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Incorporating social benefits in multi-objective optimization of forest-based bioenergy and biofuel supply chains

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HIGHLIGHTS

- Quantified social benefits of forest- based biomass supply chain.
- Developed multi-objective optimization model.
- Incorporated social benefits into multi-objective model.
- Solved the model using the AUGMECON method.
- Applied the model to a case study in Canada.

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ABSTRACT

Utilization of forest and wood residues to produce bioenergy and biofuels could generate additional revenue streams for forestry companies, reduce their environmental impacts and generate new development opportunities for forest-dependent communities. Further development of forest-based biorefineries entails addressing complexities and challenges related to biomass procurement, logistics, technologies, and sustainability. Numerous optimization models have been proposed for the economic and environmental design of biomass-to-bioenergy or biofuel supply chains. A few of them also maximized the job creation potential of the supply chain through the use of employment multipliers. The use of a total job creation indicator as the social optimization objective implies that all new jobs generate the same level of social benefit. In this paper, we quantify the potential social benefit of new forest-based biorefinery supply chains considering different impacts of new jobs based on their type and location. This social benefit is incorporated into a multi-objective mixed integer linear programming model that maximizes the social benefit, net present value and greenhouse gas emission saving potential of a forest-based biorefinery supply chain. The applicability of the model is illustrated through a case study in the interior region of British Columbia, Canada where different utilization paths for available forest and wood residues are investigated. The multi-objective optimization model is solved using a Pareto-generating method. The analysis of the generated set of Pareto-optimal solutions show a trade-off between the net present value of the supply chain and the other two investigated objectives. Moreover, there is a positive correlation between the potential to generate high impact jobs in the region and its potential to generate greenhouse gas emission savings.

1. Introduction

Sustainability concerns related to the use of conventional energy sources have promoted the utilization of biomass to produce bioenergy, biofuels and other bioproducts. In forest-rich countries such as Canada, the development of forest-based biorefineries could strengthen the economic competitiveness of the forestry sector, mitigate greenhouse gas (GHG) emissions, and promote employment, particularly in rural areas [1,2]. However, the establishment of forest-based biorefineries requires large investments and involves uncertainties and challenges related to economic and technical feasibility of the considered technologies; availability, quality and cost of biomass; and demand and price of bioproducts [3–5]. The consideration of all these challenges in the planning process of sustainable forest-based biorefinery supply chains calls for a comprehensive approach that incorporates

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economic, environmental and social targets. From an economic perspective, the large capital and operating costs of conversion technologies put strong pressure on the delivery of high-value, cost-efficient products [6]. From an environmental perspective, public awareness calls for solutions with environmental benefits compared to fossil-based products [7]. From a social perspective, the new projects should be able to create long-term development prospects for the involved communities [8]. All these factors stress the need for an optimal design of forest-based biorefinery supply chains that maximizes generated value for the industry, the environment, and the society.

In the biorefinery supply chain literature, a large number of optimization models were proposed in order to maximize the economic performance of the entire supply chain (thorough reviews of such papers can be found in [3–5,9–13]. Increased public awareness on sustainability issues resulted in a recent branch of supply chain optimization studies that analyzed the supply chain from a wider perspective, integrating an environmental and an economic objective (e.g. [14–25]. In these studies, the environmental optimization objective was formulated as the minimization of GHG emissions (e.g. [16,17,19], the maximization of GHG emission savings [14], the minimization of environmental footprints [26,27], or the minimization of overall environmental indicators based on Life Cycle Impact Assessment methods such as Impact 2002+ [21] or Eco-indicators [22,23].

Only a few studies quantified and optimized social impacts in the formulation of biorefinery supply chain optimization models. In the agricultural biorefinery supply chain optimization model developed by Čuček et al. [27], the social objective was to minimize the food footprint, which is defined as the amount of land that is converted from food production to energy production. Since biorefineries based on residual biomass are often located in remote areas, their implementation can stimulate community development by providing employment opportunities [8]. Thus, job creation has been the most used indicator to account for the social impacts of new biorefineries. In the biofuel supply chain optimization model developed by You et al. [28], the social objective was to maximize the number of accrued jobs associated with the construction and operation of a biofuel plant. In the bioenergy supply chain optimization model presented by Yue et al. [29], the social objective was also to maximize the number of jobs created during plant construction and operation. In [23], the quantification of created jobs included those related to the raw material production, transportation and processing stages. In the three studies mentioned above, input-output multiplier analysis was used to compute the total number of created jobs, based on multipliers from the IMPLAN professional model and JEDI model. Ayoub et al. [30] proposed that the job creation objective can be maximized or minimized based on the conditions of the analysis. In their case study of a bioenergy supply chain in Japan, the job creation objective was minimized due to a decreasing population that could put in risk the implementability of the proposed supply chain. To the best of the authors' knowledge, no study thus far has considered that different types of jobs in different communities may be created, and they may offer different levels of social benefits. For instance, the job-related social benefit of establishing a new forest-based biorefinery project in a community that derives most of its employment income from the forest sector might be higher than that in another (more diversified) community. Furthermore, the social benefits of creating a type of job with high unemployment rate might be preferable than that of another job with lower unemployment rate. Thus, an optimization model that considers the job-related social benefit of new forest-based biorefinery supply chains should account for both the type and location of the created jobs.

Recently, in a multi-objective optimization model of a general facility location problem, Mota et al. [20] proposed the use of a social benefit objective function which favored the creation of jobs in less developed regions through the use of region-based weights. This approach considered different levels of impact for jobs created in different locations, but it did not consider different levels of impact for different types of jobs in those locations. To the extent of the authors' knowledge, no supply chain optimization study thus far has considered both aspects simultaneously, and previous biorefinery supply chain optimization models have not considered any of them.

In this study, we propose an indicator to assess the overall job-related social benefit of a forest-based biorefinery supply chain that produces bioenergy and/or biofuels. The calculation of this social benefit indicator is based on the weighted sum of all the new jobs created across the supply chain, and the assigned weights are based on the preferability of creating each type of job (job class) in each location. Note that this social benefit indicator is different from the social benefit (welfare) used as optimization objective in optimal power flow models, where the social benefit refers to the difference between the economic gains to the consumers of the electricity minus the total cost to generators (e.g. [31,32].

The developed job-related social benefit indicator is incorporated into a multi-objective optimization model that considers social, economic and environmental objectives in the supply chain design. The current work extends previous forest-based biorefinery supply chain optimization works of Cambero et al. [33], Cambero et al. [14] in which the net present value and the greenhouse gas emission saving potential of the supply chain were quantified and maximized. Finally, the developed multi-objective optimization model is applied to a case study in the interior region of British Columbia, Canada.

2. Problem background

Canada has abundant forest resources, estimated at 348 million hectares of forests [34]. Traditionally, Canada has made use of this natural advantage through the establishment of a strong forest products sector centered on the production of wood and paper products. However, during the last decade, this industry experienced significant challenges as a result of increased global competition, the collapse of the U.S. housing market and a significant decline in newsprint demand in North America [35]. All these challenges have impacted the economic stability of a sector accountable for about 288,669 jobs across the country [36].

In the province of British Columbia, the forestry industry is one of the main pillars of the economy. Before 2007, this industry employed around 80,100 workers across the province [37], which accounted for 7% of employment [38]. Starting in 2007, the forest industry experienced a severe downturn prompted by the U.S. housing market crisis that resulted in a decline of more than 23,000 jobs [37] and a forest industry unemployment rate of 13% in 2009. Four years after the economic downturn (in 2013), the unemployment rate decreased to below 5% across the province, suggesting that a portion of the displaced workers were successful to transfer their skills to other industries, particularly those workers in the wood products manufacturing sector [37]. In contrast, workers with a set of skills particular to the forest industry such as forestry and logging workers faced higher levels of unemployment [37]. For example, in 2013, the unemployment rate for millwrights and primary production managers was 2.5%, while the unemployment rate for logging machinery operators was 26.4% [37].

Based on the data presented in Sections 4.3.3 and 4.3.4 of [37], in 2013, there was a negative correlation between the average earnings and the average level of unemployment of different types of jobs in the British Columbia forest industry (correlation