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Tactical supply chain planning for a forest biomass power plant under supply uncertainty

Nazanin Shabani [a, 1], Taraneh Sowlati [b, *], Mustapha Ouhimmou [c], Mikael Rönnqvist [d]

[a] Department of Wood Science, University of British Columbia, 2943-2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada
[b] Department of Wood Science, University of British Columbia, 2931-2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada
[c] École de technologie supérieure (ÉTS), Canada
[d] Université Laval, Canada

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ABSTRACT

Uncertainty in biomass supply is a critical issue that needs to be considered in the production planning of bioenergy plants. Incorporating uncertainty in supply chain planning models provides improved and stable solutions. In this paper, we first reformulate a previously developed non-linear programming model for optimization of a forest biomass power plant supply chain into a linear programming model. The developed model is a multi-period tactical-level production planning problem and considers the supply and storage of forest biomass as well as the production of electricity. It has a one-year planning horizon with monthly time steps. Next, in order to incorporate uncertainty in monthly available biomass into the planning, we develop a two-stage stochastic programming model. Finally, to balance the risk and profit, we propose a bi-objective model. The results show that uncertainty in availability of biomass has an additional cost of $0.4 million for the power plant. Using the proposed stochastic optimization model could reduce this cost by half.

1. Introduction

During the past decade, there has been a shift from conventional hydrocarbon-driven energy towards utilization of more sustainable and secure energy sources due to high level of emissions associated with fossil fuels, increasing energy demand, and volatility of international energy market. Bioenergy is one of the attractive alternative energy sources that can provide environmental and economic benefits for societies. Bioenergy can be produced using agricultural biomass, forest biomass, and municipal wastes. In areas covered with large forest lands and advanced forest industries, such as Canada, large amount of forest biomass is available for energy generation [1]. Forest biomass is a local and sustainable energy source which can provide heat and/or electricity and create jobs in remote communities.

The main challenge in converting forest biomass to energy is its production cost and efficiency. Effective design, planning and management of forest biomass energy plants play a critical role in reducing the energy generation cost and making it a viable energy source. To accomplish that, optimization models have been developed and employed as can be seen in numerous past studies [2–12]. These studies mostly considered profit/cost as the performance measure of the supply chain and developed models to maximize profit or minimize cost. The decision variables in these models include biomass flow within the supply network [2,5,10,11], facility location [8], system capacity [3,6,12], energy generation level [3,6,7], and technology selection for energy generation [7,9], etc. Environmental and social objectives were also considered in supply chain model of a regional biomass energy plant in Ref. [13]. Moreover, optimization techniques have also been used in process optimization of biomass to energy conversion plants [14–16]. One example of these optimization models is BeWhere which is developed by International Institute for Applied System Analysis (IIASA). It has been used to determine the optimal size and location of bioenergy plants and has been applied to different areas and case studies. In this model, the production and carbon costs are minimized [17–19].

Although deterministic models are useful to optimize forest biomass supply chains, they may not be sufficient because these models use the average values of the system parameters, while most of the parameters in forest biomass supply chains are

* Corresponding author. Tel.: +1 604 822 6109.
E-mail addresses: nshabani@interchange.ubc.ca (N. Shabani), taraneh.sowlati@ubc.ca (T. Sowlati), Mustapha.Ouhimmou@etsmtl.ca (M. Ouhimmou), mikael.ronnqvist@gmc.ulaval.ca (M. Rönnqvist).
[1] Tel.: +1 604 827 4583.

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uncertain. Ignoring uncertainty in optimization models may result in non-optimal and/or infeasible solutions for real case studies. Hence, optimization models need to be extended to incorporate uncertainty and variations in the supply chain.

Different methods, such as scenario-based analysis, sensitivity analysis, stochastic optimization and robust optimization, have been used in the literature to incorporate uncertainty in the supply chain planning [20,21]. Considering several realizations for uncertain parameters, the optimization model can be solved for each "scenario" individually and then what-if analysis can be implemented. The problem with this approach is that it does not provide a single overall optimal solution over all scenarios. Stochastic optimization is an approach which overcomes this problem. In this method, the expected objective value of different potential scenarios is optimized. In a two-stage stochastic model, some decisions are taken after the uncertainty is revealed, while the rest of the decisions are taken based on the expected value of the possible future scenarios. Stochastic programming models have also the advantage of being able to manage risks associated with supply chain performance [20,22]. Some previous studies incorporated uncertainty in supply chain optimization of other industries such as chemical and lumber industries (e.g. Refs. [23–25]). The results of these studies mainly demonstrated that incorporating uncertainties in the decision making of real case scenarios using stochastic models provided lower costs and more robust solutions compared to deterministic models.

There are few studies that included uncertainty in bioenergy supply chain models. A number of them are reviewed and presented by Awudu and Zhang [26] and Shabani et al. [27]. Some of the studies used stochastic programming in modeling bioenergy and biofuel supply chains. Kim et al. [28] developed a two-stage stochastic programming model for the design of a biofuel supply chain and included uncertainty in the price of final product, the conversion yield ratios of the two conversion processes, maximum demand and biomass availability. The authors generated 33 scenarios by changing these parameters within a ±20% range and developed an optimization model to maximize the expected profit of the scenarios. Dal-Mas et al. [29] developed a mixed integer linear programming (MILP) model for strategic design and planning of a biofuel supply chain with a 10 year time horizon. They included uncertainty in biomass cost and product selling price and produced several scenarios from combining these uncertain parameters. Two objective functions were included in this study: the expected net present value and conditional value at risk. Chen and Fan [30] incorporated uncertainty in available feedstock supply and fuel demand of a bioethanol plant that used both agricultural and forest biomass as raw materials. Their model was a mixed integer stochastic programming model integrating production, feedstock procurement, and fuel delivery to minimize costs. A two-stage stochastic MILP model was proposed by Kostina et al. [31] to include uncertainty in the demand of an integrated ethanol-sugar supply chain. Different risk measures were studied in their model including value at risk, opportunity value and risk area ratio. Another MILP model with demand uncertainty was developed by Gebreslassie et al. [32] which minimized the cost and risk simultaneously. Awudu and Zhang [33] developed a stochastic production planning model for a biofuel supply chain which included biomass suppliers, biofuel refinery plants and distribution centers. They incorporated uncertainty in the demand and price in a single period planning framework. Decision variables were the amount of purchased and consumed raw materials and the amount of produced products. Kazemzadeh and Hu [34] determined the optimal design of biofuel supply chain with uncertainties in fuel market price, feedstock yield and logistics costs. They developed two stochastic optimization models with two different objective functions (profit and conditional value at risk) and compared the results of the two models. In Ref. [35], an MIP (mixed integer programming) model was developed to provide optimum design and planning decisions for a multi-period multi-echelon ethanol supply chain. The model had multi-objectives, considering both the economic and environmental performances as well as risk mitigation preferences. Moreover, uncertainty in feedstock cost and carbon cost was captured through developing a two-stage stochastic model. For controlling risks, two risk indices were considered: expected downside risk and value at risk. Sharma et al. [36] studied the weather uncertainty in biomass supply chain through developing a scenario optimization model. The model had a one year planning horizon with monthly time steps and the objective function of minimizing the cost of biomass supply to biorefineries. Uncertainty in other parameters, e.g. yield, land rent and storage dry matter loss, was analyzed by sensitivity analysis. Osmani and Zhang [37] developed a two-stage stochastic programming model to include uncertainty in several parameters of the supply chain design problem of a bioethanol plant. The uncertain parameters were crop yield and price as well as product demand and price. They concluded that the stochastic model outperformed the deterministic model under uncertainty. In another study [38], the same authors included an environmental objective, which was minimizing carbon emissions, to the previous model. The Sample Average Approximation (SAA) algorithm was used to decompose and solve the model with large number of different uncertain parameters. Osmani and Zhang [39] also studied the problem of grid design and optimal allocation of wind and biomass resources. Uncertainties in wind speed and electricity sale price were included in a two-stage stochastic programming model.

The above mentioned studies focused on the supply chain design of biofuel plants, however, no previous study focused on forest biomass power plants and supply uncertainty. Moreover, most of the published papers did not consider supply chain planning in different time steps, and instead modeled the supply chain system in a single time-step optimization framework. The only study that provides a dynamic model is Ref. [29], which is related to a corn-ethanol supply chain. Therefore, the temporal uncertainty or seasonality of uncertain parameters in forest biomass power plants has not been considered in any of the previous studies.

Feedstock availability is one of the important factors impacting the economic viability of a forest biomass energy plant (at the strategic level planning) and energy generation cost and system efficiency (at the tactical level planning). The amount of available forest biomass varies due to a number of factors, such as market and economic fluctuations, interdependency between different forest products sectors, and forest residues accessibility during the year [40,41]. Considering supply variations is necessary in supply chain planning in order to mitigate the risk of biomass shortage and high cost of biomass procurement.

In this paper, we consider biomass supply uncertainty in a multi-period tactical model to optimize the supply chain planning of a forest biomass power plant. Uncertainty in the monthly available biomass from different suppliers is considered as a stochastic parameter during the planning horizon. Uncertainties in other parameters such as electricity prices and biomass cost are not included in our model because the power plant considered in our study has long term contracts with its customer and most of its suppliers. This means that the prices and costs do not change during the planning horizon. i.e. a year. There is a small variation in biomass cost over a year for suppliers without a fixed contract, therefore, uncertainty in biomass cost for those suppliers can be ignored as well.

This work builds on an earlier paper [42] which was a deterministic model for optimizing the supply chain of a forest biomass power plant considering forest biomass procurement and storage,

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