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Sustainable network design for multi-purpose pellet processing depots under biomass supply uncertainty

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ABSTRACT

This study develops a two-stage stochastic mixed-integer programming model to manage multi-purpose pellet processing depots under feedstock supply uncertainty. The proposed optimization model would help to minimize cost and mitigate emissions from the supply chain network. We consider three alternative Biomass Processing and Densification Depot (BPDD) technologies; namely, conventional pellet processing, high moisture pellet processing, and ammonia fiber expansion. These three technologies pre-process/pre-treat and densify different types of biomass into more highly densified intermediate products for different markets in order to improve movability and overall supply network performance in terms of costs and emissions. A hybrid decomposition algorithm was developed that combines Sample Average Approximation with an enhanced Progressive Hedging (PH) algorithm to solve this challenging $\mathcal{NP}$-hard problem. Some heuristics such as Rolling Horizon (RH) heuristic, variable fixing technique were later applied to further enhance the PH algorithm. Mississippi and Alabama were selected as a testing ground and ArcGIS was employed to visualize and validate the modeling results. The results of the analysis reveal promising insights that could lead to recommendations to help decision makers achieve a more cost-effective environmentally-friendly supply chain network.

1. Introduction

Bioenergy is considered to be a substitute source of energy that is necessary to help alleviate the reliance on petroleum energy. For decades, U.S. bioenergy production has depended heavily on conventional biomass supply systems. However, the current volatility in the crude oil market and the recent shutdown of some cellulosic bio-fuel plants necessitate the development of a more sustainable feedstock for future bio-economy growth. Feedstock can be defined as any renewable biological material including forest residue (wood), agricultural residue (corn-stover), and energy crops (switchgrass, miscanthus, sorghum). Feedstock developed for bioenergy could be made more sustainable if it had the flexibility to serve multiple markets in addition to bioenergy. Such markets could be bio-refineries, coal industries, pulp and paper industries, and animal feed markets (Bruglieri & Liberti, 2008; Vogel, Schmer, & Mitchell, 2010).

To develop a wide range of sustainable feedstocks, a biomass processing densification depot must be established in order to achieve a cost-effective outcome with the least risk. A Biomass Processing Densification Depot (BPDD) is a facility where biomass is densified into a stable feedstock to be supplied to larger facilities for energy production (Chai & Saffron, 2016; Parkhurst, Saffron, & Miller, 2016). BPDDs aggregate, store, moderately process and densify the biomass prior to delivering it to the bio-fuel markets. Although BPDD goals include such things as improving movability, derisking bio-refineries, increasing accessible resources, and enhancing quality control, the primary concerns of a BPDD system are to reduce material loss and to convert the low density biomass into a more stable, more densified product so that it can be transported over a much longer distance in a cost effective way (Eranki, Bals, & Dale, 2011; Rudolfsson, Stelte, & Lestander, 2015). Due to the diverse characteristics of biomass, various processes like grinding, densification, aggregating and mixing inside the depot produce a more uniform commodity that can be delivered to various markets in order to standardize the supply system. BPDD systems also increase the per acre utilization of biomass and enhance the usability of direct and indirect land use (Eranki et al., 2011). However,

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the seasonality and the yield variation of the biomass will directly impact the operation of a depot. For instance, the harvesting season for corn-stover starts in early September and ends in November, while woody biomass and miscanthus are available year round, except for three months in the winter. This seasonality not only impacts the operation of depot facilities for a given time period of the year but also affects the overall biomass supply chain activities. To address this challenge, supply chain managers need optimization models to decide where to locate depots and how to serve multiple markets (e.g., biorefinery, coal plants, pulp and paper industries, animal feed industries) under feedstock supply uncertainties. Three main alternative depots were identified to pre-process, treat, and densify different types of biomass into more highly densified intermediate products for different markets. The three main alternative depots are: conventional pelleting process, high moisture pelleting process, and ammonia fiber expansion.

Conventional Pelleting Process (CPP) and *High Moisture Pelleting Process* (HMPP) are conducted at standard depots whereas *Ammonia Fiber Expansion Process* (AFEX) is carried out at quality depot. A standard depot increases feedstock stability and storability and reduces material loss. In addition to the standard depot functions, a quality depot contains various processing steps such as chemical treatment, washing, hydrolysis, and leaching which help to reduce the pretreatment requirements at a client facility (Lamers et al., 2015). In a conventional pelleting process, pellets are reduced from their initial size to less than 50 mm rotary dried, and then sent for grinding to decrease particle size to less than 5 mm to meet particle size distribution requirements for pelleting (Lamers et al., 2015). Fig. 1 illustrates the steps involved in a conventional pelleting process (Lamers et al., 2015). CPP is selected to process forest residue that is transported to the depot in chip format (2–3 in.) for course size reduction through first stage grinding.

In a high moisture pelleting process (HMPP), high-moisture (30–35% MC) biomass is preheated and pelletized. In order to increase stability and reduce moisture content, final pellets are dried in a vertical grain dryer. These moderately dried pellets still contain high moisture content and require further drying so the moisture content falls below 9% to ensure safe storage and transportation. Fig. 2 illustrates the various unit operations associated with each step of HMPP (Lamers et al., 2015). An HMPP depot is suitable to handle the high moisture generated from herbaceous biomass (e.g., corn-stover, miscanthus) since it comes to the depot in a bale format.

The Ammonia Fiber Expansion (AFEX) process is fundamentally a dry to dry process since there is no watercourse produced during pretreatment (Teymouri, Laureano-Perez, Alizadeh, & Dale, 2005). AFEX ensures a higher conversion of different kinds of cellulosic biomass. Fig. 3 demonstrates the various unit operations associated with each step in a quality depot (Lamers et al., 2015). In the proposed model, the AFEX depot is selected to process corn-stover and miscanthus since AFEX pretreatment increases the glucan and xylan conversion making the biomass more attractive as a product for the animal feed market.

1.1. Related research

This section pursues two primary objectives. First, the current themes in the *biomass supply chain literature* are identified. The intent is to show some of the related methods used in biomass supply chain network and present the general thread running through these methods. Second, two main gaps are addressed in the literature. The focus is to address these two gaps by developing a two-stage stochastic mixed-integer linear programming (MILP) model

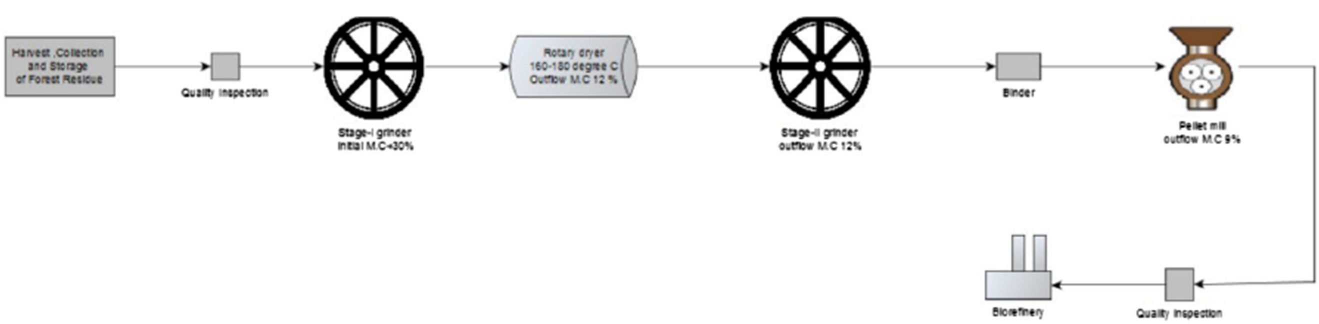

Fig. 1. Conventional Pelleting Process (CPP) flow diagram.

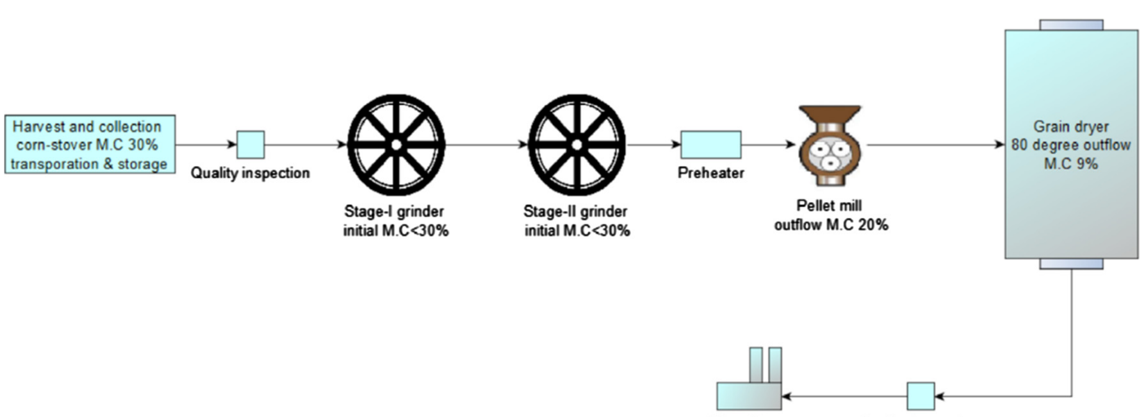

Fig. 2. High Moisture Pelleting Process (HMPP) flow diagram.