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Biorenewable fuels at the intersection of product and process flexibility: A novel modeling approach and application

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A R T I C L E I N F O

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A B S T R A C T

In recent years, governments, industry and academia have all invested increasing amounts of time, effort and resources into the production of biorenewable fuels. This interest owes, among other reasons, to our planet's growing demand for energy, depletion of fossil fuel resources and the negative effect of drilling for and burning fossil fuels on the health of our eco-systems and atmospheric chemistry. However, research suggests that biorenewable fuels have the potential to cause environmental and social calamities of their own—especially when produced in the same ways and at the expense of conventional food production. This paper proposes novel supply chains and land use plans for advanced biorenewable fuels which are measured for cost and environmental impact. A two-stage Stackelberg leader-follower mathematical optimization model is proposed. The model uses a series of integrated and sequenced linear programs to optimize the benefits of leveraging biodiversity for the production of advanced biorenewable fuels. Numerical experiments with our model show statistically significant cost, land use and environmental improvements on the order of 10% to 25%. Because the model captures two types of flexibilities (product and process) interfacing across firms, implications are drawn for production systems in other industries where distinct flexibilities meet and environmental impacts are critical.

1. Introduction

In both energy and agriculture, several changes are occurring at once: (1) Global supplies of fossil fuel are rising in price, and plausibly scarcity, as worldwide demand continues to grow; (2) industry and governments are investing heavily in alternative energies, one of the more popular being "biofuels"; (3) meanwhile, agricultural production in the developed world has become highly centralized and homogenized, commanding much larger swaths of land, employing larger fleets of equipment and generating negative environmental externalities, all of which has lead scientists, journalists, and the public to; (4) increasingly cast critical eyes towards biofuels' potential to offset fossil fuel use without causing environmental and social calamities of their own. This research sits itself at the confluence of these four troubling, and seemingly disparate, developments. This paper proposes a way that advanced biofuels can be produced more efficiently and more sustainably, with optimized supply chains that capitalize on biodiversity in order to reduce land usage, environmental degradation, and overall costs of biofuels production. Our approach entails a unique application of operations research (OR) techniques to uncover the benefits of leveraging natural biodiversity in production systems for alternative fuels.

The production system under consideration (the farmer-bioprocessor dyad) and our mathematical model of it bears broader research implications too. We frame the farmer as a supplier (in this case of plant feedstock), who is *product flexible*, meaning "The ability to changeover to produce a new (set of) product(s) very economically and quickly" (Beach et al., 2000; Browne et al., 1984). Herein, product flexibility denotes the ability of the farmer-supplier to produce different crop types from year to year. The buyer in this dyad is the bioprocessor, who purchases from farmer-suppliers feedstock for conversion into biorenewable fuels. We frame the bioprocessor-buyer as a *process flexible*, meaning "The ability to produce a given set of part types, each possibly using different materials, in several ways" (Beach et al., 2000; Browne et al., 1984). Herein, process flexibility denotes the bioprocessor's ability to convert any of the farmer-suppliers' crop types into biofuels. This process flexibility is unique to emerging advanced biorenewable fuel technology.

Production researchers have been increasingly interested in flexible manufacturing problems since the 1970s, when computer-controlled process automation and Japanese-style production systems began to be implemented across a wide variety of industries (Fine and Freund, 1990; Karsak and Kuzgunkaya, 2002). Over the years, this journal has published several modeling approaches to flexible manufacturing problems, including: Kumar

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(1995), who proposed finance literature's 'options theory' as a better way evaluate investments in expansion flexibility than traditional Net Present Value calculations; Gertosio et al. (2000), who suggested multi-layered discrete event simulation as a decision making tool for analyzing how different control systems and physical production systems interact under manufacturing flexibility; Karsak and Kuzgunkaya (2002), who proposed fuzzy multiple objective programming as a fitting methodology for evaluating the worth of flexible systems, because it uniquely incorporates both strategic and economic benefits, whereas classical analytical modeling considers only the latter; Tseng (2004), who employed elements of game theory to investigate under what types of competitive environments investments in more expensive flexible systems pay off and found that increased competition reduces firms' incentive to invest in expensive flexible technologies; and Francas et al. (2011), who optimized two types of flexibility, labor and machine, in a single-firm production system using a two-stage stochastic programming approach.

In the research literature reviewed above, each type of flexibility has traditionally been considered either in isolation, or as it interfaces with another type of flexibility in a single firm. Examples of the latter include: Chod and Rudi (2005), who used a Stackelberg model to consider resource flexibility and "responsive pricing" in a single production system; Iravani et al. (2012), who modeled one firm's tradeoffs between process flexibility and inventory flexibility; and (Francas et al., 2011). In their recent review of supply chain flexibility, Jayant and Ghagra (2013) noted that more attention should be paid to inter-organizational flexibility in order to realistically depict real-world supply chains. Proposing an approach to modeling real-world circumstances of different types of flexibilities intersecting across firm boundaries is this paper's broader contribution to research. For practitioners, this approach also has merit in the classic sense of game-theoretic models: it allows one player (supplier or buyer) with a distinct flexibility to predict the moves of their partners (who have different flexibilities) under a variety of scenarios. Over time, however, it is possible that cooperatives of biomass processors and farmers could jointly own and operate both biorefineries and their surrounding farms, and then use the model presented in this paper to find optimal management strategies. Similarly, third-party service providers working in-between growing biorefineries and farming operations could use the model presented herein to discover appropriate price incentives for lowering overall logistical costs and protecting the natural environment.

The paper continues as follows. Section 2 gives further background to the problems above. Section 3 presents our proposed solution to the issues presented in Sections 1 and 2. Section 4 presents our mathematical formulation of a biodiverse biofuel supply chain, modeled as a Stackelberg leader-follower optimization based on a sequenced series of two basic types of integrated linear programs. In Section 5 we analyze the results of simulation runs on our model. Section 6 presents implications for biofuels producers, as well manufacturing flexibility research, and limitations and suggestions for further work.

2. Problem background

2.1. Fossil fuels

Today's world faces the potential for serious energy shortages in the near-term, owing in part to: (1) our own profligate consumption of available energy sources over the last 200 years, and (2) the mounting environmental costs associated with supplying raw material for different energy conversion technologies. During the advent of coal and steam power in the 19th century, energy use by humans increased 10-fold (McNeil, 2000). The development of oil and natural gas resources in the 20th century exacerbated this withdrawal ten times over. Environmental historian McNeil (2000) calculates that humans have expended more energy since 1900 than in all of preceding human history combined. Future consumption is projected by many to grow even faster (EIA, 2010; UN, 2007). Documented affects of growth in population and energy use over the last 200 years include: depletion of economically accessible fossil fuel resources, changing atmospheric chemistry and climate, degradation of ecosystem services, contamination of freshwater, despoilment of soils, and diminishment of global plant and animal biodiversity (Costanza et al., 2007; Hall et al., 2003).

2.2. The bioeconomy solution

For these reasons, and others, governments have become increasingly interested in transforming agricultural crops into fuel and/or other products that, today, are typically made from crude oil. These "biorenewable fuels" are defined as fuels made from plant material, living or recently deceased (Brown, 2003). By federal mandate in the United States, biorenewable fuels production will grow to 36 billion gallons in 2022. Similarly, the European Union has stipulated that the European biorenewable fuels industry grow to meet 10% of its transportation fuel demand by 2020 (Robbins, 2011).

But, in the US and in Europe, biorenewable fuels are being produced in accordance with the tenants of conventional modern food agriculture—that is, by planting gigantic swaths year-after-year to single, high yielding crops that demand significant chemical and fertilizer treatments, as well as large fleets of specialized machines to harvest and transport them. This practice is referred to broadly as "monoculture". For example, in the largest ethanol producing state in the world's largest ethanol producing country, Iowa, USA, 90% of the available cropland has been devoted to only 2 crops for the past 20 years. In recent years, this land has been increasingly devoted to only corn. Fully one-third of that corn output now goes to making corn-based ethanol. In the world's second-largest producer, Brazil, ethanol is made from similarly large monocropped tracts of sugarcane.

2.3. Growing criticisms of the bioeconomy

The rise of monocropping as a standard practice in commercial agriculture is attributed by agricultural and technical historians to the substitution of capital for labor following demographic shifts in the post WWII era (Anderson, 2009; Rasumussen, 1982). But, while economically expedient, monocropping begets several negative environmental externalities, including soil erosion, water pollution and release of carbon stored naturally in soils. As land around the world has been increasingly dedicated to monocropping for biofuels production, scientists have focused renewed attention on biofuels' potential to exacerbate these problems (Foley et al., 2005). For example, Searchinger et al. (2008) forecast that increases in corn-based ethanol production around the world could double global greenhouse gas emissions over 30 years, as perennial native lands are converted to large fields of high-input mono-cropped annual corn. Similarly, Stone et al. (2010) predicted that to meet the US Federal biorenewable mandates with corn production alone would demand a 6-fold increase America's agricultural water use. (For a further review of biofuels' promise and problems, see also *Nature* 474/7352). Finally, the UN special ambassador on food has called it a "crime against humanity" to dedicate such large swaths of agricultural land to corn production for biofuels, while millions still go hungry around the world (Ferret, 2009).