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Supply chain design under uncertainty for advanced biofuel production based on bio-oil gasification

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ABSTRACT

An advanced biofuels supply chain is proposed to reduce biomass transportation costs and take advantage of the economics of scale for a gasification facility. In this supply chain, biomass is converted to bio-oil at widely distributed small-scale fast pyrolysis plants, and after bio-oil gasification, the syngas is upgraded to transportation fuels at a centralized biorefinery. A two-stage stochastic programming is formulated to maximize biofuel producers' annual profit considering uncertainties in the supply chain for this pathway. The first stage makes the capital investment decisions including the locations and capacities of the decentralized fast pyrolysis plants as well as the centralized biorefinery, while the second stage determines the biomass and biofuels flows. A case study based on Iowa in the U.S. illustrates that it is economically feasible to meet desired demand using corn stover as the biomass feedstock. The results show that the locations of fast pyrolysis plants are sensitive to uncertainties while the capacity levels are insensitive. The stochastic model outperforms the deterministic model in the stochastic environment, especially when there is insufficient biomass. Also, farmers' participation can have a significant impact on the profitability and robustness of this supply chain.

1. Introduction

As a potential substitute for petroleum-based fuel, biofuels are playing an increasingly important role due to their economic, environmental, and social benefits. However, the 2007–2008 global food crisis was claimed to be related to biofuels production [1], and this food vs. fuel debate set barriers for first generation biofuels from consumable grain and lipids. Alternatively, second generation biofuels are produced from nonedible plant residues or dedicated energy crop, such as corn cobs, corn stover, switchgrass, miscanthus, and woody biomass. As a result, the feedstocks for second generation biofuels are less land and water intensive, which will not result in significant negative impact on the food market [2]. According to the revised RFS2 (Renewable Fuel Standard) established in 2007, at least 36 billion gallons per year of renewable fuels will be produced by 2022 in the U.S., of which at least 16 billion gallons per year will be from cellulosic biofuels [3]. However, the targeted cellulosic biofuel volume requirement for 2013 was revised to be only 14 million gallons, which is significantly lower than the original target. This is mainly due to the high capital investment and logistic challenges in cellulosic biofuel. The supply chain activities of harvest, collection, storage, preprocessing, handling, and transportation dealing with uncertainties represent one of the biggest challenges to the cellulosic biofuels industry. Thus, it is timely and meaningful to study the economic feasibility of the commercialization of cellulosic biofuel considering the supply chain design under uncertainties.

Biomass can be converted to transportation fuels through a variety of production pathways, including biochemical and thermochemical platforms. One example of biochemical pathways is corn ethanol production from fermentation. Another example is the thermochemical conversion of biomass to produce transportation fuels, which has recently moved to the forefront of biofuel research and development. Fast pyrolysis and gasification are two of the most prominent technologies for thermochemical conversion of cellulosic biomass.

Fast pyrolysis thermally decomposes organic compounds in the absence of oxygen, and the products include bio-oil, bio-char, and non-condensable gases [4]. Fast pyrolysis reactors typically run at temperatures between 400 °C and 600 °C and can produce approximately 70% (by weight) bio-oil [5]. The other 30% is split between non-condensable gases (e.g., carbon dioxide or methane) and bio-char. The non-condensable gases and bio-char could be combusted to provide heat for the facility. In addition, bio-char is

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mostly organic carbon which can be sequestered or gasified to produce syngas [6]. Bio-oil has three to five times the energy density of raw biomass [7]. However, due to the high viscosity and acidity, bio-oil needs to be upgraded to be used as transportation fuels. The bio-oil upgrading has proven to be a challenging process due to low conversion efficiency and fuel quality. Unlike fast pyrolysis, biomass gasification runs at a much higher temperature (800 °C-1300 °C) and is a relatively mature technology. The syngas produced from the biomass gasification process will typically go through the Fischer–Tropsch synthesis to produce liquid transportation fuels [1]. However, commercialization of biomass gasification has been hampered by its high capital and operating costs due to the challenges of transporting bulky solid biomass over a long distance, processing solid feedstock at high pressure, and removing contaminants from the product gas stream. The techno-economic analysis of biomass gasification by Swanson et al. claims that the minimum fuel selling price is $4–5 per gallon of gasoline equivalent and the capital investment requirement is $500–650 million for a 2000 metric tons per day facility [8].

It is thus necessary to reduce system cost and improve supply chain efficiency to improve the economic feasibility and competitiveness of the advanced biofuel production pathways. To reduce feedstock transportation cost, it has been suggested that biomass can be converted to bio-oil via fast pyrolysis near harvest sites, and then the bio-oil can be transported to an upgrading plant for transportation fuels production [9]. In this paper, the proposed hybrid production pathway is to combine the two prominent thermochemical production pathways. Biomass fast pyrolysis produces bio-oil in relatively small processing plants at distributed locations so that the transportation of bulky biomass over a long distance can be avoided. After mild hydrotreating, the bio-oil is then transported to a centralized gasification facility to produce transportation fuels. This pathway could also simplify syngas cleanup as ashes in biomass played a significant role in the gasification process [10]. It should be recognized that a centralized plant has advantages such as economies of scale, an inventory buffer storage reduction, and administration overhead cost savings [11].

One of the biggest challenges of the advanced biofuel production industry is the design of supply chain networks under uncertainties. There is rich literature on supply chain network design. Shah reviewed the previous studies in modeling, planning, and scheduling with some real world examples to summarize the challenges and advantages of supply chain optimization [12]. An et al. compared the supply chain research of petroleum-based fuel and biofuel [13]. Eksioglu et al. formulated a model to determine the numbers, locations, and capacities of the biorefineries, and conducted a case study for Mississippi in the U.S. to illustrate and verify the optimization model [14]. Nixon et al. used a goal programming model to deploy a pyrolysis plants supply chain in Punjab, India [15]. Most of the literature on biofuel supply chain design assumes all the parameters in the system are deterministic. However, the biofuel industry is highly affected by the uncertainties along the supply chain such as biomass supply availability, technology advancement, and biofuel price. For example, the biomass feedstock supply is highly dependent on biomass yield and farmers' participation. As a result, it is of vital importance to design the biofuel supply chain considering the uncertainties along the supply chain. Kim et al. considered a two-stage stochastic model using bounds of the parameters to determine the capacities and locations of the biorefineries [16]. Alex et al. formulated a mixed integer linear programming model to determine optimal locations and capacities of biorefineries [17]. Osmani et al. used stochastic optimization to deal with the uncertainties in biomass yield and price as well as biofuel demand and price [18]. Since thermochemical pathways to produce cellulosic biofuel is a relatively recent technology advancement, decentralized supply chain design have not been studied extensively, especially scenario under uncertainties. This paper aims to provide a mathematical programming framework with a two-stage stochastic programming approach to design the supply chain network considering uncertainties along the supply chain. The production pathway under consideration is bio-oil gasification, with bio-oil production from biomass fast pyrolysis at decentralized facilities and syngas production and fuel synthesis in a centralized gasification facility. This model provides methodological insights for decision makers on the capital investment decisions and logistic decisions for the biofuel supply chain.

The remainder of the paper is organized as follows: in Section 2, the problem statement for the biofuel supply chain design is presented. Then, we discuss the deterministic mixed integer linear programming model and the two-stage stochastic programming models in Section 3. A case study of Iowa is conducted to illustrate and validate the optimization model in Section 4. Finally, we conclude the paper in Section 5 with a summary and potential research directions.

2. Problem statement

As mentioned, one of the most important decisions faced by the biofuel industry is the design of the supply chain networks, especially under system uncertainties. This provides the major motivation for this study.

The supply chain system schematics for the bio-oil gasification pathway are shown in Fig. 1. Biomass is collected and consolidated at the county level. Biomass is then transported to the decentralized fast pyrolysis facilities to be converted to bio-oil. Mild-hydrotreated bio-oil is transported to a centralized gasification facility to produce transportation fuels. It is assumed that each biomass feedstock supply location/county can serve multiple fast pyrolysis facilities, and that each fast pyrolysis facility can acquire feedstock from multiple biomass supply locations. The locations for the decentralized fast pyrolysis facilities and centralized gasification facility are assumed to be the centroids of counties.

The supply chain network design of biofuel production is highly affected by uncertainties along the supply chain such as biomass supply availability, technology advancement, and biofuel price. The biomass supply availability is highly dependent on crop yields and farmers' participation, the conversion rates are affected by technology advancement and operating conditions, and the biofuel price would change based on market conditions and enacted policies. Thus, it is of vital importance to make the supply network design decisions with system uncertainties taken into consideration. Stochastic programming is one of the most widely used modeling frameworks to study decision making under uncertainties.

The goal of this paper is to provide a two-stage stochastic programming framework for the biofuel supply chain optimization problem considering uncertainties. The comparison and analysis of the results provide methodological suggestions on capital investment and logistic decisions. The insights derived from this study can contribute to the body of knowledge in decision making under uncertainties.

3. Model formulation

The deterministic and stochastic models for this biofuel supply chain design problem are introduced. The objective is to maximize the annual profit for biofuel producers based on the hybrid production pathway of bio-oil gasification. The deterministic mixed integer linear programming model is firstly introduced as a