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A hybrid decomposition algorithm for designing a multi-modal transportation network under biomass supply uncertainty

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A B S T R A C T

This study presents a two-stage stochastic programming model for the design and management of a biomass co-firing supply chain network under feedstock supply uncertainty. To represent a more realistic case, we generate scenarios from prediction errors of the historical and forecasted biomass supply availabilities. We solve the model using a hybrid decomposition algorithm that combines Sample average approximation with an enhanced Progressive hedging algorithm. The proposed algorithm is validated via a real-world case study using data from Mississippi and Alabama. Computational results indicate that the proposed algorithm is capable of producing high quality solutions in a reasonable amount of time.

1. Introduction

Co-firing biomass with coal has been receiving extensive attention from the energy community due to the several added benefits of the process. First, co-firing biomass reduces green house gas (GHG) emissions due to its displacing coal with biomass (Demirbas, 2003). Second, biomass co-firing can be accomplished using the existing coal-fired power plant infrastructures. Therefore, no additional capital investment is required. Third, co-firing minimizes waste such as wood and agricultural waste and the environmental problem associated with its disposal (Roni et al., 2014). On the contrary, few studies (Karimi et al., 2014; Roni et al., 2014), address some limitations of co-firing biomass with coal: (1) co-firing biomass reduces boiler efficiency and eventually the overall systems efficiency; (2) biomass has lower heating and density values, both of which are undesirable from a production point of view; and, (3) biomass supply is dispersed geographically, adding logistical challenges. This study explores some of the logistical challenges in the biomass supply chain system that will help the managers take better decisions.

The efficiency of co-firing biomass depends on how economically the biomass is transported from the feedstock supply points to the coal plants. This process necessitates developing an integrated logistics network that efficiently connects origin fields to destination coal plants with proper transportation modes. However, designing such a network is challenging due to the physical characteristics of biomass. Biomass is bulky and difficult to transport; its supply is highly seasonal and uncertain; and biomass is widely dispersed geographically. Therefore, modes such as rail can be considered as the viable modes of transportation to deliver biomass from feedstock suppliers to coal plants. However, the operations in multi-modal facilities can be highly impacted by the seasonality of biomass. For instance, the harvesting season for corn stover follows the harvesting of corn which starts from early September and ends in November. On the other hand, woody biomass is available all year

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except three months in the winter. In addition to the feedstock seasonality, it is observed that the biomass supply fluctuates extensively from one year to another. This statement is supported by Fig. 1 which shows the fluctuation of cornstover availability in the four states Mississippi (MS), Alabama (AL), Tennessee (TN), and Louisiana (LA) in Southern United States over 1980–2014 (The U.S. Department of Agriculture, 2015). The figure shows that the availability of biomass cannot be predicted accurately. The biomass supply fluctuates highly from one time period to another depending on climatic conditions such as rain, temperature, and humidity along with other extreme events such as, natural disasters and human intervention (Persson et al., 2009). This poses a significant logistics challenge in the network and highlights the need for developing optimization models to design a cost-efficient, reliable biomass co-firing supply chain under feedstock supply uncertainty.

The study of the biomass supply chain optimization has increased rapidly in recent years. We group the existing literatures into deterministic and stochastic research to reflect the contribution of our modeling and algorithmic approaches used in this paper. Studies conducted by Zamboni et al. (2009), Eksioglu et al. (2009, 2010), Huang et al. (2010), An et al. (2011), Bai et al. (2011), Walther et al. (2012), Xie and Ouyang (2013), Awudu and Zhang (2013), Roni et al. (2014), Xie et al. (2014), and Memisoglu and Uster (2015) analyze plant location and transportation issues in biofuel supply chain networks under a deterministic setting. These studies are further extended to consider a case when the disruption in bio-refineries (e.g., Li et al., 2011; Wang and Ouyang, 2013; Bai et al., 2015) or in multi-modal facilities (e.g., Marufuzzaman et al., 2014; Marufuzzaman and Eksioglu, 2016) or in the links between the multi-modal facilities (e.g., Poudel et al., 2016) impact the biofuel supply chain network. Another stream of research in bio-fuel supply chain community develops multi-objective optimization model that not only minimizes cost but also minimizes Green House Gas (GHG) emissions from the supply chain network (e.g., Zamboni et al., 2009; Giarola et al., 2011; You et al., 2012).

All the studies discussed above assume that the model input parameters (e.g., biomass supply, demand, technology) are known and thus fail to capture the impact of system uncertainties in the biofuel supply chain network configuration. To represent a more realistic case, studies conducted by Cundiff et al. (1997), Kim et al. (2011), Chen and Fan (2012), Gebreslassie et al. (2012), Awudu and Zhang (2013), and Marufuzzaman et al. (2014) account uncertainties in biomass supply, demand, technology, and pricing. A brief overview of considering uncertainty and sustainability in a biofuel supply chain network can be found from a recent study by Awudu and Zhang (2012). Although both the deterministic and stochastic models have done a great job in capturing the overall system level design, the models did not explicitly consider the option of using long haul transportation modes such as rail or barge as a viable mode of transportation to carry biomass from multi-modal facilities to bio-refineries except the studies from Marufuzzaman et al. (2014), Roni et al. (2014), and Marufuzzaman and Eksioglu (2016). Introducing multi-modal facilities in the bio-fuel supply chain network not only reduces cost but also alleviates congestion in the highways and as a result improves safety. The case became much stronger after Idaho National Laboratory proposed a biomass delivery system that preprocess biomass prior to transporting (Hess et al., 2009). Densified biomass has physical characteristics which are similar to corn, soybean and other grains; therefore, it is easy to load/unload and transport, and thus long hauls become an option. Recent studies by Marufuzzaman et al. (2014), Roni et al. (2014), and Marufuzzaman and Eksioglu (2016) captured this specific product information in the modeling framework and identified the viability of using multi-modal facilities in a bio-fuel supply chain network. Our model can be considered as a direct extension of these studies in the sense that we captured feedstock uncertainty in a multi-time period problem to transport biomass from feedstock supply sites to coal-plants.

Although stochastic programming approaches provide more reliable solutions, they are often achieved with high computational burden. Commercial solvers fail to solve the model directly for even a small set of scenarios for most of the real life

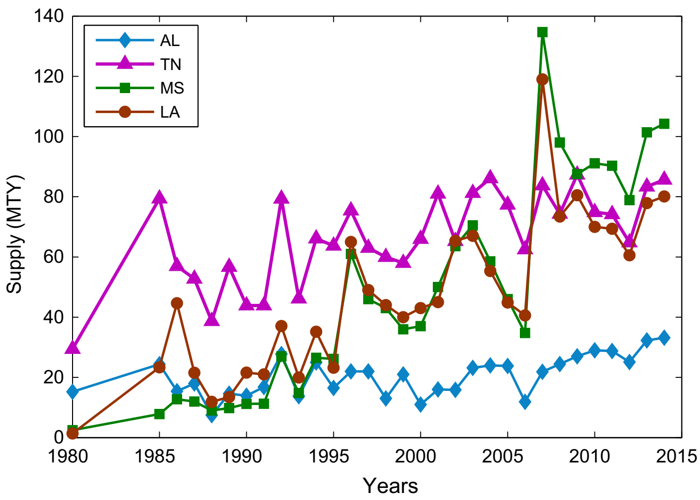

Fig. 1. 1980–2014 cornstover supply fluctuation (The U.S. Department of Agriculture, 2015).