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Multi-source capacitated lot-sizing for economically viable and clean biofuel production

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ABSTRACT

Excessive water usage and CO_2 emissions resulting from industrial systems and processes have significantly raised environmental concerns. Although biofuels help to mitigate greenhouse gas emissions, the biofuel industry itself consumes a considerable amount of water and produces CO_2 emissions during ethanol production. In this paper, we develop a mixed-integer linear programming (MILP) capacitated lot-sizing model for analyzing the economic and environmental feasibility of ethanol production using multiple biomass sources. The model minimizes the cost of ethanol production while penalizing its possible adverse environmental impacts such as CO_2 emissions and excessive water usage. The overall cost of ethanol production includes production, setup, and inventory holding costs with penalties for environmental impacts minus the income from ethanol tax credits and electricity generated from waste heat. We perform a sensitivity analysis and analyze results to improve our understanding of the economic viability of ethanol production and associated environmental effects. Results show that switchgrass is the most profitable and preferred biomass type when there is an unlimited supply of all biomass sources, while wheat and corn become more preferable in the case of a limited biomass supply. Compared to low- and medium-demand cases, when there is high demand, total costs increase significantly due to multiple production setup costs, excessive water usage, and CO_2 emissions under limited biomass supply. The solution of the proposed model also indicates that if ongoing technology investments in the conversion rate succeed, the total cost of ethanol production can decrease by up to 21 percent. Finally, results show that the proposed MILP model provides valuable insights and strategies for future investors, decision-makers, and the government to achieve sustainable and economically viable biofuel production using various biomass types.

1. Introduction

Increased consumption of fossil fuels and high greenhouse gas emissions have necessitated the utilization of environment-friendly energy sources. Biomass-based fuels are one of the most promising renewable energy sources that are necessary to achieve a sustainable and balanced energy supply (for a detailed discussion of various renewable energy supplies, see, e.g., Lund, 2014). Biofuels can reduce some undesirable effects of fossil fuels, such as CO_2 emissions and dependence on unstable foreign supplies (United States Environmental Protection Agency, 2014).

Currently, biofuel production is dominated by food crops, including corn, wheat, soybeans, and sugarcane. However, to avoid possible undesirable impacts on the safety of food resources and prevent excessive CO_2 emissions, researchers have focused on developing alternative biofuel sources such as trees and grasses, called cellulosic biomass (Akgul et al., 2012). Although biofuel is one of the cleanest sources of energy, its economic viability is a major concern (Gonela and Zhang, 2014). In order to assess the economic feasibility of biofuel production, related costs such as fixed (setup) and variable production costs must be taken into account. Furthermore, costs associated with holding ethanol inventory to meet future demand should also be considered.

In addition to the economic cost of biofuels, related environmental impacts should also be taken into consideration in order to ensure the sustainability of biofuel production. For example, leaving a carbon footprint is a major concern in ethanol production, as is the case for any other industrial and manufacturing processes.

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Nomenclature

Indices
- i biomass type
- t time period

Sets
- I set of biomass types
- T set of time periods in planning horizon

Binary decision variables
- Y_{it} 1 if there is production from biomass type i in period t; otherwise, 0.

Continuous decision variables
- X_{it} production amount of ethanol from biomass type i in period t (gallon)
- M_{it} amount of biomass type i used in period t (ton)
- I_t ethanol inventory carried at the end of period t (gallon)
- U_t CO_2 emissions exceeding predefined emission cap in period t (kg)
- S_t water usage exceeding predefined water usage cap in period t (gallon)

Parameters
- p_{it} variable cost of ethanol production from biomass type i in period t ($/gallon)
- f_{it} fixed cost of ethanol production from biomass type i in period t ($)
- r_i biomass purchasing cost for biomass type i ($/ton)
- v credit for producing ethanol ($/gallon)
- k electricity credit per each gallon of biofuel produced ($/gallon)
- h_t ethanol inventory holding cost at period t ($/gallon)
- z penalty for CO_2 emissions exceeding emissions cap ($/kg)
- μ penalty for water usage exceeding water-usage cap ($/gallon)
- q_t production capacity in period t (gallon)
- e_i biomass-to-ethanol conversion factor for biomass type i (gallon/ton)
- b_{it} amount of biomass type i available for purchase in period t (ton)
- d_t total ethanol demand in period t (gallon)
- $\hat{p}_{it}$ CO_2 emissions occurring per one gallon of ethanol production from biomass type i in period t (kg/gallon)
- c_t CO_2 emissions cap at period t (kg)
- w_{it} water usage for ethanol production from biomass type i in period t (gallon/gallon)
- Ω_t water usage cap at period t (gallon)

Čuček et al. (2012a) note that biomass energy releases a lower carbon footprint compared to fossil fuels. On the other hand, Hammond and Seth (2013) find that the carbon footprint is high for first-generation (food-based) biofuels, while the use of second-generation (cellulosic) biofuels could contribute significantly to reducing the carbon footprint.

Water footprint in biofuel production is also a big concern. Čuček et al. (2012b) define the water footprint as the total volume of direct and indirect fresh water used, consumed, and polluted. For example, a driven car would require 50 gallons of water per mile, considering the total amount of water needed for irrigation of corn and its subsequent processing into ethanol in Nebraska (Dominguez-Faus et al., 2009). The increasing demand for biofuels will adversely impact fresh water supplies further unless sustainable biofuel production policies are developed and implemented.

In the literature, a significant number of studies focus on the ethanol supply chain and corresponding economic costs, while fewer studies focus on ethanol production planning and scheduling. Xie et al. (2014) propose a multi-stage mixed-integer linear programming (MILP) model to minimize the total cost of the biofuel supply chain, feedstock harvesting, and transportation. da Silva et al. (2013) develop a multi-choice mixed-integer goal programming model for optimizing traditional collection and process methodologies for the design of production lots in an ethanol company. There are also a large number of ethanol supply chain optimization papers including those on associated environmental impacts, but relatively few of them focus on ethanol production planning optimization (see, e.g., Huang et al., 2010; Bernardi et al., 2012; Cobuloglu and Büyüktahtakın, 2014, 2015; Gonela and Zhang, 2014; Liew et al., 2014).

MILP approaches have been widely used for modeling and solving production planning problems (see, e.g., Pochet and Wolsey (2006) for a detailed discussion of these methodologies). Only a few studies focus on the environmental impacts of the general production and inventory planning processes. Benjaafar et al. (2013) demonstrate how CO_2 emission concerns can be incorporated into an MILP model that includes production, procurement, and inventory management decisions. They provide insight into the impact of operational decisions and different regulatory policies on CO_2 emissions and evaluate the benefits of investing in CO_2-efficient technologies. Retel Helmrich et al. (2012) restrict costs related to CO_2 emissions released during production, inventory, and setup by defining an emission constraint, and show that the lot-sizing problem with an emission constraint is NP-hard. On the other hand, Dai (2012) implements CO_2 emission constraints and a carbon tax into a lot-sizing model and solves the corresponding model using Lagrangian relaxation techniques. Similar to Dai (2012), in this study, we impose a strict CO_2 emissions cap in the lot-sizing model and evaluate its impact on operational decision making.

Previous work has concentrated on biofuel production supply chains without analyzing the ethanol production lot sizes from various biomass sources along with corresponding economic costs and environmental impacts. Furthermore, we have not encountered in the literature a general multi-source capacitated lot-sizing model with CO_2 emissions and water-usage constraints and associated penalties. Our study closes this gap by providing an MILP production planning model that minimizes both variable and fixed production costs as well as biomass purchasing and inventory holding costs of ethanol production while taking into account carbon and water footprints.

The expected time frame for development of a large-scale biorefinery industry with sustainable practices is about 20–40 years (Hoekman, 2009). Unless stakeholders such as biorefinery, society, and government cooperate and find common ways to make sustainable biofuel production practices economically viable, technology transformation in this area is bound to be slow. For more information regarding the interactions among interested parties and the dynamics of group interaction, we refer the reader to the detailed review of Perc and Szolnoki (2010) and Perc et al. (2013). Our paper provides analysis and recommendations on how