Computers and Chemical Engineering 73 (2015) 141–153

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Two stage stochastic bilevel programming model of a pre-established timberlands supply chain with biorefinery investment interests

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ARTICLE INFO

Article history:
Received 29 June 2014
Received in revised form 29 October 2014
Accepted 13 November 2014
Available online 21 November 2014

Keywords:
Timberlands supply chain modeling
Bilevel programming
Biofuels
Optimization
Uncertainty
Two stage multiperiod

ABSTRACT

This work studies the supply allocation problem, using a Stackelberg game, for an established timberlands supply chain with an additional decision of new biorefinery investments. In a timberlands system, harvester and manufacturer decision makers have separate objectives to maximize their respective profits. This interaction is represented with a turn based Stackelberg game. The harvesters decide first on the quantity harvested, and the manufacturers decide on how much to utilize. This game is modeled with a bilevel mathematical program. The novel feature of this paper's bilevel formulation is the inclusion of parametric uncertainty in a two stage model. The first stage problem involves logistical decisions around biorefinery investments, such as location and capacity, while the second stage problem involves a bilevel timberlands model with parameter uncertainty. Studying this problem formulation revealed interesting insights for solving multiperiod problems with bilevel stages as well as the decision maker's behavior for the timberlands model.

1. Introduction

Biofuel production is a way to replace traditional fossil fuels to meet a portion of demand for liquid fuels. Biofuels are a promising choice for sustainable transportation fuel due to the limited changes needed to existing fuel distribution and combustion technologies, particularly when converted to direct "drop-in" diesel or gasoline replacements. Timber industry management has shown interest in biofuels for market diversification. Timber demand varies due to dips in housing construction and experiences secular decline as new technologies replaces paper products, so timberland owners are looking for new outlets for timber materials. Biofuel production looks promising in this regard because it can utilize both harvested biomass and timber residuals discarded by other processes in the timberlands network. With enough residuals, significant amounts of biofuel can be produced and new revenue can be generated from them. However, investment in such a large scale project has many financial risks owing to many uncertainties. Supply chain modeling and analysis can be used to simulate adding biorefineries to the existing timberlands system and clarify some aspects of the investment as well as reveal insights about decision making behavior.

There have been many recent studies involving biofuel supply chains. Sharma et al. (2013) developed a biorefinery model that determined stakeholder value as well as optimal production decisions. Elia et al. (2013) developed a large scale mixed integer linear programming (MILP) model that simulates hardwood biomass resource flows across the entire United States. Andersen et al. (2013) used an MILP model for the design and planning of an integrated ethanol and gasoline supply chain. Daoutidis et al. (2013) provided an in depth discussion on the status of biofuel research and future directions that could be pursued. Santibanez-Aguilar (2013) proposed utilizing the water hyacinth for biofuel production as a sustainable way to remove the harmful plant from water systems and developed a supply chain model to simulate this solution. Floudas et al. (2012) provided a more general review for studies of hybrid and single feedstock liquid fuels. The paper covered biomass processes and some discussion of optimization with uncertainty.

Biofuel supply chain modeling with game theory approaches has been studied in the past. Bai et al. (2012) utilized Stackelberg game theory to model resource providers and manufacturers for a biofuel supply chain as separate decision making entities. They performed case studies to determine how cooperative or non-cooperative behavior effected the decisions made in the system.

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http://dx.doi.org/10.1016/j.compchemeng.2014.11.005
0098-1354/

Wang et al. (2013) also created a bilevel model with a Stackelberg game approach that gives insights on biofuel supply chain design under a government mandate for minimum biofuel production per year. These two papers focus on biofuels derived from food and specifically focus on the food versus fuel problem. In these studies, the interaction between the biorefinery and the biomass providers are studied with bilevel programming.

Our previous research also explored Stackelberg games and bilevel programming to model the biofuel problem, but our study does not involve biofuels synthesized from food type biomass (Yeh et al., 2014). Instead, we look at the biofuel production problem in a timberlands supply chain. We hypothesized that using this game theory approach would provide another perspective on the interactions between two major decision making sectors in the timber network: harvesters and manufacturers. Stackelberg games are a two player turn based game with a leader (first decision maker) and follower (second decision maker) (Bard, 1998). Both players have a separate set of objectives, constraints, and decisions, but have full knowledge of each other's information. The players are connected in that their decisions influence each other. As a single period turn based game, it is assumed that, after the leader makes his decision, the follower will react optimally to the given situation. Knowing this, and having the full information state, the leader can anticipate the behavior of the follower. Stackelberg games are most commonly represented with bilevel programming. Our initial study compared a single period bilevel model with a single period single level model. The results from previous analysis showed that representation in a bilevel form revealed decisions and behavior very different from the single level model (Yeh et al., 2014).

After this study on the viability of bilevel models with our timberlands system, we have continued to develop the model by including uncertainty. Investment decisions are important in supply chain modeling and must be made facing the unpredictability of macro-economic conditions and the uncertainty in technological parameters in the early-to-mid stage of process development. One of the earlier studies in biofuel supply chains under uncertainty was performed by Dal-Mas et al. (2011). Dal-Mas et al. (2011) developed an MILP model for the design of a corn to ethanol supply chain for a 10 year time horizon. This model determined optimal location logistics with product price and production cost uncertainty for maximizing profit and minimizing risk case studies. For the optimal design of hydrocarbon biorefinery supply chains, Gebreslassie et al. (2012) developed a multiperiod stochastic MILP model that included demand and supply uncertainties. Mansoornejad et al. (2013) designed a model with uncertainty in market scenarios and system network scenarios for a forest biorefinery supply chain. They used a stepwise methodology to determine the effect of design decisions on process operations. Sharma et al. (2013) also designed a biofuel production model with market uncertainty. The model covered strategic investment decisions for the biofuels through a stochastic integer programming model. Tong et al. (2014) looked at an integrated biofuel and petroleum supply chain system. The system was modeled stochastically as a two stage MILP with scenarios involving biomass availability, fuel demand, crude oil prices, and technology evolution. It was assumed that through technology evolution, material, production, and infrastructure costs would decrease.

Studies have also been performed with bilevel models and uncertainty. Capitanescu and Wehenkel (2013) determined the worst case scenarios for power flows under operational uncertainty for the determination of contingency plans. Their bilevel program was solved through heuristic approximation. A traffic control problem with traffic uncertainty was studied by Chiou (2014). A min–max bilevel program was utilized where the leader managed traffic signals and the followers were the drivers. Konur and Golias (2013) tackled a truck scheduling problem with arrival time uncertainty. They used a genetic algorithm approach to determine optimal time assignments for pessimistic and optimistic situations. Wogrin et al. (2011) developed a model that calculates long term investments in the electricity market with regards to the investments of other companies. The investing company was modeled in the upper level while the competing company decisions were considered in the lower level. Competition uncertainty was modeled through pricing variations.

The possible introduction of biofuel production within an uncertain environment means the timing of the biorefinery investment decisions must be defined in the model. We assume the biorefinery investment decisions must be set before the uncertain scenarios occur. Therefore, the model can be represented as a two stage stochastic integer program (Sahinidis, 2004). In the first stage, the biorefinery binary decision will be set. The second stage will be a scenario based uncertainty bilevel model. Multiperiod problems with uncertainty have been used extensively in system modeling (Birge and Louveaux, 2011). Paules and Floudas (1992) developed a two stage stochastic mixed integer non-linear program (MINLP) to model a multiperiod heat-integrated distillation design problem. Uncertain parameters included feed composition and flowrate, and the uncertainty was represented through discrete scenarios. Kang and Lansey (2012) used a multiperiod model to study water supply infrastructure planning. They used discrete scenarios to represent uncertainties such as increased demand from population growth, changes in regulation, and public outlook. This model analyzed the situation to determine the timing of water infrastructure investments and their size. Moreno and Montagna (2012) developed a two stage stochastic multiperiod linear generalized disjunctive programming model to study the design and planning decisions of multiperiod batch facilities with consideration to demand uncertainties. The design decisions were made in the first stage before information about the product demand was known. Zhu et al. (2011) also studied batch plant production in a multiperiod sense but approached the system with a scheduling problem. They modeled the system with a two stage stochastic integer programming model for the production of multiple products with demand uncertainties. Their model included penalties for production shortfalls and excess. Rodriguez et al. (2014) considered an inventory management problem with demand uncertainty with an MINLP. The goal of this work was to propose redesign decisions for a spare parts supply chain. With the non-linear behavior in consideration, a piecewise linearization approach was used to determine the lower bound of the optimal solution. Giarola et al. (2013) developed a multiperiod MILP model to optimize an ethanol production supply chain with uncertain market conditions. The supply chain was studied over an 18 year horizon divided into 6 time periods. The model considered factors such as carbon cost emissions, biomass crop management, and technology learning issues. Three case studies were considered: optimal economic and environmental situation, risk mitigation under an optimal economic situation, and risk mitigation under an optimal environmental situation. Kim et al. (2011) developed a two stage mixed integer stochastic program around a timberlands supply chain with biofuel production. This study utilized discrete scenarios generated by uncertain parameters to determine the optimal estimated value of the system.

There is also research involving multiperiod bilevel games, but literature with this methodology is rarer. Sinha et al. (2014) modeled an oligopolistic market with a bilevel model over multiple time periods. This research studied and solved the general formulation of a multiperiod multiple-leader-follower system. Su and Geunes (2013) designed a two stage supply chain bilevel model with uncertainty. They studied a supplier pricing problem where