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Research article

A modeling framework for the optimal forest supply chain design considering residues reuse

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ABSTRACT

In the forest industry, large volumes of residues are generated during the harvesting and lumber production, whose re-use can increase the economic opportunities in this industry. In this sense, they can be used as raw material for some products (pellets, wood panels, among others) or as fuels for energy production. Due to the great number of available production alternatives and involved elements, a supply chain approach is appropriate to address this problem. Then, taking into account the particular conditions of the forest industry in Argentina, a mixed integer linear programming formulation is proposed in order to obtain the optimal design of the forest supply chain emphasizing the appropriate use of forest and wood residues. The model determines the location and size of each production facility, the amounts of products and residues to be generated, and all the material flows between forest sites and plants, between plants, and between plants and customers, in order to maximize the total benefit. This approach is suggested as a tool to analyze the optimal configuration of the forest supply chain by assessing the viability of different production alternatives. Through the different considered scenarios, it can be concluded that a strategic design for the forest supply chain is required in order to achieve an efficient use of harvest and sawmill residues.

1. Introduction

In the forest activity two big matters can be distinguished: one focuses on forestry, particularly forest management, including planting, growing, harvesting, etc., and another one focuses on industrial production or the exploitation and transformation of forest resources. This article is concerned with the second issue, from a perspective of a supply chain (SC). The SC involves many different production stages, processes, flows and products, and it entails several aspects as logs and products transportation, energy generation, lumber, paper, medium density fiberboard (MDF) productions, among others. In particular, this SC has interesting opportunities for the production of second generation biofuels, options for process integration, utilization of harvest and sawmills residues as raw material for different final products, and many alternatives of connections and exchanges among the involved actors. Taking into account the global forest sector is becoming more complex, interlinked and cross-sectoral, a detailed analysis of the available alternatives, the involved tradeoffs and the expected results is justified (Heinimö et al., 2011; Hurmekosky and Hetemäki, 2013).

One aspect that characterizes the forest industry is the large quantity of residues generated in the mechanical transformation of wood, from harvesting to obtain final products. These residues have not received much attention until now despite having interesting applications (Uasuf and Becker, 2011). Several reasons, such as involved volumes, required facilities, distances and logistic costs, have affected their efficient employment.

During harvesting, residues like foliage, branches and leaves, are generate, which can be used for producing different products. Depending on forest supply chain design, they constitute non-commercial material left on site after harvesting, or, sometimes, are chipped for transporting and sent to a plant for a later use (Vance et al., 2018). In this work, they are referred as harvesting residues and considered as raw material for pellets and ethanol production. Sawmill (or wood) residuals are those material generated by the mechanical transformation of logs, like bark, wood chips, and dust. These materials are a key issue in this industry because the generated quantity and variety constitute a big percentage of the raw material. Fortunately, these residual materials can be useful as feedstock for other products, such as bioethanol, pellets and wood panels.

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Biofuels include a wide range of fuels which are derived from biomass. In particular, foresting and sawmill residues are an option which can be used as feedstock, benefiting the production of second generation biofuels, i.e. fuels produced from residues of crop and forest (Awudu and Zhang, 2012). Biofuels can be solid (pellets or residues used for burning) and liquid (ethanol). Even though nowadays fossil fuels dominate the market, the penetration of second-generation liquid biofuels is expected to take place by the year 2020 in favorable circumstances, not only by economical and availability reasons, but also by environmental conditions (Demirbas et al., 2011).

Different articles have analyzed proposals for the production of biofuels using forest resources. For example, Pirraglia et al. (2013) developed a techno-economic model for the production of torrefied wood pellets, considering critical production parameters, and evaluating sensitivity to changes in some key parameters as capital cost, biomass delivery costs, labor, and energy consumption of a facility. Uasuf and Becker (2011) proposed diverse scenarios by studying the production costs of pellets and energy consumption using sawmills residues in the Argentinean Northeast. Pettersson et al. (2015) proposed a geographically explicit optimization model by determining the location of the different biofuel production units from forest biomass in Sweden.

On the other hand, Whalley et al. (2017) presented an economic biomass SC model to estimate the costs of biomass delivery, harvesting and chipping of the logging residues, and transport of the biomass chips to a biorefinery for biofuel production. Sarkar et al. (2011) developed a detailed techno-economic model based on demonstrated technologies currently available for producing high quality syngas from forest biomass. Mirkouei et al. (2016) analyzed the use of mobile refineries in combination with large-scale non-mobile refineries to facilitate the production of biofuel near the source of underutilized forest harvesting residues.

Forest SC design and planning are crucial for integrating different actors and activities. An analysis framework is required, and mathematical modeling, mainly using mixed integer linear programming (MILP) is a useful tool to achieve these objectives allowing decision makers to have right insights about efficient SC designs (Mishra et al., 2017). In a recent work, Mirkouei et al. (2017) presented a literature review on techno-economic modeling and optimization efforts targeted on biofuel supply chain from forest biomass. They conclude that future biomass-to-bioenergy SC must resort to the development of efficient and effective forest biomass supply chain networks. They also highlight that, more investigation into modeling and optimization of pretreatment as a part of the upstream segment of biomass-to-bioenergy SCs is needed. In the same direction, Rönnqvist et al. (2015) addressed diverse open problems in the forest industry. In particular, for SC planning they states that even though plans for the different SC components can be set, the main effort must be done in coordinating these plans across units.

Some approaches have been proposed for forest SC optimization, including the use of forestry residues and the biofuel production from them. Mobini et al. (2013) presented a model for the pellet SC, analyzing different raw materials. Kong et al. (2012) considered an integrated market where all raw materials are taken into account, including forest and sawmill residues. Cambero et al. (2015) presented a mathematical model for the production of heat, electricity, pellets and pyrolysis biofuel from available forest harvesting and sawmills residues applied to a case study in Canada. An MILP model is formulated by Troncoso and Garrido (2005) for solving the facilities location, the freight distribution and the forest production problem. Dansereau et al. (2014) proposed a framework for forestry biorefineries to help decision-makers to identify different SC policies for a variety of market conditions. Troncoso et al. (2015) dealt with the SC planning problem, including different time horizons and emphasizing the integration among production facilities.

From the above it can be noted that, in order to achieve a sustainable and efficient design of the forest SC, it is necessary to consider all the actors involved and the different alternatives for the use of residues. Previous articles integrate some production facilities and, sometimes, residues are considered. However, to the best of our knowledge, there are few published articles that distinguish among residues types and its uses, and almost none analyze the integrated design including production of traditional products as well as biofuels in the context of forest SC optimization.

On the other hand, in Argentina exists 1,200,000 hectares of planted forests, being Pinus and Eucalyptus the main species (Ministry of Science, Technology and Productive Innovation of Argentina, MINCyT, 2013). This amount is expected to increase and there are many possibilities and advantages to improve this activity. In particular, the northeast region has suitable soils, high tree growth rates, and low production costs, among other beneficial characteristics, that make the forest industry attractive and promising. Reports from public agencies also informed that more than 70% of forest residual biomass has no use, and most of harvest residues are burnt, deteriorating the soil quality (Ministry of Science, Technology and Productive Innovation, 2013). Therefore, the study of the uses for the different harvest and sawmills residues for adding value to the forest SC represents a challenge for academic and industrial sectors.

In this context, this work proposes a mathematical model for the optimal design and strategic planning of the forest SC. Different production facilities, products and raw materials are considered, as well as integrated industrial sites conforming production clusters. These clusters are introduced in order to reduce the distances between feasible locations, favoring the use of residues among facilities. Forest industries are strongly related because a variety of residues obtained from the log and lumber processes can be used for manufacturing different products. The proposed approach considers in detail the processing of residues from harvest areas and sawmills. Usually, these elements are discarded, prioritizing the main components of the production system, but in this approach, all the resources are prioritized and integrated in order to improve the raw material consumption and ensure a sustainable production. Also, the distribution of the raw material (logs) among the different production facilities is a model decision. The proposed model takes into account all these elements for a suitable assessment of the total system contemplated in the forest SC, considering the tradeoffs that affect its design. In this way, the proposed approach can be used as a tool for analyzing and designing the forest SC from a strategic perspective, where a key element is the suitable utilization of the different generated residues. Finally, this study is based on geographic and technical parameters of the northeast region of Argentina, but this model can be easily adapted to other geographical locations.

The paper is organized as follow: the next section introduces the problem, analyzing the different production facilities involved. The optimization model is presented in Section 3. Section 4 describes the SC problems addressed in this article, whose results are shown in Section 5. Finally, Section 6 presents the conclusions of this work.

2. Problem statement

A centralized forest SC, which raw material is bought from diverse sites that do not belong to the SC firm, is considered. Several production options and uses for harvest and sawmills residues are taken into account from a strategic perspective.

The forest SC considered in this work involves three echelons: harvest areas, productions facilities and consumer regions. Harvest areas are sites that provide logs, belonging to *pinus taeda* species, of