Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant

KARI VÄÄTÄINEN, ROBERT PRINZ, JUKKA MALINEN, NUHA LAITILA and LAURI SIKANEN

1Natural Resources Institute Finland (LUKE), Joensuu, Finland, 2University of Eastern Finland (UEF), Joensuu, Finland

Abstract

The fuel supply of forest chips has to adapt to the annual fluctuations of power and heat generation. This creates inefficiency and unbalances the capacity utilization of the fuel supply fleet in the direct fuel supplies from roadside storages to power and heat generation. Terminals can offer an alternative approach for the fleet management of fuel supplies in terms of smoothing the unbalanced fleet use towards more even year-round operations. The aim of the study was to compare the supply costs of a conventional direct forest chip supply to an alternative fuel supply with the use of a feed-in terminal using the discrete-event simulation method. The influences of the terminal location, terminal investment cost, outbound terminal transport method, terminal truck utilization and quality changes of terminal-stored forest chips for the fuel supply cost were studied in the case environment. By introducing a feed-in terminal and a shuttle truck for the transports of terminal-stored forest chips, the total supply cost was 1.4% higher than the direct fuel supply scenario. In terminal scenarios, the supply costs increased 1–2% if the cost of the terminal investment increased 30%, the distance to the terminal increased from 5 to 30 km or the total annual use of a terminal truck decreased 1500 h. Moreover, a 1 per cent point per month increase in the dry matter loss of terminal-stored chips increased the total supply cost 1%. The study revealed that with the relatively low additional cost, the feed-in terminal can be introduced to the conventional forest chip supply. Cost compensation can be gained through the higher annual use of a fuel supply fleet and more secured fuel supply to power plants by decreasing the need for supplement fuel, which can be more expensive at a time of the highest fuel demand.

Keywords: discrete-event simulation, feed-in terminal, forest chips, fuel supply system, logistics, supply costs

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Introduction

Material-storing terminals are widely used in various material and goods supply logistics. Terminals and intermediate storages are required for the smooth and time-dependent running of the material supply from the initial point of supply to the final end user (Stampfer & Kanzian, 2006; Kanzian et al., 2009; Kons et al., 2014; Wolfsmayr & Rauch, 2014; Virkkunen et al., 2015). Respectively, biomass supply logistics for energy generation, especially in large scale, require fuel terminals in the supply system (Virkkunen et al., 2015). The use of terminals in the forest fuel supply has notably increased in Nordic countries (Kärhä, 2011; Palander & Voutilainen, 2013; Routa et al., 2013; Kons et al., 2014; Virkkunen et al., 2015; Strandström, 2016). The operations of a fuel supply fleet in traditional fuel supply systems have to adapt to the annual fluctuations of power and heat production. This increases the inefficiency and lowers the capacity utilization of machines, thus negatively influencing the cost efficiency of the fuel supply. For permanent workers, stable and year-round working opportunities are difficult to provide in the forest chip supply business. Difficulties also occur in the recruitment of additional workforce for the relatively short time periods during the high heating season. The use of terminals can act as a balancing element enabling year-round working opportunities and year-round machine use with benefits for both the fuel supply entrepreneurs and their operating personnel (Väätäinen et al., 2014; Raitila & Korpinen, 2016).

Understandably, a terminal as a part of the forest fuel supply structure generates additional costs compared to a direct fuel supply system from roadsides to a power plant. Depending on the size and the function of a terminal, basic investment and construction costs for its establishment can be notable (Virkkunen et al., 2016). Additional transportation, material handling and fuel quality maintenance in terminal produce extra costs (Karttunen et al., 2013; Virkkunen et al., 2016).
In Finland during 2015, 29% of forest-based fuel was transported to, stored and comminuted in terminals before further transport to energy use (Strandström, 2016). Currently, statistics on the amounts of roadside chipped material stored in terminals are not available. However, small amounts of energy biomass as comminuted material are stored for some months in terminals.

Storing demonstrations and tests have been accomplished mainly for comminuted forest biomass as in larger heaps, to follow up regarding changes in quality and material loss over monitored time spans (Björklund, 1982; Nurmi, 1990; Jirjis, 2005; Laitila & Nuutinen, 2015; Raitila & Korpinen, 2016). It is well known from previous studies that as comminuted biomass is stored, microbial activity will occur resulting in heat generation and dry matter losses (Kubler, 1987; Nurmi, 1990, 1999; Jirjis, 2005). Fines of <3 mm in length represent a health hazard because they reduce air circulation during storage, supporting bacteria proliferation with an increased risk of combustion (Jirjis, 2005). It is also known that chips made of fresh wood generate more heat and suffer greater dry material loss (DML) than if they are made of seasoned material (Björklund, 1982; Kubler, 1987; Routa et al., 2015).

The reasons for introducing a terminal to a fuel supply system can vary. Terminals offer safety to fulfill the fuel demand during divergent fuel demand and supply occasions, often when the demand becomes unexpectedly high, or when the fuel supply fleet is unable to operate normally due to challenges in the operational environment (Malinen et al., 2014). External terminals are also needed for securing fuel deliveries in cases when the size of a power plant’s buffer is limited or the number of direct deliveries from roadside storages during weekends remain low (Virkkunen et al., 2015). Bigger terminals allow better quality monitoring on fuel, and therefore, quality-based control and supply of required fuel quality could be executed. In addition, terminals offer a new approach for the fleet management of fuel supplies in terms of smoothing unbalanced fleet use towards more even year-round operations. During the low season, fuel supply units can conduct fuel transports to fill the terminals, enabling terminals to take part in fuel supply to plants during the high season to increase the year-round utilization of fuel supply units (Raitila & Korpinen, 2016).

Biomass terminals for heat and energy generation can be categorized by their main functions as a part of the fuel supply, by their size in hectares or by the capacity of stored biomass in energy or volume (Kons 2015, Virkkunen et al., 2015). To classify terminals with the functions of terminals as part of the fuel supply, the transshipment terminals are small areas, where raw and uncommimuted material is transported to and comminuted before further transports to heat or energy production. Feed-in terminals usually contain more infrastructures, such as a paved terminal area and a scaling place. The main function of the feed-in terminal is to balance the fuel supply for power and heat generation. So-called satellite terminals have their own terminal machinery and a large storing capacity with several fuel assortments. Satellite terminals are for year-round operations and serve distant and large customers (Virkkunen et al., 2015). In Sweden, with a 74% share of all forest biomass terminals, small terminals with <2 ha area are a majority (Kons et al., 2014), and in Finland 1–3 ha or 10 to 100 GWh per a terminals dominate the total number of terminals (Raitila & Virkkunen, 2016).

Thus far, only a few studies related to forest biomass supply systems for energy use have considered the influence of having a terminal as a part of the fuel supply on total supply costs (e.g. Karttunen et al., 2013; Korpinen & Aalto, 2016; Virkkunen et al., 2016). This study tackles the theme of the balanced use of a supply fleet and a more secured fuel supply to a power plant by comparing the conventional supply system to the terminal-based supply, where the feed-in terminal has been introduced into the conventional supply system.

The aim of the study was to compare the costs of the conventional direct forest chip supply to an alternative fuel supply with the use of a feed-in terminal using discrete-event simulations. The operational environment was a typical forest chip supply environment in Eastern Finland with 517 GWh of forest chips used in a combined heat and power plant (CHP plant). In terminal transport functions, the truck transport methods of the supplier’s chip truck and designated shuttle truck from the feed-in terminal to the CHP plant were studied. Furthermore, the influences of the terminal location, terminal investment cost, shuttle truck utilization and quality changes in the terminal-stored forest chips were examined.

**Materials and methods**

**Modelling the system environment**

To model the system environment and to conduct the simulations of determined scenarios, WITNESS simulation software applying the discrete-event simulation method integrated with Excel-based parameter input was used. The forest chip supply environment was framed to begin from the roadside storages of forest biomass and to end at the power plant. The simulation environment corresponded to the typical forest chip supply conditions located in Eastern Finland in the Joensuu district. In addition, the model’s parameter data closely resembled the business as usual (BAU) situation for the CHP plant’s forest chip supply. However, some simplifications and parameter...
adjustments in the system environment were carried out, expressed as followed.

The model construction was carried out by following the BAU case in the forest chip supply to the CHP plant in the city of Joensuu. The simulation model consisted of four forest chip suppliers operating with one truck-mounted chipper and two chip trucks. As a simplification in the model, each supplier had a similar operational environment in terms of operation area in size, characteristics of roadside storages and operation model of the forest chip supply. In addition, the fuel suppliers operated with a one shift weekly working schedule having Sundays off from work (Fig. 1). The sizes of the roadside storages of logging residues corresponded to the real situation of spruce-dominated final fellings located in North-Karelia, Eastern Finland (Windisch et al., 2015). The storage location, storage size in solid-m³ and the number of storages in a defined storage cluster were determined by theoretical distributions presented in Table 1.

Within the simulations, the fuel supply from roadsides was based on a distance orientation by having a mean transport distance of 60–64 km (Table 1). During the low heating season, the chip supply was oriented to the longest distance classes, whereas during the high heating season to the shortest distance classes. During the moderate heating seasons of autumn and spring, the mid-distance classes were stressed most. In terminal scenarios, forest chip transports from the roadside storages to

| Roadside storage size, solid-m³ | Mean | SD | Min | Max | Distribution |
|--------------------------------|------|----|-----|-----|--------------|
| Number of storages in cluster  | 2    | 2  | 1   | 4   | Tnormal     |
| Location and proportion of storages |      |    |     |     |              |
| - 2 km–20 km, 10%             | 2    | 20 |     |     | Uniform     |
| - 20 km–40 km, 25%            | 20.01| 40 |     |     | Uniform     |
| - 40 km–60 km, 30%            | 40.01| 60 |     |     | Uniform     |
| - 60 km–80 km, 25%            | 60.01| 80 |     |     | Uniform     |
| - 80 km–100 km, 10%           | 80.01| 100|     |     | Uniform     |

The material for the chipping was logging residues (tops and branches) from spruce-dominated final felling. The net calorific value of forest chips was set as 19.2 MJ kg⁻¹ corresponding to the representative value from Finnish studies.
coordinates from the permissible distribution class by having the location was defined using a random number generator. The generation of a new roadside storage location was controlled wherein the roadside storages were generated. Both the distance to the plant and the storage cluster distribution were determined using the truncated normal distribution (mean, SD, min and max; 47 + correction factor, 7, 25, 65) was used to determine the moisture content of roadside storages.

The monthly demand of forest chips used in simulations was derived from the local CHP plant in the city of Joensuu (Table 2). The daily variation of forest chip demand was introduced using the truncated normal distribution, where the mean value was the average daily demand of a particular month, the SD was 20% from the average, the minimum was 80% and the maximum value was 120% from the average demand. At the fuel reception, fixed parameter values were used for both driving and scaling-unloading, which were 0.05 and 0.3 h, respectively. In addition, the model recorded queuing times for each truck if queuing occurred. The capacity of the buffer for forest chips at the CHP plant was set to 6.0 GWh.

Each fuel supplier had an individual operating sector covering the whole supply area (Fig. 1). The operating radius from the business premises of each contractor was set to 55 km, wherein the roadside storages were generated. Both the distance to the plant and the storage cluster distribution controlled the generation of a new roadside storage location. The exact location was defined using a random number generator (-100 km, 100 km for x-coord and y-coord) to pinpoint the coordinates from the permissible distribution class by having 0.01 × 0.01 km grid level accuracy. The power plant’s location was at the origin (0, 0). To include the winding of roads depending on the density and the structure of the road network, a winding factor of 1.3 was used to convert straight line distances to road distances.

In BAU scenarios, where the feed-in terminal was not used, fuel suppliers had scheduled holiday periods during the low heating season. The fuel supply fleet of two suppliers was not in operation in the first two holiday months of May and June, and the fleet of the other two suppliers was in lay-down the following two months, June and August. In the terminal scenarios, the fuel supply fleet of all suppliers was able to be operated year round by having one shift system and substitute truck drivers operating during permanent drivers’ holidays.

According to the test simulation runs of one year, the terminal was emptied before the end of April. Consequently, the start of the scenario runs was defined as the beginning of May. For all terminal scenarios, initial seed buffer was set to zero for the terminal storage, thus improving the comparison between scenarios of direct supply and terminal-based supply.

Both the daily fuel demand and the alarm levels of the power plant’s buffer controlled the transports of forest chips from roadside storages to the power plant or to the terminal and from the terminal to the power plant. The lower alarm level of the plant’s buffer was set to 40% and the higher level at 90% of the buffer capacity. In terminal scenarios, during the low heating season when the buffer exceeded 90% of the capacity, fuel transports were directed to terminals, whereas if the buffer size decreased to <40% of the capacity, transports from the terminal to the CHP plant were ignited (Table 3). In BAU cases, only the high alarm level of 90% was used. If the buffer exceeded the higher alarm level, forest chip transports were stopped for the rest of the day after the unfinished load cycle of each chip truck. In situations in which the buffer was emptied, supplementary fuel (such as peat, sawdust, bark or forest chips carried out by a supplementary fuel supplier) with the fixed supply cost was introduced to the model to feed into the plant and fulfil the gap of demand and supply of forest chips.

Chippers had a 9-h normative shift schedule all weekdays except Sunday, whereas chip trucks were operated on 8.5-h shift schedule, respectively. Mobile chippers were modelled to arrive to roadside storage earlier than chip trucks to prepare the setup before the arrival of the first chip truck. If the scheduled work shift was left less than one hour, chip trucks were directed to the supplier’s business premises from the plant or from the terminal after unloading. In cases in which the scheduled work shift ended at the time when the chip truck was arriving to the roadside storage or chipping was ongoing, the chipping was carried out until the chip truck was loaded. Then, chip truck was directed as loaded to the business premises of the contractor. At the start of next working day, the loaded truck was directed either to the plant or the terminal depending on the scenario and the simulation stage. During the high heating season from December to February, 8.5- to 9-h work shifts were scheduled on Sundays as well. The logics of chippers’ and chip trucks’ daily operation are presented as flow charts in Figs 2 and 3.

The chip trucks in use were conventional container-based truck and trailer units with seven axles allowing a 64-tonne max vehicle weight in Finnish transportation. The total weight

| Correction for the mean value of moisture, per cent point | January | February | March | April | May | June | July | August | September | October | November | December |
|--------------------------------------------------------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|-----------|----------|
| Forest fuel demand, GWh | 79.9    | 70.5     | 56.4  | 32.9  | 18.8| 14.4| 9.4  | 18.8   | 37.6      | 47      | 59.2      | 70       |

Table 2 Moisture correction factor for correcting the mean value (47%) of moisture for each month (Hakkila, 2004) and monthly forest fuel demand of the CHP plant in the simulation in GWh.
of empty chip truck units was 23 tonnes, thus resulting in a 41-tonne maximum payload. The frame volume of containers was 131.6 frame-m$^3$ and load density was 0.38 solid-m$^3$ per frame-m$^3$ resulting in 50 solid-m$^3$. Preventing the overweight of trucks, the loading was controlled by calculating the fresh weight of solid-m$^3$ of forest chips. If the moisture of forest chips

Table 3  Control of fuel transports to the power plant in the simulation scenarios. RS is roadside; PP is power plant

| Main scenarios | Buffer size at power plant | Controlling rules |
|----------------|-----------------------------|-------------------|
| BAU scenarios  | Between 0% and 90%          | Transports from RS to PP or from truck park to PP |
|                | Filled over 90% level       | Transports of forest chips stopped after unfinished loads |
|                | Empty to zero               | Use of supplementary fuel |
| Terminal scenarios | Between 40% and 90% | Transports from RS to PP or from truck park to PP |
|                | Filled over 90% level       | Transports from RS to terminal or from truck park to terminal |
|                | Emptied under 40% level     | Transports from terminal to PP and RS to PP |
|                | Empty to zero               | Use of supplementary fuel |

Fig. 2  Flow chart of the logic the mobile chipper follows in the simulation model.
in storage reached 45.7%, the vehicle weight restricted overloading, whereas if moisture was under the breakeven value, the frame volume of the chip truck restricted overloading. The driving speed of trucks was determined by the speed functions of timber truck and trailer units introduced by Nurminen & Heinonen (2007).

The mobile chipper was a conventional truck-mounted drum chipper typically used in chipping at roadside storages. Normal distribution was used to determine the chipping productivity in each of the roadside storages. The mean productivity was 50 solid-m³ per effective hour, and the standard deviation was 5. Negative exponential distribution was used for generating breakdowns. The mean value for the time between failures was 9.5 h and for the duration of breakdowns was 0.5 h. A fixed setup time of 0.25 h occurred every time the chipper arrived to the roadside storage.

**Terminal characteristics**

From the results of terminal scenario runs, the maximum amount of stored chips at the terminal was used to determine the area required for storing forest chips (Table 4) utilizing the area requirement factor 1.2 solid-m² m³ (Impola & Tiihonen, 2011; Virkkunen et al., 2015). In addition, for the total space requirement of terminals, 0.7 ha was added to the calculated area requirement, thus allowing for possible greater use of terminals with additional infra. Other cost parameters for defining the investment cost of terminal, following the values used in

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Virkkunen et al.'s (2015) study, are introduced in Table 3. The feed-in terminal included a wheeled loader for terminal operations of building 5- to 7-m high heaps with forest chips, the loading of chip trucks, keeping the area free from snow and defending against the burning of chips in heaps (Table 4). The operator of the wheeled loader was the person responsible for the serving and maintenance at the terminal.

A shuttle truck was used in the terminal scenario, where outbound terminal transports were carried out with a higher capacity truck and trailer unit. The shuttle truck was a 9-axle truck-trailer unit having a maximum weight of 76 tonnes with a 157.9 loose-m³ or 60 solid-m³ load capacity. All loads were fully loaded to either the maximum weight or frame volume. In the shuttle scenario, the shuttle truck operated between the feed-in terminal and CHP plant. The chip transport was activated when the CHP plant's buffer decreased under a lower alarm level of 40% of the buffer capacity. During the high heating season, the shuttle truck operated one 8-h shift per day throughout the week if the fuel demand of the plant required a complementary fuel supply from the terminal (Table 2). During other seasons except the high heating season, the truck was used in mixed cargo transports. The amount of other transport operations was determined to be 1500 operating hours. In addition, cost sensitivity analysis with 0 and 750 h of other uses of the shuttle truck was conducted. The initial terminal location was 5 km from the CHP plant to the north.

In the initial terminal scenarios, the dry matter loss of stored material was expected to be 1% per month higher in chipped material than if stored as unchipped material at roadside storage. The dry matter loss of terminal-stored material was defined as fixed regardless of the arrival time. Fuel chip arrival and departure at the terminal was based on the first in-first out procedure. Respectively, the moisture content in initial scenarios was expected to stay at the same moisture level upon arrival at the terminal.

### Simulation scenarios

The BAU 1A1 scenario resembled the typical fuel supply scenario of the conventional forest chip supply from roadside storages to the CHP plant in Eastern Finland. All main parameters were kept as presented earlier. The main difference compared to the terminal scenarios was more fluctuated forest chip supply from roadside storages stressed to high heating season and 2 months sequenced lay-down time of the supply fleet for each entrepreneur. In addition to the BAU 1A1 scenario, scenario 1A2 with a 2-shift system during the high heating season was introduced to fulfill the initial forest chip demand of the power plant. All scenario runs are presented in Table 5.

Two main options were simulated in the terminal scenarios. Scenario 1B consisted of the utilization of forest chip suppliers’ own chip trucks for transporting fuel from the terminal to the power plant. In 1B, while the outbound terminal transports were needed, one of each contractor's chip trucks was called for terminal transports and operated in terminal transports until the lower alarm level of the power plant's buffer was fulfilled. Another chip truck of each contractor operated normally transporting chips from roadside storages to the plant. In scenario 1C, a separate shuttle truck was used for terminal transports to the power plant. In all scenario simulations, the distances had to match the distribution of distances from roadside to the power plant to have valid correspondence among scenarios.

Four distance scenarios with distances of 5, 10, 20 and 30 km from the power plant to the terminal were used to explore the influence of the terminal location both on supply operations and costs. The locations of terminal were in line from the power plant towards the north (Fig. 1).

The third main scenario comparison included an evaluation of the impact of the dry matter loss of chipped material in storing compared to the unchipped material storing at roadsides. In 3C1, no additional dry matter loss compared to the BAU scenario occurred. In 3C2, dry matter loss of 1% per month was defined for terminal-stored material as chips, whereas 3C3 had 2% per month dry matter loss, respectively. In the fourth main scenario, the influence of terminal-stored forest chip moisture in fuel supply costs was studied. In the scenarios of 4C4 and 4C5, the moisture increased 6 and 10 per cent points, both having dry matter loss of 2% per month (Table 5).

For each scenario simulation, seven replications with varying seed numbers for determining unique random number streams were applied. Average values, standard deviations and 95% confidence levels were calculated for the main output parameters of each simulation scenario. In addition to the terminal scenario runs, sensitivity analyses for the operating hours of the shuttle truck and the investment level of the terminal were investigated. The shuttle truck’s operating hours for uses other than terminal use varied 0, 750 and 1500 h, whereas the terminal's investment cost had 30% lower and 30% higher values than the initial investment cost.

### Table 4 Characteristics and cost factors of the feed-in terminal used in the cost calculations of the simulation scenarios 1B and 1C

| Terminal area | Space requirement for forest chips | 1.2 | Solid-m³ m⁻² | Purchase price of land | 5000 | € ha⁻¹ |
| - Maximum storage size in scenarios | | | | | |
| - 1B. Suppliers' chip trucks (simulation value) | 45 876 | Solid-m³ | 30 | € m⁻² |
| - 1C. Shuttle truck (simulation value) | 45 146 | Solid-m³ | 5000 | € ha⁻¹ |
| | Land area | 4.5 | ha | Interest | 4 | % |
| | Depreciation time | 15 | a | TOTAL per year | 117 900 | € |
| Wheeled loader | Terminal working hours | 1500 | h | Hourly costs, idle | 40 | € h⁻¹ |
| | Total working hours | 3000 | h | Hourly costs, operating | 60 | € h⁻¹ |

![FOREST CHIP SUPPLY BY USING A FEED-IN TERMINAL](1663)
Cost calculation

The costs of forest chip supply operations were calculated with typical cost accounting tables for machines using Excel spreadsheets. The main cost parameters accounting for the mobile chipper, the chip truck and the shuttle truck are presented in Tables 6 and 7. All cost values exclude value-added tax. The supply costs were calculated after simulations using the average values of performance and time data. The cost of the supplementary fuel supply as delivered to the plant was set to 8 € per MWh. To more clearly visualize the differences in the supply costs between scenarios, the purchase prices of fuels (forest chips and supplementary fuel) were not included. In this respect, supply costs included the costs of chipping, truck transports and terminal costs (investment and operations).

Results

Scenarios with higher amounts of forest chip supply than the BAU scenario 1A1 resulted in longer transport distances (Fig. 4). In terminal scenarios, forest chip transports to longer distances were stressed starting from the 20–40 km distance class.

Within the BAU scenario, four supply units of one mobile chipper and two chip trucks were not sufficient to meet the power plant’s annual demand while operating with one shift (Fig. 5). From the total fuel demand, 19.3% as supplement fuel was used in addition to the base supply of forest chips. To meet the demand for the forest chip supply, the external shift during the high heating season was needed for the supply fleet (scenario 1A2). In both terminal scenarios, the forest chip supply was merely enough to fulfill the demand of the power plant; the use of supplement fuel was 6.3% and 3.4% from the total demand in terminal scenarios 1B and 1C. The share of fuel delivery via the terminal was 18.0% and 17.6% in scenarios 1B and 1C.

In the 1A2 scenario with extra shift during high heating season, the average work shift length was 21% higher than the BAU scenario (Table 8). Respectively, in scenario 1B the average work shift length was 8% longer than in scenario 1A1 due to the time used for terminal transports from long distances and the timing of operations at the end of the scheduled shift. Due to the full loads of the outbound terminal transports, the mean load size of 64-tonne truck-trailer unit was slightly higher in scenario 1B than in other scenarios. In addition, in scenario 1C the shuttle truck was able to transport maximum loads as in volume due to the moisture levels of forest chips and the high transport capacity in the mass/frame volume ratio. The scenario-average load size was 90–92% from the load capacity between scenarios.

The effective chipping time was notably lower in 1B compared to other scenarios having 38.3% from the total time use (Fig. 6). In 1B, the lowest share in chipping and the highest in waiting was a result of the chip truck control for transporting forest chips from terminals during the high heating season. When comparing the work element shares of chip trucks, the greatest differences
involved elements of waiting time. Within scenarios 1A1 and 1A2, chip trucks’ waiting times were longer at roadsides, whereas in terminal scenarios 1B and 1C, chip trucks had a longer waiting time at the power plant (Fig. 6). At the beginning of shifts, the number of arrivals to the CHP plant was high, resulting the longest queuing times, while filled up trucks from the earlier shift arrived to unload at the plant.

Forest fuel transports were analysed at the weekly level in the 1A1, 1A2, 1B and 1C scenario simulations (Fig. 7). In scenario 1A1, the fuel transports from four suppliers were able to fulfil the plant’s demand until week 43, whereas scenario 1A2 fulfilled the demand until week 1. In both scenarios, the initial 4 months starting from week 18 were operated by two suppliers fulfilling the fuel demand. Between the time of calendar week 47 and 8, the amount of weekly transports was rising due to the change in the selection order of roadside storages emphasizing shorter distances.

In both terminal scenarios, 1B and 1C, all four fuel suppliers were operating during the summer being able both to fulfil the plant’s fuel demand and to supply the fuel to the terminal (Fig. 7). In total, the transported forest chip amount at the terminal was 92 950 MWh (45 876 solid-m$^3$) and 90 978 MWh (45 146 solid-m$^3$) in scenarios 1B and 1C, respectively.

Table 6  Main performance and cost factors for the mobile chipper

| Performance                          | Capital cost |
|--------------------------------------|--------------|
| Productivity, effective time 50      | Investment price 600 000 €     |
| Setup time 0.25 h                    | Depreciation time 7 y          |
| Time between failures (mean) 9.5 h   | Depreciation rate 17 %         |
| Duration of breakdowns (mean) 0.5 h  | Interest rate 4 %              |
| **Employer cost**                    | **Variable cost**              |
| Salary 16 €                          | Fuel price 0.9 € L$^{-1}$      |
| Indirect salary cost 68 %            | Fuel consumption              |
| Daily allowance 18 € per d           | - chipping 124 L h$^{-1}$      |
|                                     | - driving 55 L h$^{-1}$        |
|                                     | - other 14 L h$^{-1}$          |
| **Overheads and risk margin**        | **Repairs and maintenance 0.8 € m$^{-3}$** |
| Insurance 10 000 € per y             | Oil and lubricants 0.08 € m$^{-3}$ |
| Administration and overheads 7500 €  | Blazers 13 € h$^{-1}$          |
| Risk margin 5 %                      |                           |

Table 7  Main performance and cost factors for chip suppliers’ chip trucks and the shuttle truck

| Performance       | Chip truck | Shuttle truck | Capital cost       | Chip truck | Shuttle truck |
|-------------------|------------|--------------|--------------------|------------|--------------|
| Load space        | 131.6      | 157.9        | Loose-m$^3$        | Truck      | 144 200      | 175 000      | €          |
| Setup time at roadside storage | 0.25 | - h | Tyre, truck; trailer | 725; 450 | 725; 450 | € per piece |
| Speeds (loaded, unloaded) | From Nurminen & Heinonen (2007) | Tyre, truck; trailer | 725; 450 | 725; 450 | € per piece |
| Loading with front loader | 0.4 | 0.4 h | Truck tyres, total | 5800 | 8700 | € |
| Unloading (terminal and plant) | 0.3 | 0.3 h | Trailer tyres, total | 7200 | 8100 | € |
| **Employer cost** |            |              |                    |            |              |
| Salary 16 €        | 20 %       | 20 %         |                   | - truck    | 20 %         | %          |
| Indirect salary cost 68 % |          |              |                   | - trailer  | 25 %         | %          |
| **Overheads and risk margin** |            |              |                    | Interest rate 4 % | 4 % | % |
| Insurance 5500 € per a |              |              | Variable cost      |            |              |
| Traffic fees 2500 € per a |              |              | Fuel price 1.0      |            |              |
| Administration and maintenance 6500 € per a |              |              | Fuel consumption 55 |            |              |
| Uncompensated driving 2000 € per a |              |              | Repairs and maintenance | 14 000 | 14 000 | € per a |
| Risk margin 5 % |              |              | Oil and lubricants 2000 € per a | 3000 | 3000 | € per a |

Tyres (coating) 200 € per piece
In scenario 1B, the more the chip transports were carried out from the terminal, the less the chips were transported from the roadsides. That was a result of the supply control, where one of the each supplier’s two chip trucks was determined to carry out the outbound terminal transports to meet the increased fuel demand at the CHP plant (Fig. 7). In scenario 1C, separate shuttle truck transports did not influence the forest chip suppliers’ operations, thus increasing the total supply compared to scenario 1B.

While comparing the annual supply costs, the least costly scenario was 1A2, with an extra shift during the high season resulting in 7.1% lower supply costs compared to the BAU scenario (1A1) while an assumption of an 8 € per MWh supplement fuel cost was used (Fig. 8). From the terminal scenarios, the cheapest option with the lowest supply cost was 1C, with separate terminal shuttle use having a 1.4% higher annual supply cost than the BAU scenario 1A1. Respectively, terminal scenario 1B had a 3.1% higher supply cost. The share of terminal costs from the total supply costs was 4.7% and 4.8% in terminal scenarios 1B and 1C, whereas the separated costs of outbound terminal transports (terminal to power plant) were 2.3% and 1.5%, respectively.

In all scenarios, chipping had the highest operational cost, varying from 3.67 to 3.91 € per MWh, whereas the transport costs from roadsides varied from 3.45 to 3.74 € per MWh (Fig. 9). While taking the total forest chip supply costs into account in the terminal scenarios, the share of the terminal cost including terminal transports...
to power plant was 7.5% and 6.5% in scenarios 1B and 1C. A sensitivity analysis of the variation of terminal investment in 30% less and a higher cost resulted in a 0.9% difference in the total supply cost both in scenarios 1B and 1C.

In all distances, the terminal scenarios of using suppliers’ own chip trucks for terminal transports resulted in 1.0–2.3% higher total supply costs compared to using a separate shuttle truck for terminal transports (Fig. 10). For distances of 5–30 km between the terminal and the plant, the total supply cost varied from 7.95–8.17 € per MWh in scenarios of suppliers’ own trucks, whereas in terminal shuttle scenarios, the supply cost variation was 7.83–7.98 € per MWh. The cost difference between scenarios B and C increased based on the distance between the terminal and the plant. While using suppliers’ own chip trucks for terminal-plant transports at longer distances, mobile chippers had more idle time, and thus, chipping costs increased.

To obtain cost-effective trucking costs for the shuttle truck, terminal transports necessitated at least a moderate other use for the shuttle truck unit during the low

Table 8 Operational statistics of mobile chipper and chip truck units in the simulation scenarios of 1A1, 1A2, 1B and 1C. The confidence interval is presented as a per cent-share from the mean value (CI 95%).

|                           | 1A1. BAU-direct delivery (1-shift) | 1A2. Direct delivery (1–2-shifts) | 1B. Terminal use – chip trucks (1 shift) | 1C. Terminal use – shuttle (1 shift) |
|---------------------------|-----------------------------------|-----------------------------------|------------------------------------------|-------------------------------------|
| Working days, d per a     | 273                               | 273                               | 326                                      | 326                                 | 111                                 |
| Mobile chippers           |                                   |                                   |                                          |                                     |                                     |
| Shift length, h           | 8.8                               | 10.6                              | 9.5                                      | 9.1                                 | 9.1                                 |
| Annual production, solid-m³ per a | 50 107                         | 60 731                            | 58 517                                   | 60 148                              | 58 517                              |
| Productivity, h₀ per solid-m³ | 49.52                          | 49.52                            | 49.54                                    | 49.48                               | 49.54                              |
| Road side storages, No.   | 289                               | 349                               | 335                                      | 347                                 | 335                                 |
| Total driving, km per a   | 26 751                            | 28 281                            | 32 392                                   | 32 121                              | 32 392                              |
| Daily driving, km per d   | 98.0                              | 103.6                             | 99.4                                     | 98.5                                | 99.4                                |
| Chip trucks and Shuttle   |                                   |                                   |                                          |                                     |                                     |
| Shift length, h           | 8.6                               | 10.4                              | 9.2                                      | 8.9                                 | 8.9                                 |
| Production from roadsides, solid-m³ | 25 054                        | 30 365                            | 29 258                                   | 30 074                              | 30 074                              |
| Production from terminal, solid-m³ | 5735                           | 45.1                              | 45.9                                     | 45.3                                | 45.9                                |
| Load size, solid-m³       | 45.1                              | 45.4                              | 45.9                                     | 45.3                                | 45.9                                |
| Load size, MWh            | 94.7                              | 95.1                              | 96.8                                     | 94.9                                | 94.9                                |
| Total driving, km per a   | 80 280                            | 95 048                            | 99 238                                   | 99 641                              | 99 641                              |
| Driving per load, km per load | 144.7                          | 142.1                             | 130.3                                    | 151.1                               | 151.1                               |

Fig. 6 Distribution of work elements for the mobile chipper and chip truck in scenarios 1A1, 1A2, 1B and 1C.
Fig. 7 Weekly level statistics for the forest chip demand and transports during 1 year. The compared scenarios were 1A1, 1A2, 1B and 1C.

Fig. 8 Annual fuel supply costs of the power plant in four simulation scenarios. Terminal costs include investment and operational costs of the terminal.

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heating season (Table 9). Compared to the simulation scenario of 1500 h of other use, at a 5-km distance, the pure terminal use (0 h of other use) option had 99.2% and 750 h of the other use option had 22.0% higher trucking costs. At a 30-km distance, the respective values were 36.8% and 12.0% for 0 h and 750 h other use of trucks. The same comparison for the total fuel supply costs resulted in 1.5% and 0.3% higher costs at 5 km and 1.1% and 0.4% higher costs at 30 km, respectively.

The cost influence of the changes of terminal-stored forest chips in DML and moisture content was identified in the main scenarios of 3 and 4 (Table 10). If the moisture content of terminal-stored chips was expected to remain the same as the moisture content upon arrival, and, dry matter loss would increase more than in roadside storing as uncomminuted, the cost increase in the total forest chip supply was 1.1% and 2.0%, in 1% per month DML and 2% per month DML scenarios. A change in the dry matter loss had a clear impact on the energy content of terminal-stored material as well as on the transport efficiency by reducing the load size in MWh. If the moisture content had a 6 per cent point increase during terminal storing, the supply cost increase was 0.5% while DML remained the same and 0.8% if DML increased from 1% per month to 2% per month.

Discussion
Discrete-event simulation was applied in analysing the operational differences of a terminal-aided forest chip supply compared to a conventional direct chip supply in terms of supply costs, the machine utilization of the supply fleet and the supplied energy amount. Weekly work shift arrangements, lay-down seasons, variations in the power plant’s daily fuel demand, distance-oriented storage selection, fuel supply control by the power plant’s buffer level, as well as detailed machine
interactions were compiled within the model. This enabled the reliable investigation of the influence of the terminal on the whole forest fuel supply of a CHP plant. While comparing the supply costs to other studies, it is important to note that neither the purchase price of the fuel material, harvesting and extraction costs to roadside storage, fuel supplier entrepreneurs’ profit nor the costs of fuel supply management were taken into account in the supply costs.

Windisch et al. (2015) studied the influence of the smart selection of roadside storages for the supply of forest chips to power plants in selection terms of moisture content, the location of roadside storages and the size of roadside storages. However, they did not take into account terminals in the simulations. Eriksson (2016) has also studied supply chains without terminal options by simulations, whereas Karttunen et al. (2013) and Korpinen & Aalto (2016) have included terminals into forest fuel supply system analyses. Karttunen et al. (2013) conducted a simulation study of intermodal container supply of forest chips including big satellite terminal and train transports for outbound transports.

Terminal options were rather cost-competitive alternatives to the BAU chip supply operated by one shift.
system. In the study case of a 517 GWh forest chip supply per annum, by introducing a feed-in terminal and a shuttle truck for transports of terminal-stored chips, the total supply cost was 1.4% higher than the BAU fuel supply. In the terminal scenarios, around 20% of the total forest chip use was circulated through the terminal. If operators were available for operating an additional shift during the high fuel demands, the direct chip supply would have been 7% cheaper than the BAU chip supply. Applying a terminal to the fuel supply can be a feasible option, especially in supply situations where an additional and professional workforce is not possible to recruit during the high heating season, which is currently a significant problem in Finland (Väätäinen et al., 2014).

The influences of terminal investment costs with a variation of ±30%, the terminal location variation with distances 5–30 km from the CHP plant and the variation in the annual utilization of the shuttle truck (0, 750, 1500 h of other use) did not have a notable difference in the total supply cost, as changes were 1–2% in the annual supply costs for each case compared to base scenarios of 1B and 1C. Moreover, possible deterioration of the fuel quality in terms of increased dry matter loss or moisture content resulted in a 0.5% increase the total supply cost, whereas a 6% increase in the moisture content resulted in a 0.5–1.0% increase depending on the strength of the concurrent change of DML.

The supply cost of the supplementary fuel was defined to be 4.4% higher than the cost of forest chips in the direct supply in the BAU scenario, which could be realistic, especially during the season of the highest fuel demand with typically higher costs of fuel supply. To create successful terminal scenarios with lower costs than the BAU scenario, the breakeven points for the supply cost of the supplementary fuel were a) 8.7 € per MWh for the terminal scenario with the shuttle truck (1C) and b) 9.8 € per MWh for the terminal scenario with the use of chip suppliers’ trucks (1B). Furthermore, in terminal scenarios and the direct supply scenario of 1A2, the higher forest chip supply calls for a larger forest chip supply area. This was taken into account in the distance allocation of roadside storages (see Fig. 4).

The productivity of the chipper with 50 solid-m³ per H₀ for logging residues corresponded to the results of Kärhä et al. (2011a,b) and Mola-Yudego et al. (2015) for the corresponding engine power of chippers. The machine utilization percentage of mobile chippers was found to be low compared to earlier studies (Asikainen, 1995; Spinelli & Visser, 2009; Eliasson et al., 2012). The results were quite similar to the findings of Windisch et al. (2015) by having arguments of including all time elements in daily operation in the simulations. The shares of the relocations and idling are relatively large, as it is in reality in similar forest chip supply units. Relatively high chipping productivity resulted in a high share of idling for chippers, thus questioning the feasibility to use two chip trucks instead of three. The use of two trucks and one mobile chipper is most common in Finland, as it was the de facto for the suppliers operating in that area.

Currently, half (49%) of the truck and trailer units for energy chip transports are <65 tonnes (Venäläinen & Poikela, 2016); however, a trend to increase the total weight is ongoing in Finland (Venäläinen & Poikela, 2016). According to Korpilahti (2015), the transport costs of forest chips for 60- and 68-tonne truck-trailer units were in line with the costs of this study; for 64-tonne trucks in 60–63 km distances, unit costs followed the costs of 60 tonners applied from Korpilahti (2015).

The defined setup at the feed-in terminal was solely based on the storage of comminuted forest biomass. The terminal structure did not include a weighing station or other additional features, such as the chipping of uncomminuted material, which are more common to terminals over 5 hectares (Korpinnen & Aalto, 2016). A wheeled loader operator was expected to be available for terminal operations instantly without any delays. In addition, the overheating of chip heaps and risk of fire requires the monitoring of the terminal area manually or by utilizing sensors, thus making it obligatory to have at least one person to monitor and carry out the extinguishing of possible burning zones.

In scenario comparisons, the values for DML in the terminal storing of chipped material had 1–2 per cent unit higher DML compared to the values of uncomminuted logging residues at roadside storages. The latest results for ensuring the loss of dry matter of logging residue chips in terminal storing are 2.7% and 2.2% per month, on average, having storing times of 8 months and 4–8 months, respectively (Raitila & Sikanen, 2016). On the other hand, alternative storing in the form of uncomminuted logging residue material in windrows at roadsides have generated similar DML as well (Jirjis & Lehtikangas, 1993; Nurmi, 1999; Routa et al., 2015). Therefore, the selected DML values for the scenarios can be stated to be rather conservative for the terminal storing conditions of forest chips.

The use of a feed-in terminal as a part of the supply system is a promising option for direct supply, which unbalances the use of workforce and machinery, according to this study. Decreasing fluctuation of the workload also intensifies the use of machines and human resources. Balancing the seasonal fluctuation was stated as one of the most significant factors in developing the
forest biomass transports in the study of Vääätäinen et al. (2014). Terminals increase their importance in situations when road connections and accessibility to roadside storages drop down. The cost savings and the secured supply would have been higher for terminal scenarios if bad road conditions would have been taken into account in the simulations. There are various possibilities for utilizing terminals in terms of the size, transported material and the operations included in the terminals.

There are still many improvement possibilities in biomass supply to energy generation. For the future, research remarks including a terminal secured supply model could allow various analysis and scenario comparisons. How is the fuel supply fulfilled in cases of fuel demand variations between years? What is impact on the supply when the parameters of the roadside storages change in terms of storage size, fuel type, moisture level and location, for example? What is the influence of different sizes of trucks and mobile chippers on supply performance? How do different operations models affect the supply cost and performance? What is the effect of road trafficability and bad road seasons on the fuel supply in scenarios of direct and terminal-supported supplies? What is the role of biomass terminals for the drying of fuel by introducing different methods for enhancing the drying such as covering the stored biomass or having larger terminal area?

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