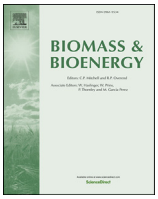
Biomass and Bioenergy 97 (2017) 116–131

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe



Research paper

Resiliency optimization of biomass to biofuel supply chain incorporating regional biomass pre-processing depots

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ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form
1 November 2016
Accepted 16 December 2016

Keywords:
Biomass supply chain
Disruption
Resiliency
Optimization
Pre-processing
Biorefinery
Cost analysis

ABSTRACT

Biomass to biofuel supply chain is subject to several potential disruptions such as flood, drought, pest attack, and equipment failure. These disruptions must be considered while designing the supply chain; especially if capital cost intensive components such as regional biomass pre-processing depots (RBPD) are to be implemented. This work develops a supply chain design optimization model that incorporates the possibility of such disruptions at the design stage. The objective function is the sum of the total cost incurred during the non-disruption and disruption scenarios weighted by their respective probability of occurrence. This also quantifies the expected disruption cost (EDC) on the operation of the supply chain. The decision variables are the locations and capacities of RBPDs and biorefinery, as well as the biomass flow across the supply chain. The model was applied to two separate case studies, namely, procurement of corn stover from farms arranged in a generic grid pattern, and procurement of corn stover, switchgrass, and Miscanthus for a region of thirteen counties in Southern Illinois. The simulation results showed that the consideration of resiliency in design reduced the EDC of supply chain by up to 38% by optimizing the RBPD locations. The results were shown to depend on the intensity and nature of disruptions. This was especially true for feedstock with higher yield such as Miscanthus. Local parameters such as yield and biomass price also affected the optimal results. Moreover, the presence of RBPDs was shown to increase supply chain resiliency.

1. Introduction

Biofuels, especially those produced from lignocellulosic biomass feedstock such as agricultural residue, forestry residue or dedicated energy crop, are expected to play a key role in the drive towards sustainable energy [1,2]. As part of the Renewable Fuel Standard (RFS) mandate of the Energy Independence and Security Act (EISA) of 2007 [3], 16 billion gallons per year of cellulosic biofuels need to be produced in the USA by 2022. Subsequently, the feasibility of providing the necessary lignocellulosic biomass was studied [4]. Similarly, the National Biofuel Policy of India has set a target of 20% blending of ethanol in gasoline by 2017 [5]. However, even as the production of lignocellulosic biofuels is being scaled up globally [6], several challenges related to biomass production and procurement, such as low energy and bulk density, highly distributed availability, and seasonal supply, need to be overcome for economically viable production [7,8]. These challenges create unique hurdles that are different from the other traditional supply chains [9]. This is especially true for a country like India, for example, where the biomass availability is highly distributed and supply at each point is very small [10]. Therefore, improving the supply chain of biomass procurement is very critical.

In this context, the concept of regional biomass pre-processing depot (RBPD) has generated much interest [11,12]. RBPDs are theoretically meant as collection and storage depots for the biomass from farms in a particular region [11,12]. They may also perform mechanical and/or chemical operations on the biomass to improve the storage and transportation efficiency [13–16]. Lin et al. [17,18] have proposed the use of centralized storage and pre-processing centers (CSPs), which are conceptually similar to the RBPDs. A typical biomass to biofuel supply system incorporating RBPDs consists of three stages (Fig. S1 in supplementary information):

1 Farms or supply points where biomass is produced or available.

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http://dx.doi.org/10.1016/j.biombioe.2016.12.015
0961-9534/

2 RBPDs receiving the feedstock from farms or supply points and processing it.
3 Biorefinery where unprocessed biomass from farms or processed biomass from RBPDs is converted into biofuel.

At RBPDs, both chemical and mechanical pre-treatment can be undertaken, which is expected to provide several benefits [11,12]. First, the pre-treatment standardizes the biomass and makes it a tradable commodity. The economy of scale reduces the per unit processing cost at the RBPDs. Moreover, the processing is expected to increase the bulk density, and thereby improve storage, transport and handling efficiency. The biomass can subsequently be transported to longer distances more efficiently. Hess et al. [12] have predicted that such a supply system could provide biomass feedstock at 33.07 $/dry Mg (30 $/dry ton) in the USA. Kim and Dale [13] found that a corn stover collection system with AFEX processing at the RBPDs and railroad transport became cost effective after 12,000 Mg/d capacity of the biorefinery as compared to centralize processing. Eranki and Dale [16] showed that use of RBPDs reduced the total greenhouse gas emissions by 3.7% as compared to a centralized processing system for collecting switchgrass and Miscanthus. Carolan et al. [15] showed that an RBPD could become feasible for a gross margin of 3.66–34.97 $/Mg (3.32–31.72 $/ton) depending on the size of the RBPD and the value attached to the byproduct. Bals and Dale [14] showed that pyrolysis was the most economic pre-processing for an RBPD of 7000 Mg/yr corn stover throughput. Another advantage of an RBPD is its function as an efficient satellite storage location providing biomass during non-harvesting seasons.

However, these benefits are subject to certain factors. Since there are multiple storage locations and long distance transportation involved, an efficiency factor is introduced at every step as far as the complete transfer of material is involved. Losses of dry matter, thus, get compounded. Under-utilization of equipment is another issue as biomass availability is seasonal and the RBPDs incur extra maintenance costs without any revenue during the off-season. RBPDs are also plagued by low total capacity if they handle only a few biomass sources from nearby locations. The equipment and technologies used for processing are generally highly capital-intensive and are not quite profitable for small capacities [11]. Optimizing the locations and capacities of the RBPDs is, therefore, important to achieve the expected benefits. This requires the optimization of the biomass supply chain design.

In supply chain design optimization, the objective is to optimize the locations of supply points, warehouses, and consumption points to achieve a specific objective such as cost or loss minimization or profit maximization. Biomass to biofuel supply chain optimization has been studied by Shastri et al. [19,20], including optimization of the supply chains incorporating RBPDs [21]. While Shastri et al. [21] optimized the capacity but not the RBPD locations, Lin et al. [22] optimized the size and location of the RBPDs for a Miscanthus supply chain in Illinois, USA for increasing regional production over a 15 year time horizon. Recently, Lin et al. [23] have extended that work to study the efficacy of RPBDs to enable long distance transportation of biomass.

While the cost efficiency of the biomass supply chain has been frequently optimized, the effect of potential natural or mechanical disruptions on the supply chain has not received much attention. Biomass production is subject to vagaries of the nature. Natural events such as flood, drought, and pest attacks can adversely impact the seasonal production, and therefore the biofuel systems [24]. These disruptions can affect biomass availability due to two reasons:

- The disruption could occur during the early part of the growing season, leading to complete crop failures. For example, floods, droughts, and cyclones have severely damaged crops in India in the past, leading to lack of harvestable material [25].
- The disruption may occur during harvesting season, restricting the ability to harvest on time. ASABE [26] reports the probability of working day (pwd) data for different regions of the USA. The pwd data show that harvesting is very difficult in winter months (December–February) in Illinois. Yet, agronomy literature recommends harvesting between December–March for optimizing yield, moisture and nutrient content [27,28]. Similarly, floods in summer in Illinois have been known to delay corn harvest, which will affect the availability of corn stover.

These disruptions can impact the supply chain performance through missed demands, quality losses, and overall revenue loss [29,30]. Additionally, disruptions common to most supply chains such as breakdown of equipment and transport infrastructure will also affect the biomass to biofuel supply chain. Therefore, developing a resilient supply chain that can handle these disruptions effectively is critical.

The objective of this work is to develop a biomass to biofuel supply chain model that balances cost efficiency and resiliency. An optimization model considering RBPDs that explicitly incorporates resiliency in the objective function is developed. Resiliency is quantified in the form of expected disruption cost. Some disruptions in the form of droughts or floods are modeled and the changes in supply chain design with and without the consideration of resiliency are highlighted.

The article is arranged as follows. The next section highlights the importance of resiliency and briefly summarizes prior literature on supply chain resiliency. Section 3 presents the optimization model details. Section 4 describes the case studies considered for model application, and section 5 reports the simulation results. The final section summarizes the conclusions and future extensions.

2. Resiliency

Resiliency is defined as a property of the system [31,32]. A resilient system is better prepared to handle the expected variability and disruptions effectively so as to minimize losses. Bruneau et al. [33] have mentioned four dimensions of resiliency, namely, robustness, redundancy, resourcefulness, and rapidity. Soni et al. [34] have identified top enablers of resiliency based on feedback from experts.

Supply chain resiliency has been a topic of extensive research in the recent past. This includes identification of appropriate measures of quantification as well as incorporation of those measures in a modeling, simulation and/or optimization framework for decision making. It has been recognized that supply chain resiliency can be improved through design optimization. Thus, in addition to economic criterion, incorporation of resiliency as a performance measure in supply chain design optimization can provide substantial benefits. Recent examples of the application of this approach include Jeong et al. [35] who designed an emergency logistical network based on efficiency, risk and robustness. Huang and Pang [29] have incorporated resiliency in the biofuel systems. There have been several other studies of supply chain design resiliency optimization [36–39].

Meepetchdee and Shah [40] have defined the resilience metric in their generalized manufacturing model based on the percent of the actual demand met, and averaging the metric over several individual component failures. Shukla et al. [41]. have elucidated a concept of the Expected Disruption Cost (EDC) faced in case of a disruption in the normal functioning of the system, and presented a