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An exact solution approach based on column generation and a partial-objective constraint to design a cellulosic biofuel supply chain

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ABSTRACT

This study provides an exact solution method to solve a mixed-integer linear programming model that prescribes an optimal design of a cellulosic biofuel supply chain. An embedded structure can be transformed to a generalized minimum cost flow problem, which is used as a sub-problem in a column generation approach, to solve the linear relaxation of the mixed-integer program. This study proposes a dynamic programming algorithm to solve the sub-problem in $O(m)$ time, generating improving path-flows. It proposes an inequality, called the partial objective constraint, which is based on the portion of the objective function associated with binary variables, to underlie a branch-and-cut approach. Computational tests show that the proposed solution approach solves most instances faster than a state-of-the-art commercial solver (CPLEX).

1. Introduction

This paper proposes an exact method to prescribe cellulosic biofuel supply chain design (BSCD), which involves determining facility locations, capacities, and technology types as well as a strategic plan for material flows related to production, transportation, and storage, allowing use of various types of cellulosic biomass. This work is motivated by the fact that cellulosic biomass, the feedstock for second-generation biofuels, offers promise to ameliorate concerns about food-price increases that may have resulted from use of first-generation feed stocks, which are edible crops (e.g., corn, sugar cane) and provide sustainable supply of energy, reducing greenhouse gas (GHG) emissions. However, such feedstock faces unique challenges: it has low energy density and high moisture content, is geographically dispersed, is harvested in specific seasons but must fulfill year-round demand, and loses dry-matter mass in storage. A method that can accommodate these challenges in designing the most profitable biofuel supply chain is vital to the economic viability of this emerging industry. The research objectives of this paper are a BSCD model that deals with the unique features of cellulosic biomass; an effective, exact solution method to solve large-scale instances; and a computational evaluation to benchmark our solution approach with the state-of-the-art, mixed-integer programming commercial solver CPLEX 12.1.

Fig. 1 depicts alternative locations in each of the five echelons of the biofuel supply chain, including feedstock supply, preprocessing, conversion in refineries, distribution, and consumption in customer zones. The term *upstream* refers to echelons that deal with biomass from suppliers to conversion plants; and *downstream*, to echelons that deal with biofuel from conversion plants to customers. Conversion plants themselves are included in both upstream and downstream. Fig. 1 also depicts possible upstream storage locations. An appropriate technology must be prescribed for each facility, depending upon its echelon. For more detail, we refer the reader to our recent studies (An et al., 2011b; An and Searcy, 2012).

BSCD has begun to attract considerable attention. Huang et al. (2010) proposed a multi-period model and applied it in a case study involving the use of waste biomass in California. Their model prescribes locations and capacities of new refineries and material flows from farms to end users over a year-long planning horizon. Ekşioğlu et al. (2010) formulated a multi-period mixed-integer program (MIP) for BSCD, using corn and corn stover biomass, to optimize the network design, modes of transportation, and material flows from feedstock suppliers to end users. Zhu et al. (2010) proposed a MIP to transport switch grass from farms to refineries, prescribing locations of biomass storage and conversion facilities, modes of transportation from farms to refineries, and flows of biomass over multiple time periods. For more detail, we refer the reader to our recent review (An et al., 2011a).

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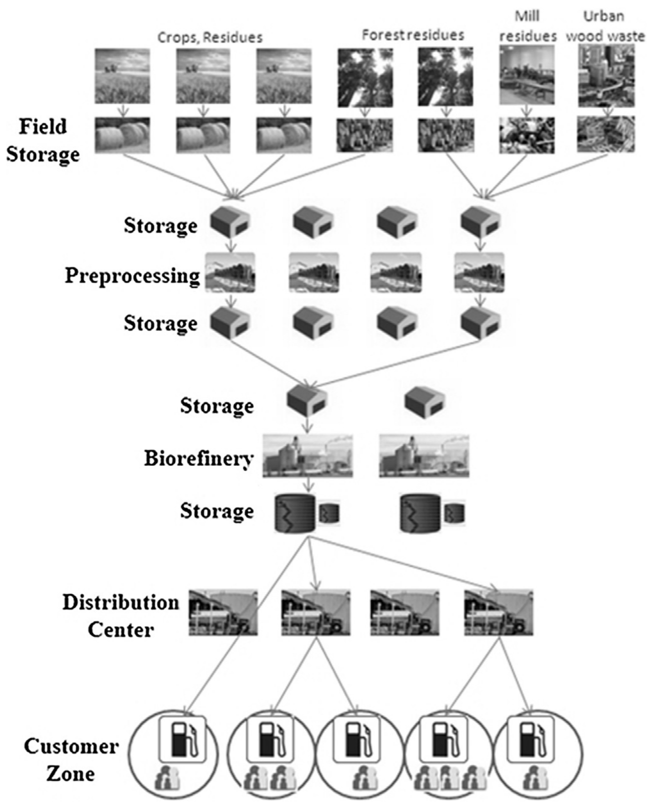

Fig. 1. The biofuel supply chain depicting alternative locations in each echelon.

In particular, this paper presents a BSCD modeling alternative to An et al. (2011b), which formulated a deterministic, time-staged, multi-commodity flow model and demonstrated managerial use in application to a region in Central Texas. Their formulation addressed several unique features of cellulosic feed stocks (e.g., high moisture content, dry matter loss in storage facilities, and single destination for feedstock supply), dealing with commodity-type changes (e.g., biomass with moisture before preprocessing to dry matter afterwards and dry biomass conversion to biofuel) in multi-commodity flow. Their model, as well as the new one we propose, can be used by managers to design profitable supply chains and by government officials to evaluate policies. In contrast to this paper, An et al. (2011b) did not propose any solution methodology; they simply applied CPLEX in their case study.

We solve our BSCD model using a column-generation (CG) decomposition approach to solve its linear relaxation at the root node by exploiting an embedded generalized network flow problem (GFP). In this CG context, we propose a backward-reaching, dynamic programming algorithm (BRA) to solve an uncapacitated, embedded GFP as a sub-problem, generating improving path-flows (i.e., columns) effectively in $O(m)$; the master problem prescribes optimal flow quantities, imposing flow bounds and other side constraints. In addition to the embedded GFP, our BSCD model involves many binary variables. To reduce runtime, we propose an inequality, a *partial objective constraint* (POC), based on the portion of the objective function associated with binary variables.

This paper is organized in four sections. Section 2 describes our BSCD model, an alternative to the multi-commodity flow model proposed by An et al. (2011b). Section 3 explains our solution methods, CG and POCs. Section 4 evaluates the performance of our solution approach through computational tests. Finally, Section 5 gives conclusions and recommendations for future research.

2. Mathematical modeling

Our earlier BSCD formulation (An et al., 2011b) deals with multi-commodity material flows, defining each commodity in the upstream as the combination of biomass type and moisture content, which depends on location and time period. In comparison, the present paper deals with a single commodity, downsizing the An et al. model and, therefore, enhancing solvability (i.e., improving the ability to be solved or, more commonly, allowing reduced run time). This section describes a two-step procedure to define each commodity and the network that represents flows, then presents our model.

We employ two devices that allow all flows to be modeled as a single commodity. The first device eliminates moisture content from biomass flows. To describe this device, let T denote the tonnage of a particular type of biomass that is harvested in a given time period and C denote the cost to transport a ton of biomass, so the total cost of transporting the harvest is CT. If the moisture content (portion by weight) of this harvest is ϕ, the dry-matter tonnage is $(1-\phi)T$. We model the flow of only dry matter, because it provides all of the biomass energy content. To compensate for transporting a lesser tonnage, we adjust transport cost per ton to $C/(1-\phi)$. These two viewpoints are equivalent because they result in the same total transportation cost: $[C/(1-\phi)][(1-\phi)T] = CT$.

The second device models the flow of energy content. Each type of (dry-matter) biomass may provide unique energy content, and tonnages can be converted appropriately into units of energy. A unit of energy that is harvested travels through the supply chain but is reduced by the amount of dry matter loss in storage and by the efficiency of the conversion technology employed. For example, if a harvested unit of energy is subject to a loss of portion $(1-h_1)$ in storage and the efficiency of the conversion process is h_2, the unit of flow that leaves the field provides a supply of less than a unit of energy at the gas pump: h_1h_2. Notice that h_1 and h_2 depend upon technologies used for storage and conversion, respectively.

We can now model the flow through the biofuel supply chain as a GFP on an acyclic graph as depicted in Fig. 2. Because the upstream flow structure for each type of biomass can be treated the same logically (An et al., 2011b), our modeling alternative forms the upstream flow network for each additional type of biomass by duplicating the nodes and arcs in the original network. Each of these flow networks is unique, however, because each type of biomass is associated with unique parameters that define moisture content, dry matter loss, and conversion efficiency. Please note that the sum of transportation capacities of arcs duplicated from an original arc is the same as that of the original arc. Fig. 2 illustrates two upstream substructures, one for each of two types of biomass. The structure of the downstream network depends upon the type of biofuel produced by the conversion technology and could represent new forms of transportation, storage and customer service for ETOH or use of existing infrastructure for drop-in fuel. Nodes i_0 and $i_{\tilde{n}}$ and the arcs incident to them are needed to form the GFP structure and are discussed later. Each other node represents an (facility, technology type, location) alternative; and each downward-pointing arc, a transport. BSCD involves selecting, from alternative nodes provided, an optimal set of (facility, technology type, location) combinations, including selections we model in echelon 1 to represent (biomass type, moisture content and harvest season, and source location).

Like the pages of a book, each time period is represented by a layer in the graph. For example, the foreground of Fig. 2 depicts flows in time period t; and the background, period $t+1$. A dashed arc that is incident from a node in period t to the corresponding node in period $t+1$ allows for inventory to be carried (i.e., stored) and dry matter loss could occur on such arcs. The path at the far left of Fig. 2 represents flow (i.e., transport) through the five-echelon