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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.

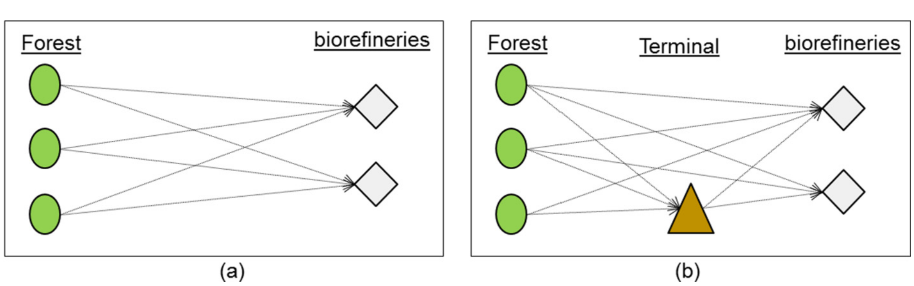

Fig. 1. Supply chain designs considered in the study.

Table 1
Decision variables of the mixed-integer programming model.

Notation	Description
F_{hcp}	Flow of biomass from cutblock h to customer c in period p
F_{hwp}	Flow of biomass from cutblock h to terminal w in period p
F_{hwcp}	Flow of biomass from terminal w to customer c in period p of material from cutblock h
F_{hwsp}	Flow of biomass from terminal w to depot s in period p of material from cutblock h
F_{hsa}	Flow of biomass from cutblock h to depot s in period a
F_{hscap}	Flow of biomass in period p from depot s to customer c of material from cutblock h that arrived in the depot in period a
I_{whp}	Inventory of biomass in terminal w of material from cutblock h in period p
I_{shap}	Inventory in period p of biomass in depot s of material from cutblock h and arrived in period a
E_{hp}	1 if biomass flows from cutblock h in period p, 0 otherwise
E_{hcp}	1 if biomass flows from cutblock h to customer c in period p, 0 otherwise
E_{hwcp}	1 if biomass flows from terminal w to customer c in period p of material from cutblock h, 0 otherwise
E_{hscap}	1 if biomass flows from depot s to customer c in period p of material from cutblock h and arrived in period a, 0 otherwise

Eq. (1) is the objective function of the model. The first element of the objective function represents the capital investment cost and terminal operation cost. Capital investment cost represents the periodic payment towards loan borrowed to construct or acquire the terminal. The second element is the cost incurred when biomass is comminuted in the forest and sent to biorefineries. The third element represents the stumpage paid to the forest owner and the cost of loading biomass to trucks when biomass is sent directly from the forest to biorefineries. The fourth and fifth elements represent the cost of transporting, comminution and loading equipment when biomass is transported from the forests directly to biorefineries. The sixth element represents cost incurred if road maintenance is required to access cutblocks. Road maintenance cost is not incurred if biomass is procured prior to deterioration of the road; this is user-defined using parameter R_{hp}. The seventh element represents the stumpage, loading and unloading cost incurred when biomass is transported from the forest to the terminal. The eighth and ninth elements account for comminution and loading costs, respectively, when biomass flows from the terminal to biorefineries. The tenth and eleventh elements represent comminution and handling costs incurred when biomass is processed in the log yard and sent to a depot for storage. The twelfth element accounts for the cost of loading biomass in the depot to trucks for transportation to the biorefineries. The thirteenth through to sixteenth elements take into consideration the costs of transporting biomass. The fourteenth and the fifteenth elements account for the inventory cost in the terminal and in the depot.

$$
\begin{aligned}
&\text{Minimize cost} = \\
&B^i + \sum_{h\in H}\sum_{c\in C}\sum_{p\in P} b^c * F_{hcp} + \sum_{h\in H}\sum_{c\in C}\sum_{p\in P}(b^s + b^l)\left(F_{hcp} + \left(\frac{m_{hp}}{100} * F_{hcp}\right)\right) \\
&+ \sum_{h\in H}\sum_{w\in W}\sum_{c\in C}\sum_{p\in P}\left(\frac{d_{hw}}{k_{hw}} + t^e\right) b^e * E_{hcp} + \sum_{h\in H}\sum_{w\in W}\sum_{p\in P} r_{hp}\left(\frac{d_{hw}}{k_{hw}} + t^e\right) b^e * E_{hp} \\
&+ \sum_{h\in H}\sum_{w\in W}\sum_{c\in C}\sum_{p\in P} r_{hp} * g_h * b^r * E_{hp} + \sum_{h\in H}\sum_{w\in W}\sum_{p\in P}(b^s + b^l + b^u)\left(F_{hwp} + \left(\frac{m_{hp}}{100} * F_{hwp}\right)\right) \\
&+ \sum_{h\in H}\sum_{w\in W}\sum_{c\in C}\sum_{p\in P} b^c * F_{hwcp} + \sum_{h\in H}\sum_{w\in W}\sum_{c\in C}\sum_{p\in P} b^l\left(F_{hwcp} + \left(\frac{m_{hp}}{100} * F_{hwcp}\right)\right) \\
&+ \sum_{h\in H}\sum_{w\in W}\sum_{s\in S}\sum_{p\in P} b^c * F_{hwsp} + \sum_{h\in H}\sum_{w\in W}\sum_{s\in S}\sum_{p\in P} b^h\left(F_{hwsp} + \left(\frac{m_{hp}}{100} * F_{hwsp}\right)\right) \\
&+ \sum_{h\in H}\sum_{s\in S}\sum_{c\in C}\sum_{a\in A}\sum_{p\in P} b^l\left(F_{hscap} + \left(\frac{m_{hp}}{100} * F_{hscap}\right)\right) \\
&+ \sum_{h\in H}\sum_{c\in C}\sum_{p\in P}\left(\left(\frac{d_{hc}}{k_{hc}} + t^v\right) * b^t\right) * \left(\left(\left(F_{hcp} * \frac{m_{hp}}{100}\right) + F_{hcp}\right)/o^t\right) \\
&+ \sum_{h\in H}\sum_{w\in W}\sum_{p\in P}\left(\left(\frac{d_{hw}}{k_{hw}} + t^v\right) * b^t\right) * \left(\left(\left(F_{hwp} * \frac{m_{hp}}{100}\right) + F_{hwp}\right)/o^t\right) \\
&+ \sum_{h\in H}\sum_{w\in W}\sum_{c\in C}\sum_{p\in P}\left(\left(\frac{d_{wc}}{k_{wc}} + t^v\right) * b^t\right) * \left(\left(\left(F_{hwcp} * \frac{m_{hp}}{100}\right) + F_{hwcp}\right)/o^t\right) \\
&+ \sum_{h\in H}\sum_{w\in W}\sum_{s\in S}\sum_{c\in C}\sum_{a\in A}\sum_{p\in P}\left(\left(\frac{d_{sc}}{k_{sc}} + t^v\right) * b^t\right) * \left(\left(\left(F_{hscap} * \frac{m_{hp} * m_{ap}^{red}}{100}\right) + F_{hscap}\right)/o^t\right) \\
&+ \sum_{w\in W}\sum_{h\in H}\sum_{p\in P} i^c * I_{whp} + \sum_{s\in S}\sum_{h\in H}\sum_{a\in A}\sum_{p\in P} i^c * I_{shap} \qquad (1)
\end{aligned}
$$

Eqs. (2)–(28) are the constraints of the MIP model. Eqs. (2) and (3) link the binary variables with continuous variables. For each cutblock, the binary variable becomes 1 when even a small amount of biomass is procured. The binary variables are subsequently used to force all available biomass to be procured in the same period using Eqs. (4) and (5). Eq. (6) ensures that the biomass procured is less than or equal to the total available in each cutblock. Eq. (7) constraints the model to fulfill demand in each of the periods. Demand is placed in the form of energy unit. The total amount of biomass required to fulfill the demand is determined through multiplying the tonne of biomass by its lower heating value. The lower heating value is calculated based on an equation published in Sokhansanj [26]. On the right hand side, the demand from each biorefinery is divided by their respective energy conversion efficiencies. Eqs. (8)–(13) link binary variables with continuous variables. The binary variables become 1 when even a small amount of biomass flows to a biorefinery from the different sources. The binary variables are subsequently used to ensure that MC of biomass is within the range specified by the customers in Eqs. (14)–(19). Flow conservation constraints for the terminal are managed using Eqs. (20) and (21). Flow conservation in the Depot is managed using Eqs. (22) and (23). Two sets of time periods were used to keep track of biomass arrival and departure periods in the terminal. Eq. (24) ensures consistency between the two time periods. Eqs. (25) and (26) restrict the storage capacity in the log yard of the terminal and in the depot. Finally, Eqs. (27) and (28) are non-negativity and binary variables, respectively.

$$E_{hp} \leqslant \sum_{c\in C} F_{hcp} + \sum_{w\in W} F_{hwp} \quad \forall h, p \qquad (2)$$

$$E_{hp} \geqslant \left(\sum_{c\in C} F_{hcp} + \sum_{w\in W} F_{hwp}\right) * Q \quad \forall h, p \qquad (3)$$

$$\sum_{p\in P} v_h * E_{hp} = \sum_{c\in C}\sum_{p\in P} F_{hcp} + \sum_{w\in W}\sum_{p\in P} F_{hwp} \quad \forall h \qquad (4)$$

$$\sum_{p\in P} E_{hp} \leqslant 1 \quad \forall h \qquad (5)$$

$$\sum_{c\in C}\sum_{p\in P} F_{hcp} + \sum_{w\in W}\sum_{p\in P} F_{hwp} \leqslant V_h \quad \forall h \qquad (6)$$

$$
\begin{aligned}
&\sum_{h\in H}(j^v - m_{hp}j^v - q^w m_{hp})F_{hcp} + \sum_{h\in H}\sum_{w\in W}(j^v - m_{hp}j^v \\
&\quad - q^w m_{hp})F_{hwcp} + \sum_{h\in H}\sum_{s\in S}\sum_{a\in A}(J^v - m_{hp}j^v - q^w m_{hp})F_{hscap} \\
&\quad \geqslant \frac{d_{cp}}{n_c} \quad \forall c, p \qquad (7)
\end{aligned}
$$

$$q * F_{hcp} \leqslant E_{hcp} \quad \forall h, c, p \tag{8}$$

$$F_{hcp} \geqslant E_{hcp} \quad \forall h, c, p \tag{9}$$

$$q * F_{hwcp} \leqslant E_{hwcp} \quad \forall h, w, c, p \tag{10}$$

$$F_{hwcp} \geqslant E_{hwcp} \quad \forall h, w, c, p \tag{11}$$

$$q * F_{hscap} \leqslant E_{hscap} \quad \forall h, s, c, a, p \tag{12}$$

$$F_{hscap} \geqslant E_{hscap} \quad \forall h, s, c, a, p \tag{13}$$

$$m_{hp} E_{hcp} \leqslant m_c^{max} \quad \forall h, c, p \tag{14}$$

$$m_{hp} E_{hcp} \geqslant m_c^{min} \quad \forall h, c, p \tag{15}$$

$$m_{hp} E_{hwcp} \leqslant m_c^{max} \quad \forall h, w, c, p \tag{16}$$

$$m_{hp} E_{hwcp} \geqslant m_c^{min} \quad \forall h, w, c, p \tag{17}$$

$$m_{hp} E_{hscap} \leqslant m_c^{max} \quad \forall h, s, c, a, p \tag{18}$$

$$m_{hp} E_{hscap} \geqslant m_c^{min} \quad \forall h, s, c, a, p \tag{19}$$

$$I_{whp} = I_{w,h,p-1} + F_{hwp} - \sum_{c \in C} F_{hwcp} - \sum_{s \in S} F_{hwsp} \quad \forall w, h \tag{20}$$

$$\sum_{c \in C} F_{hwcp} - \sum_{s \in S} F_{hwsp} \leqslant I_{whp} \quad \forall w, p, h \tag{21}$$

$$I_{shap} = I_{s,h,a,p-1} + F_{hsa} - \sum_{c \in C} F_{hscap} \quad \forall s, h, a, p \tag{22}$$

$$\sum_{c \in C} F_{hscap} \leqslant I_{shap} \quad \forall p, h, s, a \tag{23}$$

$$\sum_{w \in W} F_{hwsp} = F_{hsa} \quad \forall h, s, p = a \tag{24}$$

$$\sum_{h \in H} I_{whp} \leqslant o_w \quad \forall w, p \tag{25}$$

$$\sum_{a \in A} \sum_{h \in H} I_{shap} \leqslant o_s \quad \forall s, p \tag{26}$$

$$E_{hp}, E_{hcp}, E_{hwcp}, E_{hscap} \in \{0, 1\} \tag{27}$$

$$F_{hcp}, F_{hwp}, F_{hwcp}, F_{hwsp}, F_{hsa}, F_{hscap}, I_{whp}, I_{shap} \geqslant 0 \quad \forall h, w, s, c, p, a \tag{28}$$

2.2. Case study

The model was applied to the case of a company in Quebec, Canada with contractual agreements to supply forest biomass to a number of biorefineries. The company operates in a public forest (Fig. 2) where the supply is regulated by the Quebec ministry of forests, wildlife and parks. The government provides an annual plan outlining cutblocks available for the upcoming year. Higher quality wood is sent to forest products manufacturers, and inferior quality material (biomass) is used as feedstock for biorefineries. More specifically, throughout this case study, biomass refers to the section of a tree less than 9 cm in diameter, and excludes branches and leaves. For the purpose of the experiment, cutblocks from two annual plans (2011–2013) were selected. The forest was

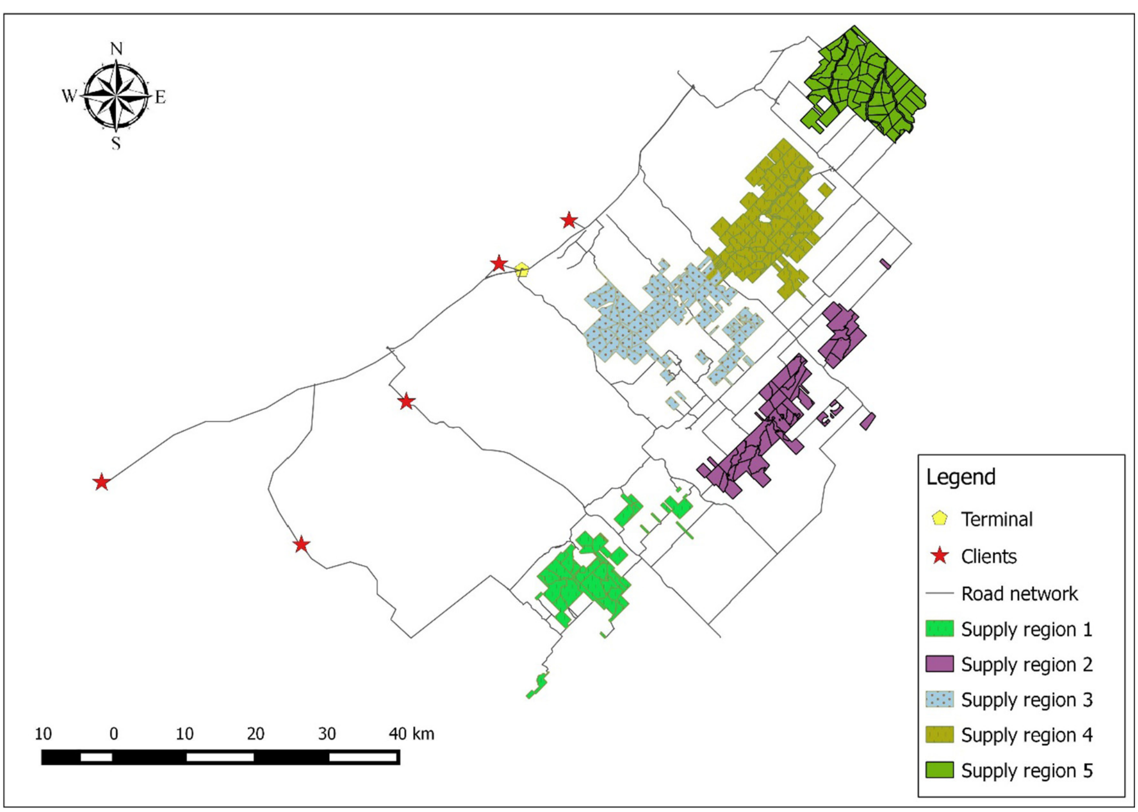

Fig. 2. A map of the case study area.

divided into several regions, and separate analyses were carried out for each region (Fig. 2). This allowed the industrial partner to identify regions ideal for biomass procurement. Also, it allowed terminal feasibility to be evaluated under various scenarios. In addition to the differences in distances, each region had varying proportions of cutblocks harvested at different times. The volumes of biomass available in the cutblocks were estimated using Eqs. (29)–(31) (from Lambert et al. [27]).

$$y_{wood} = \beta_{wood1} D^{\beta wood2} H^{\beta wood3} + e_{wood} \tag{29}$$

$$y_{bark} = \beta_{bark1} D^{\beta bark2} H^{\beta bark3} + e_{bark} \tag{30}$$

$$y_{stem} = \hat{y}_{wood} + \hat{y}_{bark} + e_{stem} \tag{31}$$

In Eqs. (29)–(31), y_i is dry biomass of wood and bark in kilograms; D is the diameter breast height (dbh) in centimetres; H is the height in metres. β_i and e_i are constants provided in Lambert et al. [27] based on tree species.

In scenarios where a terminal was made available (Fig. 1b), a configuration that included both log yard and a depot was used. Model parameters were obtained from numerous sources. The terminal investment cost was obtained from Lemieux et al. [28]. It was assumed that an amount of \$ 1,126,523 (CAD 2016) was borrowed at 5% interest with an amortization period of 20 years. This investment is required to acquire land, pave certain areas, construct depot, purchase and install weigh scale, build office space, and install other essential amenities. The operation cost of the terminal was assumed be \$ 110,000 year^{-1}. It includes payroll for two employees, maintenance and operation of the weigh scale, and government taxes. The cost of comminuting biomass was assumed to be \$20 ODt^{-1} [28], loading, unloading and handling costs were assumed to be \$3.5 gmt^{-1} each [29]. The loading, unloading and wait times were assumed to be 1 h per trip. Trucks had a capacity to transport 36 green metric tonne (gmt) per trip and charged \$125 h^{-1} to deliver biomass. The total storage capacity in the terminal was 6000 gmt (5000 gmt in the log yard and 1000 gmt in the depot). The distances between the cutblocks, terminal and biorefineries were estimated using GIS. The customers could be considered small to medium biorefineries with limited capacity to store inventory at their site. Thus processing the feedstock at the biorefinery was not an option.

Due to the lack of equations for MC estimation in the study area, approximations were based on data published in the literature. Once a tree is cut, it starts to lose moisture, gradually reaching a dynamic equilibrium [9]. Subsequently, moisture fluctuates with temperature and relative humidity. Thus, MC in biomass was assumed to be a function of time since harvest [19]. An average value was used for all material harvested in a particular time. As for the estimation of values at different points in time, data published in previous studies were used [11,30,31]. The moisture content ranged between 20 and 50% green basis (the weight ratio of water to green wood). In this manner, curves were generated that could estimate MC based on time since harvest. It was assumed that MC could be gradually reduced by 1% through placing biomass in a depot within the terminal.

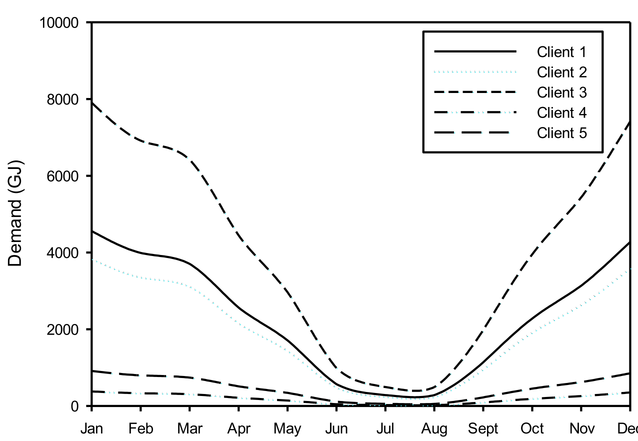

Fig. 3. Monthly demand from biorefineries used in the case study.

Demand from the biorefineries arrives in the form of energy (GJ). Demand information used in the case study is shown in Fig. 3. The actual quantity of biomass required to fulfill demand depends on MC, as well as the conversion efficiency of the biorefinery. Customers require feedstock with MC in the range of 25–40%. All input data and the mathematical model were coded in AMPL modelling language [32] and solved using CPLEX 12.5 in a 3.07 GHZ PC with 12GB RAM. The planning horizon in the experiment was 1 year divided into 12 monthly periods for each scenario. In scenarios where terminal is not incorporated, biomass is comminuted in the forest and sent directly to the biorefineries. In scenarios where a terminal is made available, there are one of three routes through which biomass is transported by the model: (i) it can be comminuted in the forest and sent directly to the biorefineries, (ii) it can be transported to the terminal where it is stored in the log yard, comminuted and sent to the biorefineries, and (iii) it can be transported to the log yard, comminuted and stored in the depot, then sent to the biorefineries.

3. Results and discussion

The total cost incurred to fulfill demand when using biomass from the different forest regions are shown in Fig. 4. For each region, the two bars represent costs incurred in scenarios with and without a terminal in the supply chain, respectively. Numbers on top of the bars indicate the minimum MC of biomass that could be delivered throughout the planning horizon. It was assumed that 0.5 km of the road needed to be upgraded for each cutblock that required maintenance. The results show that utilizing a terminal allows the supply chain to fulfill demand from the biorefineries at a lower cost. Incorporating a terminal allowed the cost to be stabilised when procuring from different forest regions. Without a terminal, the cost to fulfill demand ranged from \$332,595 to \$430,810. The cost range was much narrower with access to a terminal, from \$294,312 to \$310,382. Gunnarsson et al. [23] also observed a reduction in cost when a terminal was added to the supply chain, although MC was not taken into consideration.

Incorporating a terminal allowed the supply chain to decouple supply from demand. Subsequently, different operations strategy could be employed upstream versus downstream of the decoupling point [33]. Additionally, a terminal expands the number of sourcing options on high quality biomass for each biorefinery. Without a terminal, the supply chain is exposed to fluctuation in cost associated with road maintenance, particularly in geographical regions with severe climate conditions. The extreme heat and freeze-thaw cycle during winter can rapidly deteriorate forest roads requiring frequent maintenance to ensure accessibility [34]. Maintenance may involve one or several of the following activities: grading, resurfacing, roadside vegetation control, restoration of drainage systems, sediment control and snow removal during winter. As such, road maintenance costs vary significantly based on the state of the road. Without a terminal, the supply chain is forced to procure biomass from the forest when demand arises, incurring road maintenance cost. Fig. 5 shows the potential increases in cost due to road maintenance. Eqs. (4) and (5) ensure that the maintenance cost is incurred a maximum of one time. The y-axis represents the total cost to fulfill all demand (shown in Fig. 3). The x-

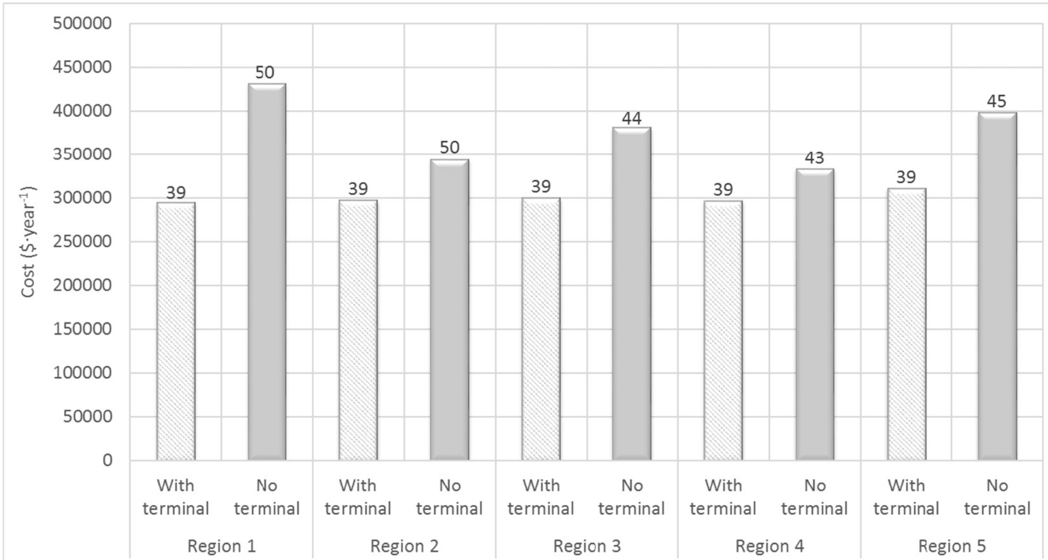

Fig. 4. Cost comparison of fulfilling demand with and without a terminal in the supply chain.

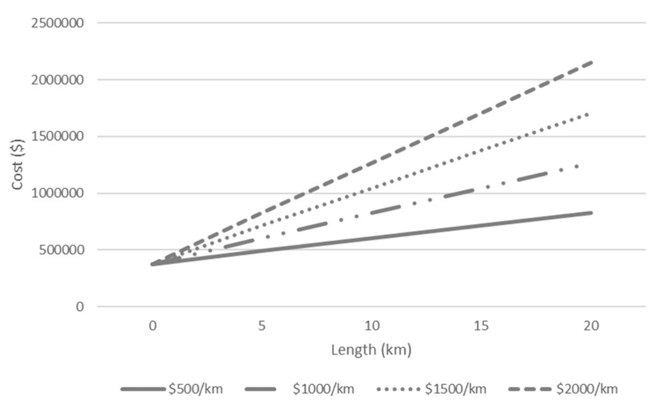

Fig. 5. The influence of different maintenance cost rates, and road length to be maintained on total cost.

axis represents the length of road that requires maintenance to access cutblocks for biomass procurement. As this length increases, so does the total cost. Each series in Fig. 5 represents different rates to repair each kilometer of road. As stated earlier, road maintenance costs vary significantly based on the state of the road. When maintenance is required, the road is graded at a minimum. Grader costs approximately \$125 h^{-1} and has a productivity of 250 m h^{-1} [35], incurring \$500 km^{-1}. Thus \$500 km^{-1} is the rate used in the lowest cost scenario. The highest cost scenario represents a rate of \$2000 km^{-1}, but the upper bound for road maintenance cost can be much higher [36].

With access to a terminal, road maintenance costs could be minimized significantly, the total cost to fulfill all demand was \$297,462. A terminal allowed biomass to be procured at a time when road conditions were favourable, avoiding snow and wet weather conditions. Without a terminal, even with 0 km of road requiring maintenance, the cost was \$376,853. The increased cost is due to the delivery of biomass with high MC. With access to a terminal, the supply chain was able to deliver biomass that was lower in MC by 4–11%. This provides an explanation for the lower cost achieved in scenarios with a terminal. Transporting biomass with high MC has a compounding impact on cost. In addition to inefficiency during transportation, high MC in biomass also decreases the lower heating value [37]. Consequently, a greater amount of biomass is required to generate an equal amount of energy, adding to the overall cost. It must be stated that the advantages associated with a terminal may be underestimated in this case study. It was assumed that placing biomass in a depot would gradually reduce its MC by 1%. This was a conservative estimation as there is a lack of published data on this matter. Nonetheless, the purpose of this study was to compare two scenarios with and without a terminal, and the results show that benefits can be realised even at 1% reduction of MC. The capacity to further reduce the MC in the depot should only increase the advantage associated with a terminal.

Despite the advantages observed in the case study, the results indicate that the benefits of a terminal are fairly sensitive to operations costs. When procuring from regions 1, 3 and 5, cost reductions of over \$80,000 were observed, but the differences were below \$50,000 in regions 2 and 4. The differences in cost reductions between regions are due to: (i) varying distances of the regions, which had an impact on the transportation cost, and (ii) the fact that each region had varying proportions of cutblocks harvested at different times, influencing biomass moisture content. A slight increase in procurement costs in regions 2 and 4 could nullify the benefits of a terminal. This points to the need for continuing efforts to reduce operations cost, not just at the terminal but throughout the supply chain. Production capacities must be set at a level where inefficiencies are minimized [22]. Under or excess capacity can be detrimental to the supply chain with such low profit margins. The model was used for the purpose of determining optimal inventory capacity in the terminal. Generally, a total inventory capacity is determined for a terminal [38]. It was noted that cost reduction can be achieved through different combinations of capacities in the log yard and in the depot within a terminal. The combinations of inventory capacities that minimizes cost is shown in Fig. 6, with log yard capacity in the x-axis and the depot capacity in the y-axis. If the current combination lies below the frontier, cost could be reduced through increasing inventory capacity. A combination beyond the frontier does not contribute to further cost reduction. The frontier is best described as being a piecewise linear curve. However, the curve will certainly vary when applied in another case study. Nevertheless, the result demonstrates the potential of the model to generate valuable information to support decision-making in the biofuels supply chain network.

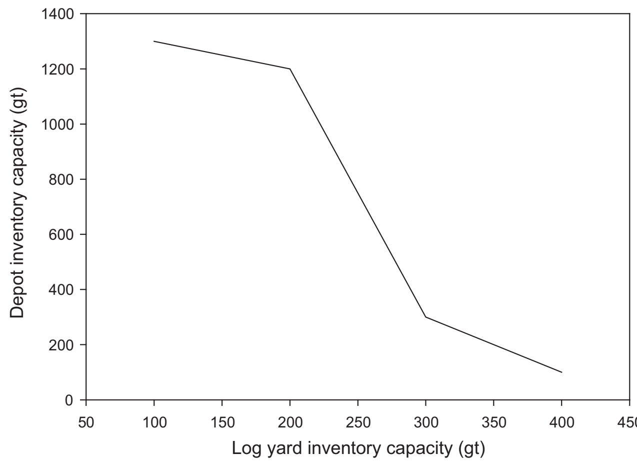

Fig. 6. Optimal inventory frontier for a terminal showing capacity combinations of depot and log yard that minimizes procurement cost.

The developed model is an important part of a future decision support system for planning sustainable biofuel production from forest biomass. The model takes into consideration the various complexities of the supply chain to develop an integrated plan. The application of the model to the case study has demonstrated its capability to evaluate the role of a terminal in the supply chain. The model can similarly be used as an analytical tool to support decision-making at operational, tactical and strategic levels. At the operational level, the model should be used to develop short-term plans in a rolling time horizon basis. Such an approach allows practitioners to overcome both supply and demand related uncertainties in the biofuels industry. At the tactical level, practitioners can use the model to carry out scenario analysis for the purpose of capacity setting in the terminal. Under or excess capacity in the CTCB can be detrimental to the supply chain's competitiveness. Similarly, at the strategic level, the model will facilitate in choosing an optimal location for a terminal. A terminal requires a significant capital investment, and the decision is practically irreversible once it is made. The model will prove to be an instrumental tool in identifying optimal locations with the greatest probability of generating value.

4. Conclusion

It is important to deliver high-quality feedstock to support sustainable biofuel production. However, it is a challenge to supply forest biomass feedstock of high quality at low cost. Incorporating a terminal in the supply chain can help overcome the challenges, but adds a significant cost. Decision support systems based on mathematical models are important analytical tools to assess the feasibility of incorporating a terminal in the supply chain. This paper presents such a model to quantify the benefits of a terminal. The contribution of this model in relation to others in the literature is that it integrates information on biomass quality, harvest schedule, and seasonality in supply and demand to quantify the benefits of a terminal. Application of the model to a case study showed that incorporating a terminal leads to a greater likelihood of delivering biomass at a lower cost. Cost reductions of 11–31% were observed when procuring from different forest regions. Furthermore, a terminal permitted the supply chain to deliver biomass with MC lower by 4–11%. Biomass with high MC had a compounding impact on cost. Firstly, it led to inefficiency during transportation. Additionally, considering that high moisture negatively impacts the lower heating values, a greater amount of biomass was required to fulfill demand, further increasing cost. Another key reason for cost reduction with access to a terminal was that it alleviated the impact of seasonality. The supply chain could procure biomass from the forest when road did not require maintenance and it could be stored at the terminal. In scenarios without a terminal, the supply chain was forced to access the forest even when road conditions were not ideal, and incur road maintenance costs. A sensitivity analysis showed that the length of road to be maintained proportionally increases the total procurement cost. Even with the lowest budget option, each additional kilometer increased the cost significantly. Nevertheless, it was observed that the benefits of a terminal are quite sensitive to operations costs. Efforts to reduce such costs must continue to qualify forest biomass as a viable option for advanced biofuels production. Future studies

Table A.1
Description of the sets in the mixed-integer programming model.

Notation	Description
H	Set of cutblocks from which biomass can be procured
W	Set of terminals where biomass can be stored
S	Set of depots where biomass can be stored
C	Set of clients with demand for biomass
P	Set of time periods
A	Set of time periods in which biomass enter depots

Table A.2
Input parameters of the mixed-integer programming model.

Notation	Description
b^i	Capital investment cost and terminal operation cost (\$ year^{-1})
b^c	Comminution cost (\$ ODt^{-1})
b^s	Stumpage fees paid to the government (\$ gt^{-1})
b^l	Cost incurred to load biomass for transportation (\$ gt^{-1})
b^u	Cost incurred to unload biomass after transportation (\$ gt^{-1})
t^e	Total time taken to load and unload equipment for transportation (h)
b^e	Payment rate to equipment transportation company (\$ h^{-1})
r_{hp}	Period p in which cutblock h was harvested obtains a value of 0, 1 otherwise
g_h	Length of road that requires upgrade when procuring from cutblock h (km)
b^r	Payment rate to upgrade roads (\$ km^{-1})
b^h	Handling cost of material in the terminal (\$ ODt^{-1})
t^v	Total time taken to load and unload a load of biomass from a truck (h)
b^t	Payment rate (\$ h^{-1}) to trucking company
o^t	Maximum payload (green tonne)
d_{hc}	Distance (km) from cutblock h to customer c
d_{hw}	Distance (km) from cutblock h to terminal w
d_{wc}	Distance (km) from terminal w to customer c
d_{sc}	Distance (km) from depot s to customer c
k_{hc}	Traveling speed (km h^{-1}) from cutblock h to customer c
k_{hw}	Traveling speed (km h^{-1}) from cutblock h to terminal w
k_{wc}	Traveling speed (km h^{-1}) from terminal w to customer c
k_{sc}	Traveling speed (km h^{-1}) from depot s to customer c
i^c	Inventory cost at terminal and depot
v_h	Amount of biomass available(ODt) in cutblock h
d_{cp}	Demand of energy (GJ) by customer c in period p
o_w	Storage capacity of biomass in terminal w (gt)
o_s	Storage capacity of biomass in depot s (gt)
m_{hp}	MC of biomass from cutblock h in period p in dry basis
j^v	The higher heating value of biomass (GJ t^{-1})
m_c^{max}	The maximum value of MC that can be transported to customer c
m_c^{min}	The minimum value of MC that can be transported to customer c
m_{ap}^{red}	Percentage reduction in MC in period p of material that entered the depot in period a
n_c	Ratio between input of energy content of biomass and energy output
q^w	Constant 2.447 to represent the latent heat of vaporization of water
q	A small number

should integrate the presented model with forest level models. Such integration will reveal deeper insights on the sustainability of forest biomass utilization for biofuels production.

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Appendix A

See Tables A.1 and A.2.

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