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A stochastic programming approach towards optimization of biofuel supply chain

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A B S T R A C T

Bioenergy has been recognized as an important source of energy that will reduce dependency on petroleum. It would 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 challenges with supplying biomass to a biorefinery and shipping biofuel to demand centers. A stochastic linear programming model is proposed within a multi-period planning framework to maximize the expected profit. The model deals with a time-staged, multi-commodity, production/distribution system, facility locations and capacities, technologies, and material flows. We illustrate the model outputs and discuss the results through numerical examples considering disruptions in biofuel supply chain. Finally, sensitivity analyses are performed to gain managerial insights on how profit changes due to existing uncertainties.

1. Introduction

Energy can be considered to be at the center of environmental, economic and social analyses; it affects all three pillars of sustainability [1]. The use of fossil fuels to produce energy has induced both increased CO_2 concentration in the atmosphere and associated climate change and dependencies on politically sensitive international oil markets. These consequences have stimulated both considerable research on alternative energy sources and vigorous policy debates about policies to support them [2]. As a result of growing visible damage to the environment connected with the use of fossil fuels, biomass is increasingly becoming a topic in economic and political energy discussions. Also, the limitation of fossil fuels and the associated dependency on international energy markets make a change of view to the direction of an energy supply based on biomass increasingly necessary [3]. Biomass has the potential to become one of the major global primary energy sources during the next century, and modernized bioenergy systems are suggested to be important contributors to future sustainable energy systems and to sustainable development in industrialized countries as well as in developing countries [4].

Biomass can be used for the production of fuels, and chemicals with reduced life cycle (greenhouse gas) emissions. Currently, these fuels and chemicals are produced mainly from natural gas and other fossil fuels. In Western Canada, forest residue biomass is gasified for the production of syngas which is further synthesized to produce different fuels and chemicals. Two types of gasifiers: the atmospheric pressure gasifier (commercially known as SilvaGas) and the pressurized gasifier (commercially known as RENUGAS) are considered for syngas production [5]. Disadvantages of fossil fuel derived transportation fuels (greenhouse gas emissions, pollution, resource depletion, unbalanced supply demand relations) are strongly reduced or even absent with bio transportation fuels. Of all biofuels, ethanol is already produced on a fair scale (about 14–26 Mtonnes worldwide) and is easily applicable in present day ICEVs (internal combustion engine vehicles), as mixing with gasoline is possible [6].

Recent advances in computational tools have made it possible to build mathematical models for analysis and optimization of complex supply systems. These tools are applied successfully to manufacturing, transportation, and supply chain management of many goods and services [7]. This paper describes the implementation of these tools for simulation of supply and transportation of different types of biomass and finally producing of biofuel in refineries and distributing to demand centers. Further motivating factors regarding the attractiveness of biofuel

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production are the price history of crude oil and natural gas in recent years, as well as international efforts to reduce greenhouse gas emissions but emissions from transport are still growing. Moreover, technological advances and innovations in biofuel production, the past price developments of agricultural commodities and substitutes, as well as agricultural capacities are other drivers [8]. Ekşioğlu et al. [9] presented a summary of traditional biomass feedstock sources and conversion methods that can be used to produce biofuels that is shown in Fig. 1.

In this paper, a three echelon supply chain is considered to maximize the profit of biorefineries as focal firms of the study. Several types of biomasses are taken into consideration, which could be used to produce several types of biofuels. Biofuels could be produced via different types of technologies in biorefineries. In the third layer, several consumption markets are considered to satisfy demand of end users. A stochastic programming model is used to optimize tactical decisions in the proposed supply chain network. In order to cover dynamic aspects of a biofuel supply chain, the planning horizon proposed mathematical model includes several time periods in which a number of input parameters of the model are changed over the planning horizon. Moreover, a scenario-based stochastic programming is used to cover stochastic parameters of the problem while certain connection links between layers of the chain as well as some biomass fields might be disrupted. Prices of biofuels are assumed to be stochastic. Due to rapid fluctuations of price of biofuels, a geometric Brownian motion is used to model price uncertainties. According to above descriptions, this paper attempts to design an optimal supply chain network for biofuels covering both dynamic and stochastic issues.

The remaining of this paper comprises the following sections. In Section 2, a literature review of biofuel supply chains has been performed. Section 3 gives a summary of the problem description. This section describes our mathematical notations and model formulation and discusses a numerical example based on related references. Section 4 analyzes impacts of several economic factors based on computational results. Finally, conclusions and future directions are provided in Section 5.

2. Literature review

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 [10].

First group of previous studies are review papers in biofuel supply chain which comprises studies that focused on the supply element of the biomass processing chain. Berndes et al. [4] discussed the contribution of biomass in the future global energy supply. The discussion was based on a review of 17 earlier studies on the subject. Sims et al. [11] presented an overview of second generation biofuel technologies. The objectives were to examine the current state of technological development with emphasis on bio-ethanol, evaluate and compare the production costs, outline the policies necessary to best overcome constraints and support development and deployment; and determine the future challenges to be reached if full commercialization is to occur. A review of those academic works attempting to deal with problems arising within the bioenergy sector using MCDM (multi-criteria decision-making) methods is provided by Scott et al. [12]. These methods are particularly suitable to bioenergy given its multi-faceted nature but could be equally relevant to other energy conversion technologies. Related articles appearing in the international journals from 2000 to 2010 are gathered and analyzed. An et al. [13] provided a comprehensive literature review of research on the biofuel supply chain. They classified prior researches according to decision time frame as well as level in the supply chain. In addition, they reviewed related researches on agricultural products, which have some commonalities relative to harvesting and perishability; petroleum-based fuels, which have some commonalities related to distribution (some biofuels can be mixed with gasoline but others cannot); and generic supply chains, which provided some applicable modeling structures.

A number of previous studies which have attempted to optimize biofuel supply chains in deterministic environments exist. The integration of ethanol production with combined heat and power plants has been studied by Leduc et al. [14]. An energy balance process model has been used to generate data for the production of ethanol, electricity, heat and biogas. An optimization model has thus been used to determine the optimal locations for plants in Sweden. The entire energy supply and demand chain from biomass outtake to gas stations filling is included in the optimization. The results show that the biomass cost, biomass availability and district heating price are crucial for the positioning of the plant and the ethanol to be competitive against imported ethanol. In Ren et al. [15], a linear programming model has been developed for the design and evaluation of biomass energy system, while taking into consideration demand side characteristics. The objective function to be minimized is the total annual cost of the energy system for a given customer equipped with a biomass CCHP (combined cooling, heating and power) plant, as well as a backup boiler fueled by city gas. In Frombo et al. [16], a GIS (geographic information system)-based EDSS (Environmental Decision Support System) for the optimal planning of forest biomass use for energy production is presented. A user-friendly interface allows the creation of scenarios and the running of the developed decision and environmental models. Moreover, different energy products and different definitions of the harvesting and pretreatment operations are taken into account. Čuček et al. [17] presents an MCO (multi-criteria optimization) of regional biomass supply chains for the conversion of biomass to energy through the simultaneous maximization of economic performance and minimization of the environmental and social FPs (footprints).

Supply and costs of biomass feedstock sources are uncertain for a number of reasons. First, feedstock are agricultural products, in which 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 feedstock 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 feedstock are high as these products have high inventory holding costs because of their seasonality; 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, MSW (municipal solid waste), and perennial grasses, to produce bioenergy [9]. This paper considers both agricultural feedstock and lignocellulosic biomass to be used to produce biofuels (e.g. bioethanol).

A number of studies have considered the uncertainties associated with biofuel supply chain network problems. In a review