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Supply chain model to assess the feasibility of incorporating a terminal between forests and biorefineries

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HIGHLIGHTS

- A mixed-integer programming model that integrates quality aspect is presented.
- Feasibility of incorporating a terminal in the supply chain is assessed.
- A terminal stabilised cost is when procuring from different supply regions.
- Feedstock with higher quality could be delivered with access to a terminal.
- Benefits sensitive to terminal operations cost.

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ABSTRACT

This study examines the advantages of incorporating a terminal for forest biomass in an advanced biofuels supply chain network. Forest biomass as a feedstock is non-uniform, voluminous and high in moisture content (MC). This leads to inefficiencies during transportation and energy conversion process, posing a challenge for supply chains to remain profitable. The problem is exacerbated by seasonality in both supply and demand. A terminal in the biomass feedstock supply chain could help overcome these challenges, but adds a significant cost. A novel multi-period mixed-integer programming (MIP) model capable of taking into consideration biomass quality, seasonality, and weather related supply restrictions was developed. The model was applied in a case study to assess the benefits of incorporating a terminal in the supply chain. It was demonstrated that a terminal allowed delivery of feedstock 4–11% lower in MC, while reducing procurement costs by 11–32%. The benefits reported are sensitive to transportation and operating costs. The proposed model will serve as a valuable tool for practitioners to design supply chains, and assess the feasibility of using forest biomass for sustainable biofuels production.

1. Introduction

There is a growing interest in the utilization of forest biomass for advanced biofuels production [1]. In order for biofuels projects to successfully reach the commercialization phase, there needs to be certainty in the availability of suitable feedstock. Feedstock has to be cost competitive, permitting supply chains to be viable in the marketplace, while also meeting quality requirements. Logging residue and biomass salvaged from areas naturally disturbed in the forest are potential sources of sustainable feedstock to supply the biofuels industry [2]. However, forest biomass is voluminous with relatively low energy density, and high variability in quality characteristics [3]. The issue of quality is particularly important for small and medium scale plants, which require feedstocks to be uniform [4]. Thus, it is a significant challenge for forest supply chains to deliver uniform feedstock to biorefineries [5]. The problem is exacerbated by uncertainty and seasonality in both supply and demand. A potential method to overcome these challenges is to place a terminal between forests and biorefineries, where raw material can be processed to meet quality requirements [6,7].

In the context of forest biomass utilization for energy, the most important characteristics are moisture content (MC), heating value and ash content [3]. MC is the amount of water present in wood, heating value is the energy released by biomass during combustion, and ash content is the percentage of inorganic material

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present in biomass [8]. These three characteristics are interrelated and fluctuate over time. Water represents over half of the total mass in a living tree. Once cut, wood gradually releases water until it reaches a state referred to as the equilibrium MC [9]. At this state, MC fluctuates with the relative humidity of air. The net energy emitted by biomass depends on the MC; energy is consumed to vaporize water during combustion [10]. The amount of ash also reduces the net energy from biomass.

All the characteristics discussed above influence biomass procurement cost. Transporting large volumes of water embedded in biomass adds significant cost [10]. The ideal practice would be to leave biomass in the forest after harvest, allowing it to lose moisture to an acceptable level, prior to recovery and transport [11]. This practice, however, presents a logistical challenge as it requires two trips into the forest – one to recover merchantable timber, and second to recover biomass residues. This would incur additional equipment and transportation costs and potentially increase environmental damage to the forest. Transporting equipment over long distances for the sole purpose of procuring biomass is generally not profitable [12]. Furthermore, majority of access roads constructed in forests have a relatively short durability [13]. Secondary and tertiary roads are built for the specific purpose of transporting wood, thus, these roads deteriorate soon after. Residual forest biomass being a low value by-product of the logging industry, it may not be financially justifiable to maintain roads solely for its procurement. Moreover, transportation can be halted altogether during certain seasons due to weather restrictions [14]. Procurement during winter presents additional challenges. Roads have to be cleared of snow, adding significant cost to the supply chain. Also, snow mixed in with biomass will further increase MC of each truck load. To add to the challenge, the demand for energy is generally much greater during the winter season.

A terminal can be located between forests and biorefineries to overcome these logistical challenges [8,15]. Terminals can provide numerous services to the supply chain, such as sorting, storage and node for intermodal transportation [16]. It can be used as a decoupling point where inventory can be stored to deal with supply and demand uncertainties, as well as seasonality. Terminals can also be utilized as a center where feedstock can be processed to meet the quality requirements. As such, a terminal can be effective in achieving supply chain's goal of delivering homogeneous feedstock to customers in a timely manner [16,17]. However, incorporating a terminal adds significant cost to the supply chain. Kanzian et al. [18] report a cost increase of up to 26% when terminals are used. Conversely, improvement in feedstock quality, particularly in terms of reduced MC, can lead to denser biomass and reduced costs for further transportation. Acuna et al. [19] report that up to 33% less volume would be required if feedstock can be dried prior to delivery to the energy conversion plants.

The potential advantages of incorporating a terminal in the supply chain depend on a number of factors. These factors include feedstock quality, state of the road network, seasonality, and cost of operating the terminal itself [20,21]. A number of models have been proposed in the literature to support decision-making in the biomass feedstock supply chain [18,22–24]. However, there is a literature gap in terms of models that explicitly take feedstock quality dynamics into consideration in determining feasibility of incorporating a terminal. Given that one of the advantages of a terminal in the biomass feedstock supply chain is to improve feedstock quality, it is important that this be considered in the analysis. This study aims to address this gap. The specific objectives of the study are to (i) develop a mathematical model for designing a bioenergy supply chain, that tracks quality as biomass flows through the network, (ii) taking quality into consideration, assess the benefits of incorporating a terminal in biomass feedstock supply chains and (iii) determine the conditions under which a terminal becomes a viable option.

2. Method

A model was first developed to support decision making on biomass procurement planning. The material flow starts in the forest and is destined for biorefineries. Construction and demolition wood waste is another potential biomass source for biorefineries [25], and can be incorporated in the model if it is an option in a particular case. The model takes into consideration quality changes of biomass as it flows through the supply chain. The model was subsequently applied to a case study in Quebec, Canada. The case represents an instance of vendor managed inventory (VMI) where the supplier is responsible for maintaining inventory along the supply chain. A comparison between two supply chain designs were made using the biomass procurement model. The first design (Fig. 1a) represents a scenario where biomass is procured from the forest and delivered to customers without the use of a terminal. In the second design (Fig. 1b), a terminal is incorporated in the design, allowing biomass to be stored and processed prior to delivery to the final customers. The next subsection provides a detailed description of the MIP model.

2.1. Biomass procurement model

The biomass procurement model can be classified as a mixed-integer programming (MIP) model with an objective to minimize cost. The material flow starts in the forest which is divided into much smaller units called cutblocks, each with known quantity of biomass. Biomass can only be procured once the cutblocks are harvested, so information regarding harvest period is an input for this model. From the cutblocks, biomass can be either comminuted and transported to the biorefineries (clients) or to the terminal for storage. There are two options for biomass storage in the terminal. (1) It can be stored in the log yard (outside storage at the terminal) and sent to the biorefineries, or (2) it can be stored inside a depot (an open shed) within the terminal where quality can be further improved. Once biomass quality reaches a desired level, it can be sent to the biorefineries. The model sets and input data are provided in Tables A.1 and A.2 in the appendix, and the decision variables of the are presented in Table 1.

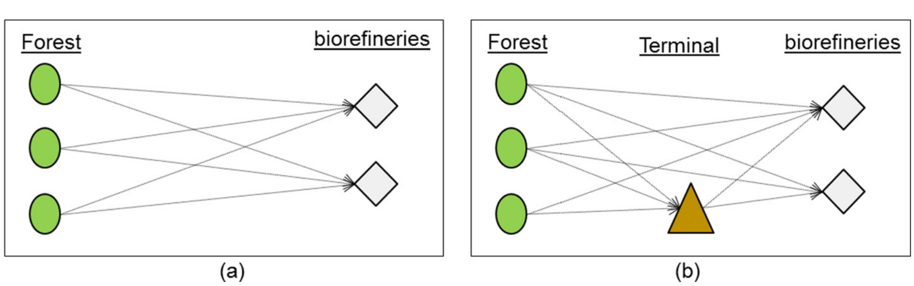

Fig. 1. Supply chain designs considered in the study.