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A robust programming approach towards design and optimization of microalgae-based biofuel supply chain

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ABSTRACT

Despite their inherent attractive characteristics, microalgae do not play a significant role in the green energy market because of high production cost. In order to propel this nascent industry one step further towards commercial viability, the present study expands the narrow outlook of previous studies which is restricted to a single location into a perspective with a nationwide network by proposing a sustainable supply chain model capable of revealing opportunities and limitations of algae industry's future. The proposed model is formulated based on batch and continuous production systems which completely cover the possible future configuration of microalgae-based biofuel supply chain and also offers managerial implications contributing to cost mitigation. Moreover, the uncertainty whose importance is accentuated in the case of algae production due to lack of real-world implementation is captured by the utilization of robust optimization under two norms of the uncertain data vector. A real case study is carried out to explore the applicability of the proposed model. Furthermore, robust sensitivity analysis technique is performed, allowing decision makers to analyze the effect of uncertain parameters on production cost based on their confidence levels.

1. Introduction

Concerns with the rapid depletion of natural resources, oil crisis and greenhouse effects have spurred interests in the development of biofuel industry. The first-generation biofuels which are made from edible feedstock such as corn and soybean have now reached aneconomic level of production. However, Biofuel production from these resources has resulted in a series of problems like subsequent surge in food prices and competition for arable land (Mata, Martins, & Caetano, 2010). To overcome such problems, researchers have focused their efforts on fuel production from non-edible energy crops. Microalgae are a promising option for addressing this issue due to the following reasons: (1) yielding several orders of magnitude more biomass per hector than terrestrial crops; (2) storing phenomenal amounts of lipid in their cells which can be transformed to biodiesel; (3) removing of CO_2 from industrial emissions while producing biofuels; (4) being cultivated in artificial ponds on non-arable land; and (5) ability to use saline and wastewater for biofuel production (Chisti, 2007; Hunter-Cevera et al., 2012).

Although lots of efforts have been made to optimize different stages of biofuel production process, microalgae-based biofuel has not been able to penetrate the current energy market due to high production cost. Developing an efficient supply chain model capable of being employed for national production plays a leading role in commercialization of biofuel production. It can also manifest opportunities and limitations of algae industry which need to be more investigated to support this industry in future. Generally, types of biomass feedstock from which microalgae are not excluded deal with manifold issues differentiating biomass supply chain from the traditional ones. Seasonal variability of biomass production, spatial fragmentation of biomass resources and year round demand for transportation fuel are a few instances of such issues (Ekşioğlu, Acharya, Leightley, & Arora, 2009; Yue, You, & Snyder, 2014). To handle these issues, supply chain modeling and optimization is an appropriate approach which ensures that all activities, from source to the end user, are carried out as effectively and efficiently as possible (Pishvaee, Torabi, & Razmi, 2012). Supply chain optimization for biomass systems has been investigated by researchers to optimize (1) biomass storage and allocation of biomass to biorefineries (e.g., Kanzian, Kühmaier, Zazgornik, & Stampfer, 2013; Sokhansanj, Kumar, & Turhollow, 2006) (2) location and production capacity of biorefineries as well as biomass and product flows between supply chain components

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(e.g., Azadeh, Arani, & Dashti, 2014; Kim, Realff, & Lee, 2011) (3) selection of biomass-to-biofuel conversion technologies (e.g., Kim et al., 2011; Liu, Qiu, & Chen, 2014) and (4) economic and environmental performance of biomass supply chain (e.g., Liu et al., 2014; Osmani & Zhang, 2014).

Previously conducted economic studies concerning algal biofuel have been under intense debate by critics arguing that the calculated final cost is associated with a high degree of variability. This argument not only demonstrates the unreliability of previous results, but also points out a high degree of uncertainty in both current status and future of algae biofuel production. More importantly, in current circumstances that the need for private sector investments to expedite commercialization of microalgae biofuel is strongly felt, a risky and uncertain environment jeopardizes future investments. Large variability in reported biofuel cost is a consequent of the fact that precise estimation of influential factors in different stages of production process is a challenging task since algae biofuel production is still in a premature stage of development and large scale production is not implemented yet.

Despite the importance of analyzing uncertainty in algae production, to best of our knowledge there is no research devoted to it. In optimization literature, different operation research techniques such as stochastic programming and robust optimization (RO) have been developed to cope with the uncertainty. There are two major handicaps associated with stochastic programing making it less applicable: (1) stochastic programming needs the knowledge of probability distribution of uncertain parameters but in many real-world problems, obtaining the actual probability distribution function is not possible; (2) scenario-based stochastic programming requires a large number of scenarios to represent the uncertainty, leading to computational complexity (Pishvaee, Rabbani, & Torabi, 2011). On the contrary, RO only needs the upper and lower bounds of uncertain data and does not cause computational intractability. Hence, this approach can be used to address the uncertainty of parameters in optimization problems as a complementary alternative. There are several well-known RO approaches that can be classified into two categories: conservative robust programing (e.g., Li, Ding, & Floudas, 2011; Soyster, 1973) and flexible robust programming (e.g., Ben-Tal & Nemirovski, 2000; Bertsimas, Pachamanova, & Sim, 2004; Bertsimas & Sim, 2004). In this study, two RO approaches under L^1-norm (Li et al., 2011) and D-norm (L^∞ and L^1-norms) (Bertsimas & Sim, 2004) are adopted due to the following reasons: (1) L^1-norm ensures maximum robustness against uncertainty though incurring a high cost, which appeals to risk-averse decision makers who seek a solution that remains optimal for all possible realizations; (2) D-norm makes a trade-off between robustness and its cost, appealing to risk-seeking decision makers who prefer a solution which is optimal in most of the cases not all in order to incur less cost; and (3) L^1 and D-norms preserve the linearity of the nominal problem contrary to some RO approaches (e.g., Ben-Tal & Nemirovski, 2000) which transform a linear programming problem into a nonlinear one. Therefore, this paper deals with uncertainty using computationally tractable RO models which accommodate different risk preferences.

To benefit from abilities and functionalities of supply chain modeling and robust optimization methodology regarding microalgae biofuel production, a robust mathematical modeling framework is suggested which addresses the current gaps in relevant literature as follows:

- Even though supply chain network design is recommended as a prerequisite to developing a new business especially on large scale, not enough attention has been paid to designing microalgae-based biofuel supply chains. The present study offers a supply chain model which systematically designs and optimizes the overall supply chain ranging from raw material acquisition to final product distribution. Therefore, it can have a critical role in propelling the algae industry to commercialization by remedying sub-optimal supply chain performance and efficiently managing the complexities in strategic and tactical decision levels.
- Capturing various sources of uncertainty through the studied supply chain using two interval RO approaches which ensure that supply chain configuration and total production cost are highly stable when facing uncertainties caused by imprecise data.
- Designing the microalgae-based biofuel supply chain based on batch and continuous production systems which totally cover the future of microalgae industry. In addition, it can come up with solutions contributing to lower biofuel production costs.
- Offering robust sensitivity analysis which enables us to analyze the effects of changes in input data on system's output based on decision maker's reliability level.

The rest of this paper is organized as follows. The microalgae-based biofuel supply chain is described in Section 2. Section 3 presents the deterministic mathematical models. In Section 4, robust optimization under aforementioned norms is explained and also the robust counterpart formulations are presented. In Section 5, the robust models are implemented in a real case study. Moreover, Section 5 performs the robust sensitivity analysis. Finally, Section 6 is devoted to conclusions and future research directions.

2. Problem statement

Microalgae can be turned into several types of biofuel (e.g., ethanol, gasoline and diesel) depending on the techniques and species that have been used (Brennan & Owende, 2010; Hunter-Cevera et al., 2012). Biodiesel production from microalgae-derived oil has had prior engagement in this field and is also the only viable option to satisfy current world diesel demand (Sheehan, Dunahay, Benemann, & Roessler, 1998). From a simplistic point of view, microalgae-to-biodiesel production chain comprises multiple stages starting with a cultivation unit developed by two different technologies, open pond and closed photobioreactors. Open cultivation systems used in this study are currently more acceptable in industrial scale production due to lower costs (Davis, Aden, & Pienkos, 2011). After being grown with nutrients and water in open ponds, algae are separated from growing media employing harvesting method and dried to be protected against decay. Then the dehydrated biomass proceeds to lipid-extraction process and finally extracted lipid is transformed into the main product (biodiesel) and a by-product (glycerin) using chemical reactions (Mata et al., 2010). To reduce the total production cost, residual biomass after lipid-extraction is converted to biogas by anaerobic digestion and then the biogas is used to generate electricity (Lundquist, Woertz, Quinn, & Benemann, 2010).

2.1. Batch and continuous production

To date, most researchers have utilized continuous production system which considers all production stages in a continuous facility. The associated disadvantage is that the chosen scale of each stage is heavily dependent to that of the others. Considering current technologies, scale up of open pond cultivation is one of the most arduous tasks of whole biodiesel production process. The limitation caused by constructing low capacity cultivation units results in forcing sequent units to be also built with low capacity. While lipid extraction and conversion process face a smoother path to scale up because of the similarities between biodiesel