomass in a given region and the transportation distances and related costs as well as to assess the impacts of spatial feedstock subtraction for different chain designs. A GIS-based decision support system for selecting least-cost bio energy locations when there is a significant variability in biomass farm gate price and when more than one bio energy plant with a fixed capacity has to be placed in the region was presented in Panichelli and Edgard (2008). A methodology using a GIS focused on logistics and transport strategies that can be used to locate a network of bioenergy plants around the region was developed to contribute by outlining a procedure for achieving an optimal use of agricultural and forest residue biomass (Perpina et al., 2009).

Beyond the configuration of the supply component of the chain is the production component that converts the biomass into fuel products. These models often include specific geographic regions in their analysis to test the model formulations. A combined production and logistics model was presented in Dunnet, Adjiman, & Shah (2008) to investigate cost-optimal system configurations for a range of technological, system scale, biomass supply and ethanol demand distribution scenarios specific to European agricultural land and population densities.

A mathematical programming model was proposed to design the supply chain and manage the logistics of a biorefinery, Eksioglu, Acharya, Leightley, & Arora (2009). The model determines the number, size and location of biorefineries needed to produce biofuel using the available biomass and the model was used for the State of Mississippi as a test case. A mixed integer linear programming (MILP) model was presented to determine the optimal geographic locations and sizes of methanol plants with heat recovery and gas stations in Austria, Leduc, Schwab, Dotzauer, Schmid, & Obersteiner (2008).

These static models can be extended to consider planning over multiple periods. A mathematical model that integrates spatial and temporal dimensions was developed by Huang, Chen, & Fan (2010) for strategic planning of future bioethanol supply chain systems. The planning objective is to minimize the cost of the entire supply chain of biofuel from biowaste feed-stock fields to end users over the entire planning horizon, simultaneously satisfying demand, resource, and technology constraints. This model is tested to evaluate the economic potential and infrastructure requirements for bioethanol production from eight waste bio-mass resources in California as a case study. The environmental aspects of the supply chain were integrated into a general modeling framework conceived to drive the decision-making process for the strategic design of biofuel supply networks as presented in Zamboni, Shah, & Bezzo (2009a), Zamboni, Bezzo, & Shah (2009b). The design task is formulated as a mixed integer linear program (MILP) that accounts for the simultaneous minimization of the supply chain operating costs (Zamboni et al., 2009a) as well a the environmental impact in terms of greenhouse gas (GHG) emissions (Zamboni et al., 2009b). The model is devised for the integrated management of the key issues affecting a general biofuel supply chain, such as agricultural practice, biomass supplier allocation, production site locations and capacity assignment, logistics distribution, and transport system optimization.

A number of studies have considered the uncertainties associated with supply chain network problems. Grossmann and Guillen-Gosalbez (2010) reviewed major contributions in process synthesis and supply chain management, highlighting the main optimization approaches that are available, including the handling of uncertainty and the multi-objective optimization of economic and environmental objectives. This paper emphasized there is a clear need to develop sophisticated optimization and decision-support tools to help in exploring and analyzing diverse process alternatives under uncertainty, and to determine optimal trade-offs between environmental performance and profit maximization. A dynamic spatially explicit mixed integer linear programming (MILP) modeling framework was devised to optimize the design and planning of biomass-based fuel supply networks according to financial criteria and accounting for uncertainty on market conditions (Mas et al., 2010). The model capabilities for steering strategic decisions are assessed through a real-world case study related to the emerging corn-based bioethanol production system in Northern Italy.

Aside from the biofuel network problem, there have also been efforts to address other alternative fuel network problems. The design problem for a hydrogen supply chain was addressed considering various activities such as production, storage and transportation (Kim et al., 2008)Kim, Lee, & Moon, 2008). The purpose of this study was to develop a stochastic model to take into account the effect of the uncertainty in the hydrogen activities and examine the total network costs of various configurations of a hydrogen supply chain in an uncertain environment for hydrogen demand. Another model was developed to consider the availability of energy sources (i.e. raw materials) and their logistics, as well as the variation of hydrogen demand over a long-term planning horizon leading to phased infrastructure development (Almansoori and Shah, 2009).

Given that many mathematical or computational models are being developed to design supply chain for biofuels, it is important to develop approaches to identify and incorporate a wide range of sources of uncertainty that can be coupled to these types of models. Good modeling practice requires sensitivity analysis (SA) to ensure the model quality by analyzing the model structure, selecting the best type of model and effectively identifying the important model parameters. Global sensitivity analysis (Sobol, 2001) can be used to identify the most important input parameters, and to understand the contributions of various parameter subsets to the overall objective variation.

In this paper, we formulate a general MILP model for a simple biorefinery network structure for single and multiple design scenarios. We start with a single nominal scenario 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 optimization model to design and analyze optimal network systems that process biomass into crude bio-oil and then to biodiesel, using a realistic data set covering the Southeastern region of the United States. We compute $\pm$ deviations of the profit of the optimized single scenario design using individual ranges on problem