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The cost of closed terminals in the supply chain for a potential biorefinery in northern Sweden

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ABSTRACT
Establishment of biorefineries for processing forest biomass in the Nordic region is extremely costly due to the high investment, running, and procurement costs. Procurement costs could be reduced by allowing all actors to open access to all available terminals in an area (regardless of ownership) and allowing trucks with higher gross weight. These impacts of changes were evaluated for deliveries of logging residue and energy wood chips to a potential biorefinery, from two suppliers in northern Sweden. Open access to all terminals reduced the terminal-procurement costs by 2–6% and the terminal-to-biorefinery transportation costs by 7–9%. When 74 tonnes trucks were used instead of 60 tonnes, the terminal-to-biorefinery transportation costs were reduced by 4 and 3%, in the current situation and with open access to terminals, respectively. However, the largest effect of open access was that the fraction of short-distance transportation to terminals and train transportation from terminals increased significantly. This indicated that open access to terminals and relatively heavy trucks between terminals and the biorefinery are preferable from both environmental and economic perspectives. Furthermore, the estimated cost saving was adequate and should allow the deliverers to pay a reasonable fee for the use of terminal space.

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GIS; biomass terminals; wood logistics

Introduction

A decrease in the use of fossil fuels and fossil feedstocks and increased energy production and production of products from renewable sources are desired in order to mitigate the impact of climate changes resulting from human activity (European Commission 2011; Swedish Enviromental Protection Agancy 2012). These sources can include wind, solar, hydro, and biopower, as well as materials generated from biological feedstocks, as biomass from forests, agricultural, and aquatic systems. However, these developments rely on an adequate supply of input (biomass, wind, water, and sun), competitive production systems, and long-term solutions capable of competing with fossil energy and products (Giuliano et al. 2016). Northern Sweden represents a potential source for forest biomass (Fridh and Christiansen 2015; Athanassiadis and Nordfjell 2017), and plans for increasing the number of biorefineries in the region have been proposed (e.g. Lundin 2017). However, the high cost of the forest biomass procurement systems and lack of long-term regulations have limited investments in the region (Börjesson et al. 2017). Therefore, reducing costs and improving the efficiency of the supply chain are essential for transitioning to a bio-based economy.

The logistic chain of forest biomass is complex and there are many different options for transportation from the forest to end-users (Routa et al. 2013; Wolfsmayr and Rauch 2014). The forest biomass can be transported either directly to the end-user or via a terminal. Terminals are mainly used when reloading, processing, or storing of the biomass (before delivery to the end-user) are required (Asmoarp 2013; Kons 2015). Reloading is mainly required for long-distance transportation by train. Currently, processing consists mainly of biomass comminution, either for increased bulk density or for delivery to end-users that lack comminution capacity. Storage is needed during periods characterized by bad forest-road conditions, e.g. the spring-thaw period when forests are inaccessible. Weather-wise fluctuations in the feedstock demand of heat and power plants also lead to storage requirements.

Woody biomass assortments may be transported via various methods (Berglund and Larsson 2012; Iwarson-Wide and Palmer 2015). Energy wood can be transported with timber trucks from the forest as it is or comminuted at landings and transported as chips. Logging residues, can also be comminuted at the landing or transported loose in logging residue trucks. Comminution at landings can be conducted with a chipper that either directly loads trucks, or chips the material into piles. A self-loading chip truck can then load material from these piles or a wheel loader can load a chip truck from the piles. The comminution and transportation can also be performed by chipper trucks that both comminute and transport the material. Long-distance transportation from terminals is usually performed by trains or by trucks that have lightweight frames, in order to maximize the payload (Enström et al. 2013). Moreover, trucks with a relatively high gross weight have recently been employed for transportation (Zachrisson 2017). These trucks are currently utilized in

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transportation work (where allowable) between terminals and end-users, but can subsequently be used for forest-to-terminal transportation work, depending on the forest-road suitability.

The forest biomass procurement cost for different supply systems (current and theoretical) in the Nordic countries have been reported (e.g. Tahvanainen and Anttila 2011; Joelsson et al. 2016; Laitila et al. 2016; Berg and Athanassiadis 2019). Athanassiadis and Nordfjell (2017) presented marginal procurement cost curves for logging residues and stumps in northern Sweden, based on costs from forests to terminals/end-users in the region. However, the effect of long-distance train transportation from the terminal to other regions remains unexplored.

Supplying biomass to potential biorefinery sites along the coast of northern Sweden remains a major challenge, because of long transportation distances and high costs. Furthermore, there are terminals with accessibility constraints, i.e. some terminals can be used by all actors in the area (open terminals) while others can only be used by the owner (closed terminals). This limits the access of some actors to the railroad network, leading to both increased cost and environmental impact. To evaluate this limitation the total cost and transportation work from forests to end-user should be estimated.

Aim

The aim of this study was to evaluate the procurement cost of forest biomass supply (by different potential suppliers) to a potential biorefinery when different terminal configurations are used, and to determine the effect of heavier trucks on the transportation costs.

Material and methods

The supply area considered in this study was located in northern Sweden, more specifically in Jämtland and the inland parts of the Norrbotten and Västerbotten regions (Figure 1). Two potential suppliers of forest biomass were identified in the area; the forest company Sveaskog (FCS) and a theoretical combination of private forest owners and small institutional owners (FOCO) consisting of physical persons, estates of deceased persons, municipalities, and the Swedish church (Table 1). FOCO is not a real present-day operator, but does resemble a forest owners association. A potential biorefinery was located at the coast in northern Sweden, i.e. in Örnsköldsvik (latitude 63.28899, longitude 18.71319). This biorefinery had a planned yearly forest biomass demand ($dBio_{bio}$) of ~183,000 bone dry tonnes (BDt). Productive forest areas associated with FCS (55 areas) and FOCO (153 areas) were extracted from the Forest Ownership map of Sweden (Table 1 and Figure 1). Deliveries to terminals of logging residues (tLR) and energy wood (tEW) were assumed to be proportional to the size of the terminal, when less than demanded volume could be delivered (Tables 1 and 2).

Harvesting potentials for logging residues (sLR_f) and energy wood (sEW_f) for FCS and FOCO areas were extracted from the SKA 15 study (Claesson et al. 2015). In SKA 15, estimations of forest development and forest fuel harvest potential were performed with the Heureka Regwise simulator (Wikstrom et al. 2011). The Heureka tool uses the sample plots (both permanent and temporary) of the Swedish national forest inventory obtained from 2008 to 2012 (Toet et al. 2007; Fridman et al. 2014; Anon. 2018). The estimations of FCS's and FOCO's supply potential were based on sample

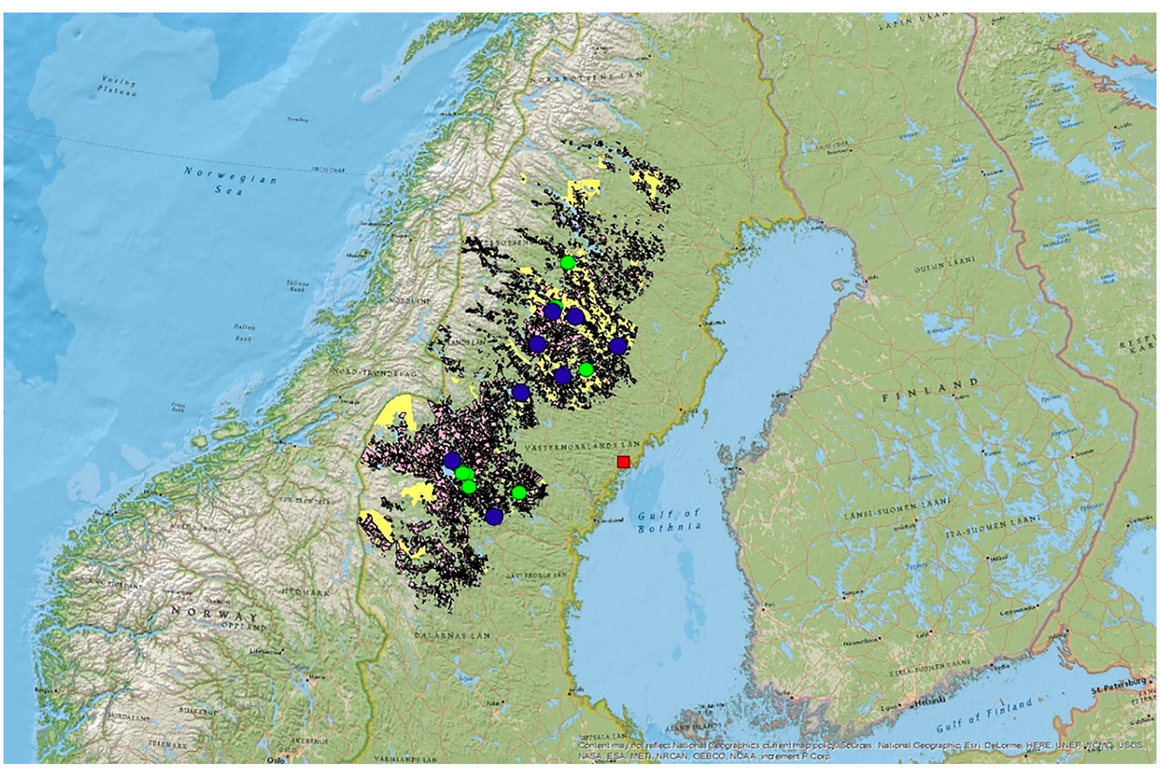

Figure 1. Overview of the studied region. Yellow areas, pink areas, green dots, blue dots, and the red dot represent FCS regions, FOCO regions, open terminals, closed terminals, and sthe biorefinery, respectively.

Table 1. Characteristics of the two forest owners, FCS and FOCO, included in the study.

	Potential			
	Thinning area (ha/year)	Regeneration felling area (ha/year)	Energy wood[a] (BDt/year)	Logging residues[b] (BDt/year)
FCS	5,341	8,664	600	175,402
FOCO	13,980	19,563	1,677	652,971

[a]corresponds to $\sum_{f}^{F} sEW_f$ for the two suppliers. [b] corresponds to $\sum_{f}^{F} sLR_f$ for the two suppliers.

plots (denoted in the optimization equations as $_f$) that had fallen on their respective estates.

The current study focused on logging residues (branches and tops) and energy wood (non-commercial pulpwood). The following assumptions were made: (i) logging residues were harvested in regeneration fellings (RF) i.e. in stands that were clear cut and in stands where seed trees were left standing (Table 1), (ii) energy wood was harvested in RF and thinnings, and accounted for 2% of the pulpwood, (Table 1) and (iii) energy wood chips and logging residue chips have different dry bulk densities (Table 3), whereas energy wood from RF and thinning have the same densities. All volumes and masses were converted to BDt (Table 3). After discussion with industrial partners it was assumed that, in average, 2% of the pulp wood volume gets degraded due to fungi and/or rotting and can be used as energy wood.

Transportation systems and costs

The procurement systems included in the study are presented in Table 4, and a schematic view is provided in Figure 2. The procurement systems are denoted as "Forest to terminal" and "terminal to biorefinery".

Terminals

Eighteen forest biomass terminals were identified in the region (Figure 1 and Table 2). Eight of the terminals were identified as closed (i.e. affiliated neither with FCS nor with FOCO) and under normal conditions were neither used by FCS nor FOCO for transportation of biomass. Two scenarios were formulated: (i) an open-access scenario where FCS and FOCO were allowed to deliver logging residues and energy wood to both the open and the closed terminals and (ii) a restricted access scenario where biomass could only be delivered to the ten open terminals. In both scenarios, the biomass flow through the terminal was directly correlated to the area of the terminal. The annual flow through a terminal was assumed to be 0.17 BDt per m^2 and 0.357 BDt per m^2 (2.1 times greater) in the open access and restricted access scenarios, respectively. Therefore, in both scenarios, the total capacity of the terminals was slightly greater than 183,000 BDt (Table 2), that is just enough to cover the $dBio_{bio}$ of the biorefinery.

Table 2. Characteristic of the terminals included in the study.

Terminal	Status	Area (m^2)[a]	Access to railroad	Biomass turnover (BDt)+		Distance to biorefinery (km)	
				Open access scenario	Restricted access scenario	Train	Truck
T_1	Closed	145,000	Y	24,650		345	266
T_2	Closed	60,994	Y	10,369		255	234
T_3	Closed	88,983	Y	15,127		228	186
T_4	Closed	77,718	Y	13,212		359	249
T_5	Open	87,419	Y	14,861	31,208	356	257
T_6	Closed	80,000	Y	13,600		252	180
T_7	Open	20,000	Y	3,400	7,140	195	174
T_8	Open	115,000	Y	19,550	41,055	324	247
T_9	Open	12,000	N	2,040	4,284	-	179
T_10	Open	40,000	N	6,800	14,280	-	239
T_11	Open	70,000	Y	11,900	24,990	303	246
T_12	Closed	48,139	Y	8,184		306	210
T_13	Closed	21,600	N	3,672		-	151
T_14	Open	4,500	N	765	1,607	-	312
T_15	Closed	43,000	N	7,310		-	238
T_16	Open	54,490	N	9,263	19,453	-	148
T_17	Open	30,000	N	5,100	10,710	-	181
T_18	Open	80,000	N	13,600	28,560	-	246
Sum		**1,078,843**		**183,403**	**183,287**		

[a]50% of the terminal area is assumed to be occupied by terminal buildings, roads and railway lines. Y indicated yes, and N indicates no. + Corresponding to dLR_T and dEW_T for the two suppliers.

Table 3. Values used for conversion of input variables to bone dry mass in the study.

	Moisture content	BDkg/m^3solid	kg/m^3solid	BDkg/m^3loose	kg/m^3loose	m^3top measured[C]/m^3solid[C]
Logging residues	50[R]	395[R]	790[x]	-	-	-
Logging residue chips	45[R]	-	-	170[C]	309[x]	-
Energy wood	50[R]	409[JC]	819[x]	-	-	1.56[C]
Energy wood chips	45[A]	-	-	176*	319[x]	-

- indicates no value. [A]indicates that the values was assumed. [C]Christiansen (2015). [JC] indicates that the value is estimated based on pine 408 BDkg/m^3solid, spruce 382 BDkg/m^3solid and that birch was assumed to be 20% heavier the spruce (458 BDkg/m^3solid) (Jonsson 1985), and the proportion of tree species was 48% pine, 33% spruce and 19% birch (Ringman 1996; Christiansen 2015). [R]Ringman (1996). *indicates that the value was calculated 170/395×409 to give the same relative difference in BDkg/m^3loose as in BDkg/m^3solid. [x] indicates that the value was calculated based on density and moisture content.

Table 4. Characteristics of the procurement systems included in the study.

Procurement system	Truck type	Gross weight (tonnes)	Comment
From forest to terminal			
PS_A	Logging residue	60	Logging residues were transported uncomminuted and comminuted at terminals. The trucks were equipped with cranes for loading and unloading.
PS_B[a,d]	Chip	60	Transportation of logging residue chips. The trucks were assumed to be directly loaded by a chipper at the landing.
PS_C[a,d]	Chipper	60	Logging residues were chipped at the landing by the chipper truck before transportation to terminal.
PS_{DRF}	Timber	60	Transportation of energy wood from regeneration fellings. Trucks were equipped with cranes for loading at the landing. Unloading was done with separate loaders at the terminal. Energy wood was then comminuted at the terminal.
PS_{DT}	Timber	60	Transportation of energy wood from thinnings. Trucks were equipped with cranes for loading at the landing. Unloading was done with separate loaders at the terminal. Energy wood was then comminuted at the terminal.
From terminal to the biorefinery			
PS_{60L}[a,b,d]	Chip	60	Logging residue chips were transported to biorefinery
PS_{60E}[a,b,d]	Chip	60	Energy wood chips were transported to biorefinery
PS_{74L}[a,b,d]	Chip	74	Logging residue chips were transported to biorefinery
PS_{74E}[a,b,d]	Chip	74	Energy wood chips were transported to biorefinery
PS_{TL}[b,c,d]	Train	-[e]	Logging residue chips were transported to biorefinery
PS_{TE}[b,c,d]	Train	-[e]	Energy wood chips were transported to biorefinery

[a]Trucks were unloaded by tipping the chips in the ground at terminal or the biorefinery. [b]Chip bins were assumed to be loaded by a wheel loader at the terminal. [c]A forklift was assumed to unload the chip bins at biorefinery. [d]A wheel loader was assumed to push the tipped material in to a stack [e]Train wagons had a gross weight limit of 61.2 tonnes and a volume limit of 138 m^3loose (Enström and Winberg 2009).

Costs

The Woodflow UX tool (Creative Optimization Sweden AB, Halmstad, Sweden) was used to optimize the routes from the forest to the terminals by minimizing the transportation cost (TC). The objective functions to be minimized were the following:

$$minTC_{LR\_open\_access\_FOCO} = \sum_{f=1}^{90}\sum_{t=1}^{18} CLR_{ft} \times tLR_{ft}$$

$$minTC_{LR\_open\_access\_FSC} = \sum_{f=1}^{30}\sum_{t=1}^{18} CLR_{ft} \times tLR_{ft}$$

$$minTC_{LR\_restricted\_access\_FOCO} = \sum_{f=1}^{90}\sum_{t=1}^{18} CLR_{ft} \times tLR_{ft}$$

$$minTC_{LR\_restricted\_access\_FSC} = \sum_{f=1}^{30}\sum_{t=1}^{18} CLR_{ft} \times tLR_{ft}$$

$$minTC_{EW\_open\_access\_FOCO\_thinning} = \sum_{f=1}^{63}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$minTC_{EW\_open\_access\_FCS\_thinning} = \sum_{f=1}^{21}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$minTC_{EW\_open\_access\_FOCO\_finalfelling} = \sum_{f=1}^{90}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$minTC_{EW\_open\_access\_FCS\_finalfelling} = \sum_{f=1}^{34}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$minTC_{EW\_restricted\_access\_FOCO\_thinning} = \sum_{f=1}^{63}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$minTC_{EW\_restricted\_access\_FCS\_thinning} = \sum_{f=1}^{21}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$minTC_{EW\_open\_restristed\_FOCO\_finalfelling} = \sum_{f=1}^{90}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$minTC_{EW\_open\_restristed\_FCS\_finalfelling} = \sum_{f=1}^{34}\sum_{t=1}^{18} CEW_{ft} \times tEW_{ft}$$

$$tEW_{ft}, tLR_{ft} \geq 0 \qquad \forall ft$$

$$\sum_{f}^{F}\sum_{t}^{T} tLR_{ft} \leq sLR_f \qquad \forall f$$

$$\sum_{f}^{F}\sum_{t}^{T} tEW_{ft} \leq sEW_f \qquad v\forall f$$

$$\sum_{f}^{F}\sum_{t}^{T} tLR_{ft} \geq dLR_t \qquad \forall t$$

$$\sum_{f}^{F}\sum_{t}^{T} tEW_{ft} \geq dEW_t \qquad \forall t$$

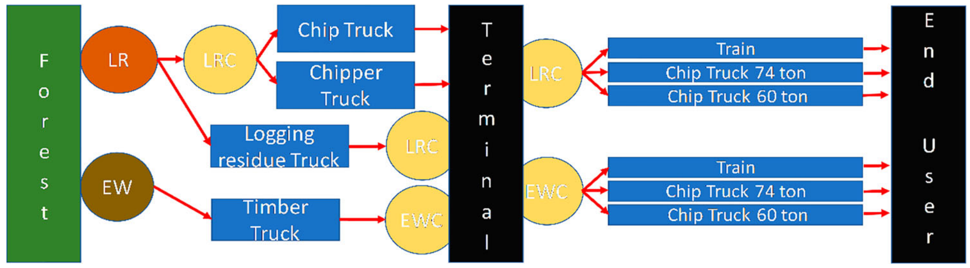

Figure 2. Schematic view of the transportation system from the forest to the biorefinery (LR: logging residues, LRC: logging residue chips, EW: energy wood, and EWC: energy wood chips).

where CLR is the procurement cost for logging residues, CEW is the procurement cost for energy wood, f … F = index for forests with available product, t … T = index for terminals, dLR is the demand of logging residues and dEW is the demand of energy wood.

The tool could choose the least expensive option among procurement systems PS_A, PS_B, and PS_C for delivery of logging residues, and between PS_{DRF} and PS_{DT} for delivery of energy wood. The procurement costs (CLR and CEW) depended on procurement system and on transport distances for the different procurement systems and were used as input data for the Woodflow tool. These procurement costs were calculated by first calculating the transportation cost from forest to terminal and then add fixed cost for the purchase of biomass, harvesting, forwarding, comminution and unloading at the terminal (Table 5). The transportation costs were calculated in the excel application FLIS (von Hofsten et al. 2005) and were based on fixed time and costs for different work elements, and variable distance-dependent costs (Tables 6 and 7).

The terminal-to-biorefinery transportation cost was calculated based on fixed distances from the terminal to the biorefinery for procurement systems PS_{60L}, PS_{60E}, PS_{74L}, PS_{74E}, and fixed costs and times for different work elements, and variable costs depending on the transportation distance (Tables 6 and 7). The transportation cost for PS_{TL} and PS_{TE} was based on the function reported by Tahvanainen and Anttila (2011). All transportation costs from terminals to biorefinery included the cost for loading and unloading. The cost for loading PS_{TL} and PS_{TE} was set to 13 and 12 SEK/BDt, respectively (Tahvanainen and Anttila 2011). The cost for unloading PS_{TL} and PS_{TE} was set to 8 and 7 SEK/BDt, respectively (Tahvanainen and Anttila 2011). The cost for unloading and loading PS_{60L} and PS_{74L} was assumed to be equal to that of PS_{TL}. Moreover, the cost for unloading and loading PS_{60E} and PS_{74E} was assumed to be equal to that of PS_{TE}. Where necessary, currencies were converted from Euro (€) to Swedish crowns (SEK), using a conversion rate of 9.94 SEK=1€.

Table 5. Fixed cost (SEK/BDt) added to truck transportation costs of logging residues transported with logging residue trucks (PS_A), logging residue chips transported with chip trucks (PS_B) or chipper trucks (PS_C), and energy wood from regeneration fellings (PS_{DRF}) or thinning (PS_{DT}) transported with timber trucks from the forest to a terminal to estimate to procurement cost from forests to terminals.

	PS_A	PS_B	PS_C	PS_{DRF}	PS_{DT}
Land owner compensation	182 [B]	182 [B]	182 [B]	282 [B]	282 [B]
Harvesting	-	-	-	130 [BA]	252 [BA]
Forwarding	209[A]	209[A]	209[A]	98 [A]	157 [A]
Chipping at landing	-	171 [T]	-	-	-
Unloading at terminal	-	18 [T]	18 [T]	2.4[S]	2.4 [S]
Comminution at terminal	121 [T]	-	-	44[BT]	44 [BT]

- indicates no value. [B]Brunberg (2015). [A]Bogghed (2013). [BA]indicates that the values were estimated from Bogghed (2013) and Brunberg (2006). [BT]indicates that the values were calculated based on Brunberg (2010) and Tahvanainen and Anttila (2011). [S]Sondell (2006). [T]Tahvanainen and Anttila (2011).

Calculation of transportation work

The transportation work was calculated both from forests to terminals and from terminals to the biorefinery as tonnekm, i.e. the amount of BDt transported multiplied by the transportation distance. These calculations were based on the amount of biomass that was delivered to each individual terminal from each individual supply point, the transportation distance between the individual terminals and forests, and the fixed terminal-to-biorefinery transportation distance.

Results

Cost functions

PS_A, PS_C, and PS_B were the most cost-effective procurement systems for short (<23 km), medium (23–50 km), and long (>50 km) transportation distances (Table 8 and Figure 3), respectively. PS_{DRF} was the most cost-effective procurement system for energy wood.

PS_{TL} and PS_{TE} were the most cost-effective options for long-distance transportation from the terminal to the biorefinery (Table 8 and Figure 3) while PS_{74L} and PS_{74E} were less costly for distances below 55 and 50 km, respectively. For distances lower than 45 km, PS_{60L} and PS_{60E} were less costly than trains. However, transportation was always more cost effective for 74 tonnes trucks than for 60 tonnes trucks (1–67 SEK/BDt). Similarly, the transportation of energy wood chips was always less costly than the transportation of logging residue chips. This difference was marginal for truck transportation (<1 SEK/BDt), and more significant for train transportation (3–10 SEK/BDt).

Procurement optimization

The total procurement costs of logging residue to terminals were 153.5 and 130 MSEK for FSC and FOCO, respectively, in the restricted access scenario. These costs were reduced by 5.5% (145 MSEK) and 2.3% (127 MSEK), respectively, in the open-access scenario. In the restricted access and open

Table 6. Input variables to calculate the transportation cost (SEK/BDt) in the FLIS excel application (von Hofsten et al. 2005) for logging residues transported with logging residue trucks (PS_A), logging residue chips transported with chip trucks (PS_B) or chipper trucks (PS_C), and energy wood from regeneration fellings (PS_{DRF}) or thinnings (PS_{DT}) transported with timber trucks depending on the distance between landings and terminals (km). Input variables to calculated cost for 60 tonnes gross weight trucks transporting logging residue chips (PS_{60L}) or energy wood chips (PS_{60E}), and 74 tonnes gross weight trucks transporting logging residue chips (PS_{74L}) or energy wood chips (PS_{74E}) depending on the distance between the terminals and the biorefinery.

	PS_A	PS_B	PS_C	PS_{DRF}/PS_{DT}	PS_{60L}/PS_{60E}	PS_{74L}/PS_{74E}
Fixed machine costs						
Investment (M SEK)	2.83[FB]	2.5 [BL]	5.8 [BL]	2.9243[M]	2.5 [BL]	4 [S]
Service life (year)	5 [FS]	7 [La]	7 [FS]	7 [FS]	7 [La]	7 [FS]
Interest (%)	5.5	5.5	5.5	5.5	5.5	5.5
Salvage value (SEK)	321,430[J]	450,000[S]	500,000[FS]	157,248[M]	450,000[S]	600,000[S]
Tax (SEK/year)	40,000[FS]	40,000[FS]	25,000[NM]	34,387 [L]	40,000[FS]	40,000[FS]
Insurance (SEK/year)	65,000[FS]	42,000[FS]	70,114[NM]	53,045[M]	42,000[FS]	45,000[FS]
Other fixed costs (SEK/year)	28,500[FS]	39,500[FS]	110,000[FS]	137,000 [L]	39,500[FS]	40,000[FS]
Machine utilization						
Workdays (No)	207[S]	207[S]	207[S]	207 [S]	207 [S]	207 [S]
Shifts (No)	2	2	2	2	2	2
Hours (h/shift)	8.0	8.0	8.0	8.0	8.0	8.0
TU, G_{15}/U-time	1.00 [FS]	1.00[FS]	0.95[FS]	1.00 [FS]	1.00 [FS]	1.00 [FS]
Operator costs						
Personal cost/ (SEK /operator & year)**	420,269	420,269	420,269	420,269	420,269	420,269
Variable machine cost						
Fuel price ex. VAT (SEK /l)	12.5	12.5	12.5	12.5	12.5	12.5
Lubrication and hydraulic oil (SEK /l)	39	39	39	39	39	39
Fuel road, (l/10 km)	5.6 [J]	5.5[La]	5.5 [FS]	5.73[L]	4.41 [A]	4.97[A]
Fuel, loading (l/ G15-h)	7.7 [J]	7 [FS]	48.7 [EP]	7 [FS]	7 [FS]	7 [FS]
Fuel, unloading, (l/ G15-h)	7.7 [J]	4 [FS]	4 [FS]	7 [FS]	4 [FS]	4 [FS]
Lubrication and oil (l/G15-h)	0.05	0.05	0.05	0.05	0.05	0.05
Maintenance cost (SEK /10 km)	20 [N]	20 [N]	8.69 [FS]	17.2[JV]	22.2*	28.2 [EH]
Consumption material (SEK /BDt)	-	-	10	-	-	-
Other variable costs, (SEK /10 km)	5	4.61	5 [FS]	7.6[JV]	4.61/-	-
Time consumption						
Loading time (min)	47.5 [N]	77.6[BL]	99[T]	34[M]	22.2[LJ]	29.5[+]
Unloading time (min)	20 [N]	16.6 [BL]	20 [N]	17[M]	16.6 [BL]	16.6 [Sam]
Waiting (min)	9.5 [N]	30/15	15	15	15	15
Velocity (km/h)	15-71[R]	15-71[R]	15-71[R]	15-71[R]	68[A]	64[A]
Load size (BDt)	11.5 [N]					
Load capacity (t)		37 [La]	28[JG]	37.9[L]	37 [La]	49.1 [A]
Load capacity (m^3)		129 [La]	100 [T]		129 [La]	

- indicates no value. [A]Asmoarp et al. (2015). [BL]Berglund and Larsson (2012). [EH]Enström and von Hofsten (2015). [EP]Eliasson and Picchi (2010). [FB]Friberg and Hansson (2012). [J]Joelsson et al. (2016). [JG]Johansson et al. (2014). [JV]Johansson and von Hofsten (2017). [L]Lindström (2014). [La]Laitila et al. (2016) (two shift). [LJ]Laitila (2008). [M]Magnusson (2011) (including crane). [N]Näslund (2006). [NM]Nilsson (2015). [R]Ranta (2002) varies with transportation distance. [S]Spånberg (2016). [T]Trolin (2013). *indicates that the value is assumed to have the same relative difference as other trucks. [+]indicates that the value is assumed increase or decrease relative to truck weight. [Sam]indicates that the value is assumed to be the same as for another truck. [FS]indicates that the value is assumed to increase or decrease relative to truck weight, ** for calculation details see Table 7.

Table 7. Calculation of yearly salary costs for truck drivers.

	Value
Base salary (SEK/hour)	150
Pensions- & vacation addition (%)	22
Social charge (%)	32.42
Workdays (no/year)	210
Work hours (h/day)	8
Unsocial hours pay (hour/day)	4
Unsocial hours pay (SEK/hour)	27.36[W]
Σ driver cost (SEK/year)	**420,269**

[W] based on data from Widman (2015)

access scenarios, the total procurement costs of energy wood to the terminal were: 470 kSEK (FSC), 1,298 kSEK (FOCO), and 3.2% lower, i.e. 455 kSEK (FSC) and 1,256 kSEK (FOCO), respectively.

The total amount of logging residues transported from FCS and FOCO regions varied with the scenario (Tables 9 and 10). Approximately 175,000 BDt and ∼183,000 BDt of logging residues were delivered by FCS and FOCO, respectively, in both scenarios. However, the amount of energy wood transported was the same for both the restricted access and open access scenarios.

Table 8. Procurement cost functions (SEK/BDt) depending on the distance between landings and terminals (km) for logging residues transported with logging residue trucks (PS_A); logging residue chips transported with chip trucks (PS_B) or chipper trucks (PS_C); and energy wood from regeneration fellings (PS_{DRF}) or thinning (PS_{DT}) transported with timber trucks. Calculated transportation cost functions depending on the distance between the terminals and the biorefinery (km) for 60 tonnes (gross weight) trucks transporting logging residue chips (PS_{60L}) or energy wood chips (PS_{60E}), 74 tonnes (gross weight) trucks transporting logging residue chips (PS_{74L}) or energy wood chips (PS_{74E}), and trains transporting logging residue chips (PS_{TL}) or energy wood chips (PS_{TE}).

	Procurement system										
	To terminal					To biorefinery					
	PS_A	PS_B	PS_C	PS_{DRF}	PS_{DT}	PS_{60L}	PS_{74L}	PS_{TL}	PS_{60E}	PS_{74E}	PS_{TE}
Constant	584.59	633.59	597.69	587.01	767.98	40.531	40.590	87.924	39.846	39.905	84.931
km	2.8134	1.5475	2.2237	1.713	1.713	1.3546	1.2322	0.3771	1.3546	1.2322	0.3643

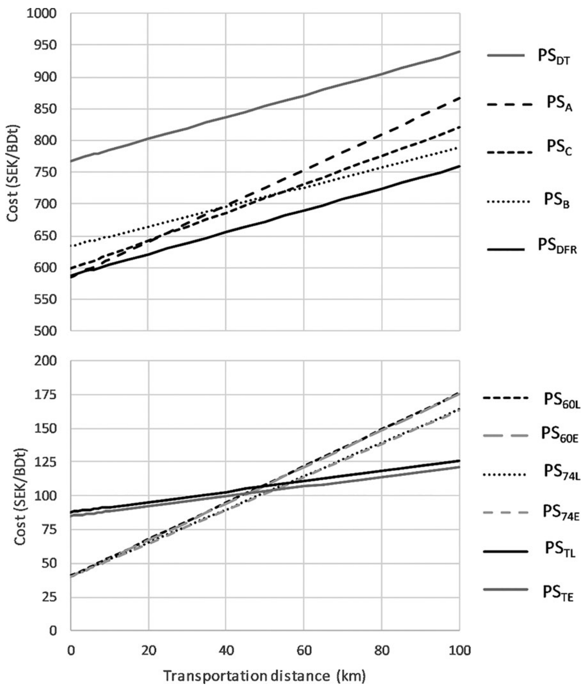

Figure 3. Calculated procurement cost (SEK/BDt) from forests to terminals (top panel) for logging residues transported with logging residue trucks (PS$_A$); logging residue chips transported with chip trucks (PS$_B$) or chipper trucks (PS$_C$); and energy wood from regeneration fellings (PS$_{DRF}$) or thinning (PS$_{DT}$) transported with timber trucks. Calculated transportation cost (SEK/BDt) from terminals to the biorefinery (bottom panel) for 60 tonnes (gross weight) trucks transporting logging residue chips (PS$_{60L}$) or energy wood chips (PS$_{60E}$), 74 tonnes (gross weight) trucks transporting logging residue chips (PS$_{74L}$) or energy wood chips (PS$_{74E}$), and trains transporting logging residue chips (PS$_{TL}$) or energy wood chips (PS$_{TE}$).

Consider the delivery of logging residues to the terminal. FCS and FOCO required 27,631,425 tonnekm and 9,341,333 tonnekm, respectively, in the restricted access scenario, but respective values of only 22,019,337 tonnekm (20.3% decrease) and 7,830,094 tonnekm(16.2% decrease) in the open-access scenario. Similar trends were observed for energy wood deliveries to the terminal. FCS and FOCO required 51,081 tonnekm and 132,516 tonnekm, respectively, in the restricted access scenario, but only 42,428 tonnekm (16.9% lower) and 108,574 tonnekm (18.1% lower) in the open-access scenario. Furthermore, the open-access scenario resulted in a shift in the procurement system used for delivery of the logging residue to the terminal (Tables 9 and 10). The deliveries with PS$_B$ decreased for FCS and FOCO in the open-access scenario, while the deliveries with PS$_A$ and PS$_C$ increased. This shift was more significant for FOCO (than for FCS) where the volume transported with PS$_B$ decreased by 37%, and the volume transported with PS$_A$ and PS$_C$ increased by 137% and 58%, respectively. The corresponding values for FCS were a 10% decrease, and a 42% and 34% increase, respectively.

Transportation from the terminal to the biorefinery

Train transportation was always chosen when the terminal had a railroad connection, even when the transportation distance was substantially longer with train than with truck (Table 2). The total cost for transportation from terminals to the biorefinery was higher for FOCO than for FCS, due to different delivery volumes (Table 11). However, the cost per BDt from terminals to the biorefinery was the same for both suppliers.

Compared with the open-access scenario, the restricted access scenario was associated with higher costs for both FCS and FOCO (Table 11). The total transportation cost for FCS chip deliveries to the biorefinery from terminals when terminals without railroad access was assumed to use PS$_{60L}$, PS$_{74L}$, PS$_{60E}$, and PS$_{74E}$ was reduced by 9.0%, 7.7%, 9.5%, and 8.2%, respectively, in the open-access scenario. The corresponding values for FOCO were 8.9%, 7.6%, 9.5, and 8.2%.

The use of 60 or 74 tonnes gross weight trucks for terminals without railroad access lead to that the cost for logging residue chips from FCS and FOCO was reduced by 4.26% when PS$_{74L}$ (rather than PS$_{60L}$) was used in the restricted access scenario (Table 11). A 2.94% decrease was realized for the open-access scenario. The cost of energy wood chip deliveries decreased by 4.33% and 2.88% in the restricted and open access scenarios, respectively, when PS$_{74E}$ (rather than PS$_{60E}$) was used, for both FCS and FOCO.

Table 9. Volume, average transportation distance (Avg.distance), cost, and transportation work (Transport) in the restricted access scenario for logging residues transported with logging residue trucks (PS$_A$); logging residue chips transported with chip trucks (PS$_B$) or chipper trucks (PS$_C$); and energy wood from regeneration fellings (PS$_{DRF}$) or thinning (PS$_{DT}$) transported with timber trucks

	FOCO					FCS				
	PS$_A$	PS$_B$	PS$_C$	PS$_{DRF}$	PS$_{DT}$	PS$_A$	PS$_B$	PS$_C$	PS$_{DRF}$	PS$_{DT}$
Volume (BDt)	7,785	117,446	58,053	1,213	464	3,581	137,156	34,655	433	166
Avg.distance (km)	11.1	62.6	32.8	84	66	21.0	191.5	37.2	85	86
Cost (SEK/BDt)	614	734	674	733	881	644	929	684	734	917
Transport (k BDt km)	86	7,349	1,906	102	31	75	26,266	1,290	37	14

Table 10. Volume, average transportation distance (Avg.distance) cost, and transportation work (Transport) in the open access scenario for logging residues transported with logging residue trucks (PS$_A$); logging residue chips transported with chip trucks (PS$_B$) or chipper trucks (PS$_C$); and energy wood from regeneration fellings (PS$_{DRF}$) or thinning (PS$_{DT}$) transported with timber trucks

	FOCO					FCS				
	PS$_A$	PS$_B$	PS$_C$	PS$_{DFR}$	PS$_{DT}$	PS$_A$	PS$_B$	PS$_C$	PS$_{DRF}$	PS$_{DT}$
Volume (BDt)	18,456	73,445	91,506	1,213	464	5,077	123,772	46,553	433	166
Avg.distance (km)	13.5	62.1	33.0	70	51	16.3	162.3	39.7	70	73
Cost (SEK/BDt)	621	733	674	708	857	629	885	690	708	894
Transport (k BDt km)	250	4,562	3,019	85	24	83	20,091	1,846	30	12

Table 11. Description of procurement system from terminals to the biorefinery for logging residue (LRC) and energy wood (EWC) chips in the open access (Open) and restricted access (Rest) scenario.

	FOCO				FCS			
	LRC		EWC		LRC		EWC	
	Open	Rest	Open	Rest	Open	Rest	Open	Rest
Delivered volume (BDt)	183,407	183,284	1,677	1,677	175,402	175,392	599	599
Delivered volume by truck (BDt)	48,551	78,893	444	722	46,432	75,496	159	258
Delivered volume by train (BDt)	134,856	104,391	1,233	955	128,970	99,896	440	341
Transportation work by truck (k BDt km)	10,163	16,524	93	151	9,710	15,813	33	54
Transportation work by train (k BDt km)	41,166	33,376	376	305	39,369	31,938	134	109
Total cost with 60 tonnes trucks (kSEK)	43,116	47,346	385	426	41,234	45,307	138	152
Total cost with 74 tonnes trucks (kSEK)	41,875	45,328	374	407	40,047	43,376	134	146

Table 12. Total estimated procurement cost from forests to the biorefinery in the open access (Open) and restricted access (Rest) scenario. Transportation from terminals without rail road access to the biorefinery was assumed to be done with 60 tonnes or 74 tonnes gross weight trucks transporting logging residues (PS60L and PS74L, respectively) and energy wood (PS60E and PS74E, respectively).

	PS60L		PS74L		PS60E		PS74E	
	MSEK	SEK/ BDt	MSEK	SEK/ BDt	kSEK	SEK/ BDt	kSEK	SEK/ BDt
FOCO Rest	177.3	968	170.1	957	1,724	1,028	1,705	1,017
FOCO Open	170.1	928	168.9	921	1,641	979	1,630	972
FSC Rest	198.8	1,134	186.2	1,122	622	1,039	616	1,028
FCS Open	186.2	1,062	185.0	1,055	593	989	589	983

The cheapest option of logging residue trucks (PSA), chip trucks (PSB) and chipper trucks (PSC) was assumed to be used for transportation from each forest to the terminals. Energy wood was transported from forest to terminals with timber trucks from both regeneration fellings (PSDRF) or thinning (PSDT).

The transportation work required for transportation from terminals to the biorefinery differed between the scenarios. For FCS and FOCO, the transportation work for logging residue chips in the open-access scenario with (i) trucks decreased by 38.4% and 38.5%, respectively, and (ii) train increased by 29.1% and 29.2%, respectively, compared to the restricted access scenario. For both FCS and FOCO in the open-access scenarios, the transportation work with trucks for energy wood chip deliveries decreased by 38.5%, compared to the restricted access scenario. The transportation work with trains, in contrast, increased by 29.0% and 29.1%, respectively.

Total cost

The overall procurement cost was lower for FOCO than for FCS in both scenarios regardless of if the transportation from terminals without railroad access to the biorefinery was made with 60 or 74 tonne gross weight trucks (Table 12). The cost per BDt in the restricted access scenario for FOCO chip deliveries to the biorefinery from the forest was 14.7, 14.7, 1.1, and 1.1% lower than for FSC when terminals without railroad access used PS_{60L}, PS_{74L}, PS_{60E}, and PS_{74E}, respectively. The corresponding values in the open-access scenario were 12.6%, 12.7%, 1.0, and 1.1%.

Discussion

The procurement cost per BDt for logging residue deliveries from forest to terminals were higher for FCS than for FOCO. This resulted from the fact that FCS was unable to fulfill the delivery requirements to the biorefinery, even when all available volume was delivered (Tables 1 and 2). Therefore, deliveries from forests located far away from the terminals were necessary, resulting in a relatively high forest-to-terminal procurement cost. A similar trend was observed, albeit with a smaller difference, for the energy wood deliveries where delivery of all available volume was required for both FCS and FOCO. These differences indicated that the location of the forest influences the forest-to-terminal transportation cost (Table 1 and Figure 1). Moreover, FOCO, having a greater harvestable area than FCS, constituted a more favorably located share of the forest. For FOCO, the average transportation distance to terminal from the forest increased for PS_A and PS_C in the open-access scenario, while it decreased for PS_B (Tables 9 and 10). For FCS, the average transportation distance to terminal from the forest increased for PS_C in the open-access scenario, while it decreased for PS_A and PS_B. While the volume delivered by PS_A and PS_C increased, and the volume delivered by PS_B decreased for both suppliers. These changes further imply that there are differences in the location and the amount of the forest for the two suppliers, and that FOCO have a more favorable situation. These differences also lead to that the cost reduction associated with the open access scenario was larger for FCS than for FOCO, as the introduction of new terminals reduced the transportation distance more for FCS than for FOCO. Compared with the cost, the forest-to-terminal transportation work (BDt×km) was affected by the same factors and exhibited similar characteristics. The transportation work by FCS was approximately three-fold that of FOCO in the restricted access scenario for logging residues, and ~2.8 times larger in the open access scenario (Tables 9 and 10). These results indicated that FOCO is the preferred main supplier and that the open access scenario is preferable (to the restricted access scenario) from both an economical and environmental perspective.

The transportation cost per BDt for logging residues and energy wood from terminals to the biorefinery was the same for both FCS and FOCO. However, the transportation cost associated with the open-access scenario was lower than that corresponding for the restricted access scenario. Similarly, for both scenarios, the transportation costs between terminals and the biorefinery were lower for trucks with a gross weight of 74 tonnes than for trucks with a gross weight of 60 tonnes. These results are consistent with those reported by Laitila et al. (2016) who found that depending on assortment either 69 tonnes or 76 tonnes truck were preferable to 60 tonnes trucks. However, the most prominent fact in the present study is that the amount of train transportation was significantly higher in the open-access scenario (than in the restricted access scenario). This results from the fact that more terminals with railroad access were available to FCS and FOCO (compared with those available in the restricted access case). These differences indicate that (compared with the restricted access case) the open-access scenario is preferable from an economic and environmental viewpoint for transportation from terminals to the biorefinery. The transportation work of 74 and 60 tonnes gross weight trucks was the same, although fewer trucks are needed when 74 tonnes trucks were used and, hence, the cost and environmental impact were reduced. These results indicate that terminals should be open and preferably located next to a railway. If the terminal lacks railroad access, then roads suitable for 74 tonnes trucks should be readily available close to the terminal. There are currently an increased number of public roads that allow 74 tonnes transportation, but there still not a complete coverage in the study area (Natanaelsson 2019; Swedish Transport Administration 2019a; 2019b).

The total cost per BDt from the forest to the biorefinery was higher than the cost reported by Athanassiadis and Nordfjell (2017). However, the cost in the present study included long-distance transportation to one biorefinery at the coast, and the costs are therefore probably comparable.

In the present study, landowners using the forest biomass for owner-operated industries were excluded. Landowners with a major possession close to the mountains were also excluded, as harvesting of logging residues in those regions is questionable. An interesting aspect for further investigation would be to allow deliveries from additional landowners and a mix of different landowners, thereby probably yielding further reductions in the transportation cost and work. This combination was neglected in the present study, as the aim was to investigate the potential of open access terminals for FCS and FOCO in the forest biomass supply chain. Quite small volumes of energy wood were considered in the present study. Transportation of this wood only would be too expensive due to the small volumes on each landing. Therefore, in practice, the energy wood would probably be transported with the normal pulpwood or timber to industries or terminals and then separated. The amount of energy wood was assumed to be 2% of the pulpwood volume. This estimation is probably valid for RF and late thinnings, in current market conditions. However, the value could be significantly higher in early thinnings, where the energy wood harvest can be more profitable than the pulp wood harvest (Iwarson-Wide 2011; Routa et al. 2013; Karttunen et al. 2016). Depending on the minimum requirements for pulpwood, energy wood may represent a significant share of early thinning. Other market conditions with relative higher price on energy wood compared to pulp wood could also increase the amount of energy wood. Hence, procurement-cost estimations for this wood are warranted. Regardless of the limitations is it clear that the open-access scenario reduces the procurement cost and transportation work from forests to terminals.

The cost functions for the biomass are based on a literature survey about Nordic conditions and, therefore, uncertainties regarding the transport conditions at an individual terminal are always encountered. This uncertainty may be significant if some terminals are characterized by conditions that deviate considerably from *the average,* e.g. old machines with a relatively long unloading time. However, in the present study, these differences are expected to have only a modest impact on the results regarding the preferred scenario and supplier. Nevertheless, the potential differences in the transportation system, suppliers, and terminal machines associated with different terminals could be considered in future studies.

The cost function constructed in the present study is largely consistent with that reported by Eliasson (2015), where PS_A, PS_C, and PS_B were the most cost-effective options for short, medium, and long transportation distances (Table 8), respectively. However scale effects (e.g. size of logging sites), which are important for PS_B as it is most suited for mid-sized and large landings, have been neglected in our study (Asmoarp 2013). This could influence the results on individual landings, thereby rendering PS_C preferable for small landings on longer transportation distances. The cost function for the train transportation used in the present study was mainly based on relatively long transportation distances and, hence, the cost for short distances may be dubious. However, the results concur with those of previous studies, i.e. (i) truck transportation is the preferred option for short transportation distances, (ii) an increase in the truck weight has only a marginal effect on whether the train is the preferred option, and (iii) the train is the preferred option for long transportation distances (Lööf 2015).

Direct transportation to the biorefinery was not investigated as the closest forest was located relatively far from the biorefinery (Figure 1). Furthermore, Tahvanainen and Anttila (2011) found that at 135–165 km, train transportation becomes more profitable than at other options. An estimate based on the cost function presented in this paper (Table 8) revealed that an initial 20 km "backward" transport to a terminal and a subsequent 150 km train transport to the biorefinery would be more profitable than a direct 130 km transport. However, from a cost perspective, 74 tonnes trucks require far longer distances before reloading at a terminal would be profitable. This finding indicated that, for reduced transportation costs, terminals without railroad connections are interesting. However, connection-free terminals may still be useful for supply security reasons, and if the biorefinery lacks comminution ability (Kanzian et al. 2009; Rauch and Gronalt 2010). From an economical point of view, transporting biomass directly from some forest to the biorefinery could be better than the investigate transportation via terminal. This may be considered in future studies, while this topic was neglected in the present study as the aim was to compare the open access and the restricted access scenarios.

The current market price (for 2019) for forest chips at the biorefinery is ∼199 SEK/MWh (Swedish Energy Agency 2020), which translates to a price of ∼1,061 SEK/BDt (Ringman 1996). Therefore, most deliveries from FCS will be profitable, whereas all from FOCO could be profitable.

However, other costs that were neglected in the present study must be added to the cost of the biomass before profitability can be assessed. The rental cost of the terminal, which is difficult to access in the current market, must be added. Administrative costs and risk margins must also be included (these costs can vary significantly between different companies and were therefore excluded from the present study).

Despite the limitations of the study, the results clearly revealed that the open access scenario was better than the restricted access scenario. However, conditions where all terminals are open are difficult to achieve. The openness depends mainly on the difficulty associated with determining the amount the terminal guest should pay the terminal owner. Moreover, some companies could view terminals as a strategic advantage, and therefore competitor use of the terminal (even for a fee) is undesired. Therefore, steering and regulations may be required for achieving this openness, which is difficult to implement for terminals that were built by private companies. However, this openness could be implemented for new terminals when the companies apply for a building permit.

Conclusions

The total forest-to-terminal procurement cost associated with the open access scenario was 2–6% lower than that of the restricted access scenario. In the open-access scenario, there was a clear shift towards relatively short transportation distances with increasing use of PS_A and PS_C (rather than PS_B). This shift resulted in a 16–20% decrease in the transportation work required for delivering the biomass to a terminal. The terminal-to-biorefinery transportation cost associated with the open-access scenario was 7–9% lower than that corresponding to the restricted access scenario. The transportation cost could, in both scenarios, be reduced by using 74 tonnes trucks (rather than 60 tonnes trucks). However, the largest impact was that a large part of the transportation work was shifted from truck to train in the open-access scenario (in contrast to the restricted access scenario).

From a cost and transportation perspective, FOCO was the preferred main supplier for the biorefinery considered in the present study. Therefore, in the ideal situation, FOCO would serve as the main deliverer of biomass, all terminals are open, and 74 tonnes trucks are allowed on all roads that connect a terminal (without a railroad connection) to a biorefinery.

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