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A multistage stochastic programming model for a multi-period strategic expansion of biofuel supply chain under evolving uncertainties[☆]

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A B S T R A C T

We develop a multistage, stochastic mixed-integer model to support biofuel supply chain expansion under evolving uncertainties. By utilizing the block-separable recourse property, we reformulate the multistage program in an equivalent two-stage program and solve it using an enhanced nested decomposition method with maximal non-dominated cuts. We conduct extensive numerical experiments and demonstrate the application of the model and algorithm in a case study based on the South Carolina settings. The value of multistage stochastic programming method is also explored by comparing the model solution with the counterparts of an expected value based deterministic model and a two-stage stochastic model.

1. Introduction

The cellulosic biofuel (e.g., converted from biowastes) is a promising renewable energy solution to addressing climate change issues, improving energy security, and invigorating the agricultural industry (INL, 2010). For these benefits, policies and mandates are available to stimulate the biofuel production. For example, the Renewable Fuels Standard (RFS) sets a goal of annually producing 36 billion gallons of biofuel by 2022; among this, 16 billion gallons are advanced renewable fuels, including cellulosic biofuels (110th U.S. Congress, 2007). A mature biofuel supply chain is necessary to meet this goal. However, like many other capital intense infrastructure systems, the biofuel supply chain is not likely to reach full capacity all at once. Instead, we need a long-term multi-period strategic planning to better inform decision makers of where and when to establish and expand the biofuel supply chain.

A full knowledge of parameters (e.g., feedstock supply and biofuel demand) is important for the best strategy of planning a biofuel supply chain. However, these parameters are inevitably uncertain and are subject to many volatile factors such as weather, disasters, technology breakthrough, and even future policy. Under a long-term multi-period planning horizon, these uncertainties could evolve over time. In this study, we propose a multistage, stochastic modeling framework, which allows for sequential decisions on expanding the supply chain under *evolving uncertainties over time.*

There is a pool of extensive literature regarding biofuel supply chain strategic planning, and we summarize them into the

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following six categories: (1) single-period (e.g. one year) deterministic planning (Aksoy et al., 2011; Bowling et al., 2011; Kim et al., 2011), (2) single-period deterministic planning with seasonality (Gebreslassie et al., 2013; Xie et al., 2014; You et al., 2011), (3) multi-period deterministic planning (Ebadian et al., 2013; Giarola et al., 2011; Huang et al., 2010a), (4) single-period stochastic planning (Awudu and Zhang, 2013; Chen and Fan, 2012; Osmani and Zhang, 2013; Quddus et al., 2017), (5) single-period stochastic planning with seasonality (Cundiff et al., 1997; Huang et al., 2014; Poudel et al., 2016), and (6) multi-period strategic planning under uncertainty (Dal-Mas et al., 2011; Osmani and Zhang, 2017; Poudel et al., 2017). There are many other studies focused on biofuel supply chain operations, including multimodal transport (Poudel et al., 2016; Poudel et al., 2017; Xie et al., 2014) and biomass preprocessing (Osmani and Zhang, 2013; Quddus et al., 2017). Readers are referred to papers (Awudu and Zhang, 2012; Osmani and Zhang, 2017; Yue et al., 2014) for comprehensive reviews.

The model proposed in this study belongs to the category (6). Most existing studies in this category adopted a two-stage stochastic programming framework (Birge and Louveaux, 1997). They all have an implicit assumption that uncertainty, though for multiple periods, is immediately revealed for the entire planning horizon so that the planning decisions are only made once at the beginning of the horizon. This assumption is more defensible for a short-term single-period system design, because its planning horizon is relatively short and uncertain parameters are immediately revealed once the planning decisions are made. However, for a multi-period strategic planning, the two-stage stochastic programming method lacks the capability of the sequential decision-making process based on evolving uncertainties over time. To enable this modeling capability, we consider the multistage stochastic programming method (Birge and Louveaux, 1997) in this study.

The multistage stochastic programming models are more challenging due to the nested modeling structure and exponential growth of scenarios with time stages (Birge and Louveaux, 1997). A handful of solution methods have been used. One type of the solutions is Lagrangian-based methods which decomposes the model by scenarios (or as known as horizontally) including the progressive hedging algorithm (PHA) introduced by Rockafellar and Wets (1991), which has been applied in solving multistage models (Escudero et al., 2017; Gade et al., 2016). The PHA was also recently integrated with a stochastic dynamic programming framework that reduces the size of the problem by considering only one scenario a time (Huang et al., 2010b). However, the effectiveness of this method usually relies on a policy restriction assumption on infrastructure expansion (i.e., one facility installed per period) for the reduction of possible states. The other type of the solutions is based on the recourse function approximation, which decomposes the problems into master and subproblems (or as known as vertically). One extensively used method is the nested decomposition (ND) method (Birge, 1985), which extends the L-shaped method (Slyke and Wets, 1969) with outer linearization approximation. The ND method was primarily used for solving quadratic multistage programs (Louveaux, 1980) and linear multistage programs (Birge, 1985). The method can also solve mixed-integer programs if the block-separable recourse property holds (see discussions in Section 2), with a few recent applications in the literature (Edirisinghe and Patterson, 2007; Shiina and Birge, 2003).

However, due to the modeling and computational challenges (Birge and Louveaux, 1997), compared to two-stage stochastic programing method, multistage stochastic programming method has scarce real-world applications, including supply chain design (Nickel et al., 2012), electricity power system (Hochreiter and Wozabal, 2010; Pereira and Pinto, 1991; Shiina and Birge, 2003), financial portfolio management (Consigli and Dempster, 1998; Golub et al., 1995; Gulpinar et al., 2002; Kouwenberg, 2001), and water resource management (Archibald et al., 1999; Li et al., 2006, 2008; Watkins et al., 2000; Zhou et al., 2013).

To the best of our knowledge, this study is the first study applying multistage stochastic programming method in the multi-period biofuel supply chain optimization. The model integrates facility spatiality, time dynamics, and evolving uncertainties into a single optimization framework. After showing that the problem has the block-separable recourse property, we propose an enhanced ND method that is strengthened with maximal non-dominated cuts (Sherali and Lunday, 2013), namely ND-Max. As far as we know, this study is at the first to integrate the maximal non-dominated cuts (Sherali and Lunday, 2013) into the ND method in improving the solution of a multistage stochastic program. We conducted extensive numerical experiments to understand the complexity of the model and explore the solution efficiency by both ND and ND-Max. A case study based on South Carolina setting is included in the paper to demonstrate the application of the model and the ND-Max solution in real-world applications. We also justify the use of multistage stochastic programming method by comparing the solutions with the solutions of the counterparts of expected value based deterministic model and a two-stage stochastic programming model.

In the remaining of the paper, we present the multistage stochastic model formulation and its mathematical properties in Section 2. The decomposition methods with solution procedures are presented in Section 3. The results of numerical experiments and the case study of South Carolina are included in Section 4. The study is concluded and a few future research directions are outlined in Section 5.

2. Modeling

2.1. Problem statement

We use Fig. 1 as an example to illustrate a multistage expansion of a biofuel supply chain under demand uncertainty. In particular, there are three infrastructure layers geographically distributed: (1) *feedstock fields*, where biomass is collected, (2) *refineries*, where biomass is converted into biofuel, and (3) *city gates*, where blended fuels are distributed to consumer markets. Note that in this study, the supply chain ends at city gates and further fuel dispensing to individual refueling stations is omitted. Design of such a complex system is not trivial due to several tradeoffs in the system. First, a centralized facility takes advantage of economies of scale, but may result in higher transport cost. The temporal dimension is also important, along which supply chain parameters could vary over a multi-period planning horizon. For modeling, the planning horizon is typically divided into stages, $t = 0,\ldots,T$, where "0" is the