Original scientific paper

Impacts of a High-Capacity Truck Transportation System on the Economy and Traffic Intensity of Pulpwood Supply in Southeast Finland

Olli-Jussi Korpinen, Mika Aalto, Pirjo Venäläinen, Tapio Ranta

Abstract

High-capacity transportation (HCT) of roundwood is a road transport concept that is currently being demonstrated in Finland and Sweden. In Finland, HCT trucks are in most cases unable to access roadside storages, but they are expected to bring cost savings in highway transportation between transshipment terminals and mill yards. Evaluating the optimal solutions is challenging due to the complexity of the transportation systems. This paper presents a dynamic simulation model, SimPulp, which was developed to generate information about the impacts of substituting HCT for a part of the present pulpwood transportation system. A case study in the area of the most intensive pulpwood use in Finland was conducted. The results indicate that HCT has potential for reducing transport costs and especially the traffic intensity of roundwood procurement in the studied area. The economic advantages of pulpwood HCT could be more significant in a larger area or in the use of inter-terminal backhauling.

Keywords: roundwood, supply chain, logistics, high-capacity transportation (HCT), decision support, simulation modelling, agent-based modelling (ABM)

1. Introduction

Enhancing the forest-industry logistics and transportation infrastructure was a central issue in the Strategic Programme for the Forest Sector in Finland, which was administered by the Ministry of Employment and the Economy (2012) in 2011–2015. An important target, which is gradually being fulfilled, was the increase in vehicles' carrying capacity in road transportation. In 2013, the maximum permissible gross weight of full-trailer trucks in Finland was raised from 60 t to 76 t with a precondition of modifications to the axles and cargo space (Government decree 407/2013). At present, 38% of trucks used in roundwood transportation fulfil the conditions of 68 t and 55% of trucks the conditions of 76 t maximum weight (Venäläinen 2017a).

The total cost savings due to the increased weight allowance can be considered significant because road transport represents 76% of all roundwood transportation in Finland, and trucks are also involved in rail and waterway transport chains (Strandström 2016). It has been estimated that at distances longer than 100 km, the average timber transport cost with a 76 t truck is circa 20% less than that of a 60 t truck (Venäläinen and Korpilahti 2015).

Currently, the Finnish Transport Safety Agency is investigating possibilities to allow high-capacity transportation (HCT) trucks on certain parts of the Finnish road network (Lahti and Tanttu 2016). By the end of the year 2017, there were five trucks in timber transportation and four trucks in wood chip transportation with a gross weight allowance higher than 76 tons (Finnish Transport Safety Agency 2017). During the experimental period, data from onboard recorders is collected to analyse fuel consumption in different conditions and vehicles' suitability for e.g. intense traffic flow or extreme weather. Identical recorders have been mounted on 76 t trucks to obtain comparable data from regular vehicles (Heinonen 2016).

Roundwood HCT has also been demonstrated with 90 t and 74 t trucks in Sweden (Asmoarp et al. 2018), where the maximum permissible gross weight has been recently raised to 74 t (Swedish Transport Agency 2018). At present, the greater weight allowance applies only on designated roads, mostly in Northern Sweden (Swedish Road Administration 2018), but in the future, the network is envisioned to cover also other roads currently permitted for 64 t trucks.

In Finland, most HCT trucks operate between terminals (Finnish Transport Safety Agency 2017). In timber transportation, this means that wood transshipment from regular trucks to HCT trucks takes place in an economically feasible location in the transportation system and the HCT truck delivers the wood to the mill. Transshipment can be done in different ways, e.g. directly from a regular truck onto an HCT truck, by trailer interchange, via a storage pile or with a mix of these methods. Also, special equipment, such as separate loading machines or demountable truck bodies, can be used to speed up the work (Fig. 1).

The HCT system is largely similar to intermodal systems that include truck transportation from roadside storages to the loading point of a train or a vessel. However, the number of potential locations for HCT terminals in a system is usually manifold. This is due to the extensive road network and relatively low establishment and maintenance costs of terminals in comparison with rail or port terminals (Iikkanen and Sirkiä 2011, Impola and Tiihonen 2011). HCT trucks are less liable to delays than trains and vessels, which are usually dependent on other traffic on single-track rail lines and narrow waterway passages (e.g. sluices).

In a feasibility analysis of HCT, the comparison with a conventional fleet should not include only the route between terminals. Instead, the overall performance of an HCT system should be assessed. Investigating the economic advantages, losses and break-even points of conventional and more advanced methods is a complex matter that includes uncertainty and case-specific variables. Many of the variables are not only location-dependent but also time-dependent because the balance of demand and supply varies over time.

In operations research, complex supply chains are usually studied with mathematical optimization or simulation models (Almeder et al. 2009). For example, backhaul systems in wood procurement have been previously studied with linear programming (LP) methods (e.g. Palander and Väätäinen 2005, Carlsson and Rönnqvist 2007), which are suited for cases where study problems and modelling elements can be generalized and aggregated to a high abstraction level. In such cases, empirical data from the vehicles are usually sufficiently available, and thus, model parameters are typically well known before the implementation of the model. Simulation models' primary purpose is not to find the optimal state of the system, but rather to increase understanding about causalities and interconnections for the implementation or development of real-world systems (e.g. Biswas and Narahari 2004).

This paper deals with the modelling of an HCT system with a holistic simulation approach. The paper presents the design of a dynamic simulation model, SimPulp, and a case study where the model has been implemented. The objective of the study was to assess the impacts of replacing a proportion of the present truck transportation system of pulpwood with an HCT system in Southeast Finland. The study was carried out by simulating the system in scenarios with varying numbers of vehicles and transshipment terminal locations. Economic indicators were used for assessing the performance of the vehicles, and transport intensity indicators were used for evaluating the impacts on the transportation network. The paper finishes with a discussion about the findings of the case study and further research needs arising from the output of SimPulp.

Fig. 1 Transshipment of pulpwood from regular trucks and terminal stock onto an HCT truck (5+5 axle full trailer, 84 t gross weight) equipped with a demountable truck body. Photo: Esa Hirvonen

2. Methodology

2.1 Model overview

SimPulp was designed to simulate operations in pulpwood transportation by road in a visualized spatial environment of two road transport networks: a regular network and an HCT corridor network. Other transport modes than road, i.e. rail and waterway transportation, were not modelled in detail but they were included as factors affecting the truck transportation system.

The main principle of SimPulp is to fulfil the demand of pulp mills by delivering wood from roadside storages and intermediate terminals. The model produces performance data about the transport fleet operating in:

- ⇒ the existing road transportation system of pulpwood
- ⇒ a system including HCT and transshipment terminals.

This data will, thereafter, be used for e.g. economic and environmental impact analyses.

SimPulp was developed as an agent-based simulation model (ABM), which has been documented as a useful approach in studies of complex systems including spatially explicit geographical information (Crooks and Castle 2012). AnyLogic 7.2.0 Professional was used as the software for the design and development of SimPulp.

2.2 Agents and state variables

SimPulp includes five agent types: »Main«, »Demand Point«, »Supply Point«, »Vehicle« and »HCT Terminal«. All agent types have their own characteristics and populations (i.e. groups of individuals) in the model. »Demand Point« includes a population of points representing the pulp mills. The population of »Supply Point« represents groups of roadside storages in a small area (5×5 km grid cell) and transit points between the studied area and the surrounding area. »Vehicle« represents timber trucks and includes two populations representing regular and HCT trucks. The availability of trucks is modelled with state variables indicating whether the truck is reserved for an existing transport task or available for a new delivery. »HCT Terminal« contains the population of terminals required for pulpwood transshipment from regular trucks to HCT trucks. Pulpwood as transported goods is not represented by any agent or »entity« (specific to discrete-event modelling approaches) but by two values with which the agents communicate: the amount of wood (as double value) and wood type (as option list, i.e. pine, spruce or hardwood).

»Main« is the connecting platform for the interactions between all other agents. »Main« includes a linkage with the geographical information system (GIS), which is the environment for logistical actions of the agent populations. The »Demand Point«, »Supply Point« and »HCT Terminal« populations are stationary, while the geographic locations of the »Vehicles« population change over time. The visualization of the GIS environment includes a tiled background map and a road network with routing options, both provided by OpenStreetMap (AnyLogic Company 2017).

2.3 Source data and experiment setup

SimPulp requires a quantity of input datasets that initialize the model before each simulation run. The datasets are uploaded from spreadsheet tables containing the following information:

- ⇒ Dataset 1: Locations of demand points and their annual demand by wood type
- ⇒ Dataset 2: Locations of supply points and their annual supply by wood type
- ⇒ Dataset 3: Locations of HCT terminals
- ⇒ Dataset 4: Daily demand distribution (daily demand per annual demand) by wood type
- ⇒ Dataset 5: Daily supply distribution by wood type
- ⇒ Dataset 6: Distribution and variation of arriving trains at demand points
- ⇒ Dataset 7: Distribution and variation of arriving vessels at demand points
- ⇒ Dataset 8: Transport distances and transport times between supply points, demand points and HCT terminals
- ⇒ Dataset 9: Route ranking matrix according to supply costs from supply points.

The locations are given with WGS84 geographical coordinates. Two separate GIS analyses are required to produce the data for Dataset 8. Transport distances and times are calculated for regular trucks in the first analysis, and for HCT trucks in the second analysis. Dataset 9 includes all routing options from supply point to demand point, including routing via each HCT terminal.

In addition to the datasets, scenario-specific data is entered into SimPulp in the startup window. This data includes the number and transport capacities of regular and HCT trucks available, and terminals (from Dataset 3) that are selected for the simulation run.

2.4 Process overview

There are two pulpwood delivery methods: direct delivery from »Supply Point« to »Demand Point« and delivery from »Supply Point« to »Demand Point« via »HCT Terminal«. The first method involves only regular trucks. In the second method, both HCT and regular trucks participate. Regular trucks transport material between »Supply Point« and »HCT Terminal«, and HCT trucks transport material between »HCT Terminal« and »Demand Point«.

The main principle of operation is the following:

⇒ the supply point generates wood according to a given speed and time distribution (Dataset 2) and always offers wood to the demand points when a full truckload of wood becomes available. The offers are made in the order defined by Dataset 9

⇒ the demand point accepts the offer if its storage volume has not been exceeded

⇒ the supply point reserves an available truck for loading when the demand point accepts the offer

⇒ the truck returns to the same supply point, and if the supply point does not address a new task for the truck, the truck becomes available for all supply points.

Fig. 2 provides an overview of the whole process. The process is accomplished individually for each wood type. However, the same truck population is used for the transportation of all wood types. One truckload can include only one wood type at a time. Additionally, the population of »HCT Terminal« contains as many agents as there are possible transport destinations from each terminal location to each mill. This is because, regardless of the delivery method, wood is routed from the supply point across to the final destination and the truckloads routed to different mills cannot be mixed at the same terminal location.

HCT terminals behave like demand points when wood is offered to them and like supply points when wood is forwarded to demand points. Accordingly, a route including HCT is selected when the first location accepting the offer is an HCT terminal. By default, the demand point begins accepting offers after the storage at the demand point drops under 1/121 of the annual consumption (i.e. average demand of ca. three days) of the respective wood type, and stops accepting offers when the storage exceeds 1/52 of the annual consumption (i.e. average demand of one week). HCT terminals, serving the same demand point, reject offers if their total storage has exceeded 1/24 of the annual demand (i.e. average demand of ca. 1/2 months) for the respective wood type at the respective demand point. The terminals begin to accept wood again when the inventory drops below the threshold.

2.5 Generalization and system boundaries

SimPulp includes only the transportation system between supply points, demand points and transshipment terminals for HCT transportation. Forest operations (i.e. harvest and forwarding) and mill-yard operations (e.g. transfer from buffer storage to conveyor) are excluded from the model. SimPulp does not take into account different variations of transshipment methods at HCT terminals or different unloading methods of trucks and trains at pulp mills. The following standard time consumption parameters are used:

⇒ load truck at roadside or HCT terminal: 85 s/t

⇒ unload truck to the conveyor at demand point: 19 min/truck

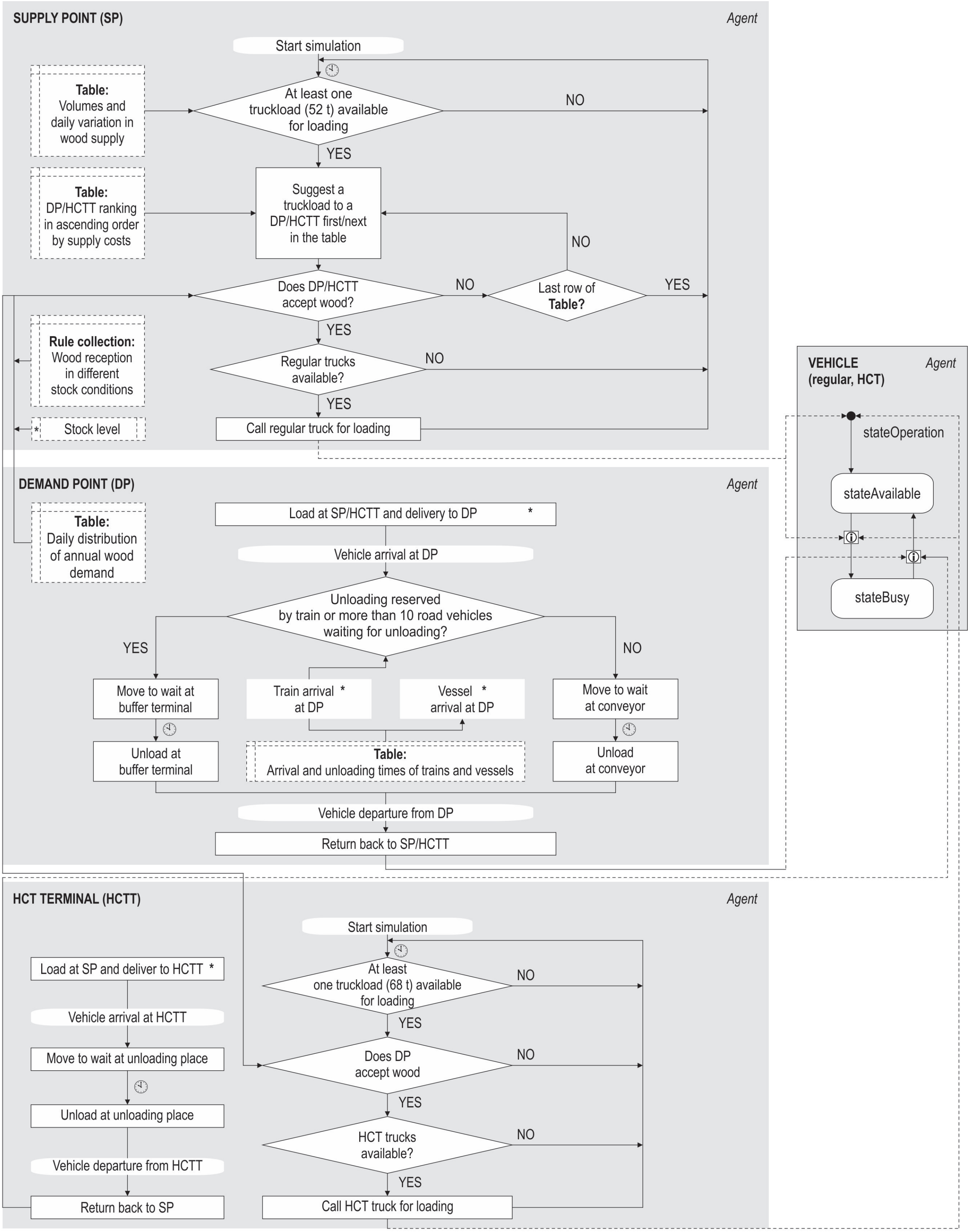
⇒ unload truck to HCT terminal or buffer terminal at demand point: 42.5 s/t

⇒ unload train or vessel at demand point: 30 s/t.

The transportation fleet includes regular trucks and HCT trucks with default payloads of 52 t and 68 t, respectively. Individual underweight deliveries or deliveries without a trailer, which are occasional for regular trucks in the real world (Venäläinen and Korpilahti 2015), cannot be included in SimPulp. The total haulage per truck is accumulated only from transport tasks, i.e. wood deliveries and empty returns, and transfers between wood supply regions or depots are not taken into account. Accordingly, time consumption and utilization rates of trucks are based only on the transport tasks and the time spent at supply points, demand points and HCT terminals. Other time (i.e. »stateAvailable« in Fig. 2) is not considered as utilization of the truck.

The geographical extent in SimPulp is not limited, but according to the test runs in different geographical areas, a large studied area with a plenitude of locations (supply points, demand points and HCT terminals) increases the computing time significantly. The resolution of the supply point grid should be adjusted according to the scale of the studied area and processing capacity of the hardware. We used a standard desktop PC with an eight-thread Intel processor of a 3.5 GHz clock speed and 32 GB RAM.

The map-based visualization of the system may look illogical if the model is applied in geographical regions with poor coverage of OpenStreetMap road data, for example sparsely populated areas in developing countries (Mooney 2015). This does not, however, affect the decision-making in SimPulp because the decisions are based on Datasets 8 and 9. Instead, GIS data used for the analysis producing Datasets 8 and 9 should be of a high quality.



* indicate the randomness related to the events and stopwatches possible time delays

Fig. 2 Decision-making process of the agents and agent communication in the SimPulp model

Table 1 Output types used for runtime evaluation of a simulation run

Subject	Model output	Unit	Subtype division	Presentation format
Vehicles	Available trucks	n	Regular, HCT	Time plot
	Vehicle utilization	%	Regular, HCT	Time plot
System performance	Pulpwood at supply points available for transport	t	Pine, spruce, hardwood	Time plot
	Pulpwood at demand-point stocks	t	Pine, spruce, hardwood	Time plot
	Accumulated pulpwood shortage at demand points	t	Pine, spruce, hardwood	Time plot
Pulp mills (Demand-point specific information)	Stock at demand point	t	Pine, spruce, hardwood	Time plot
	Stock at HCT terminals	t	Pine, spruce, hardwood	Time plot
	Accumulated costs	€	Direct deliveries, via HCT terminal Distance-based, time-based, terminal-based	Bar graph
HCT terminals (Terminal-specific information)	Pulpwood time in HCT terminal	d	Pine, spruce, hardwood	Histogram
	Available pulpwood in terminal	t	Pine, spruce, hardwood	Time plot

2.6 Warm-up, follow-up and initialization of simulation run

The simulation run lasts from 1 January 2015 to 31 December 2016. The first year from 1 January 2015 to 31 December 2015 is a warm-up period where no data is collected. The transportation system is assumed to be in steady state by 1 January 2016 when the data collection begins. The year 2016 is, therefore, called the follow-up period.

Before the start of the simulation run, the user enters the number of vehicles and their transport capacities and cost function constraints to the model. The user also enables or disables the HCT system in the experiment. If HCT system is enabled, the user also selects which HCT terminals from Dataset 3 are used for the experiment. After the start command, the input datasets are imported to the model and the simulation run begins. The first decision (Fig. 2) is made at the supply point when the accumulating supply volume at the supply point equals or exceeds one full truckload.

2.7 Random events

The accumulation of supply at supply points is based on annual supply volumes defined in Dataset 2 (point specific) and the daily proportions of the annual volumes defined in Dataset 5 (universal for all supply points). A random seed is used for each simulation run, and the random generator determines the time of the daily accumulation for each point. However, the accumulation is allowed to take place between 08:00 and 00:00 only. The arrival times of vessels and trains are also determined by the random generator. Time constraints and arrival probabilities are given in Datasets 6 and 7. For example, vessel arrivals can be disabled for the winter to match the conditions of the real world.

2.8 Model output

Output data from the simulation run is collected for runtime evaluation and post-run analysis. The data used in runtime evaluation is presented as graphical information, principally as time plots (Table 1). Vehicle utilization and system performance can be monitored at a general level, and the traffic at pulp mills and HCT terminals can be followed up individually. Together with the map-based presentation about trucks' movement in the system, runtime graphics are a useful way to validate and verify the model.

Data is exported to post-run analysis by five functions collecting data from the follow-up period. »Get terminal costs«, »Get utilizations« and »Get total supply« have a similar purpose as the output types in Table 1, and »Get route data« collects the number of routes travelled between all locations in the system. »Write to excel« sorts out the results of these functions and exports the data to a spreadsheet file.

3. Case study

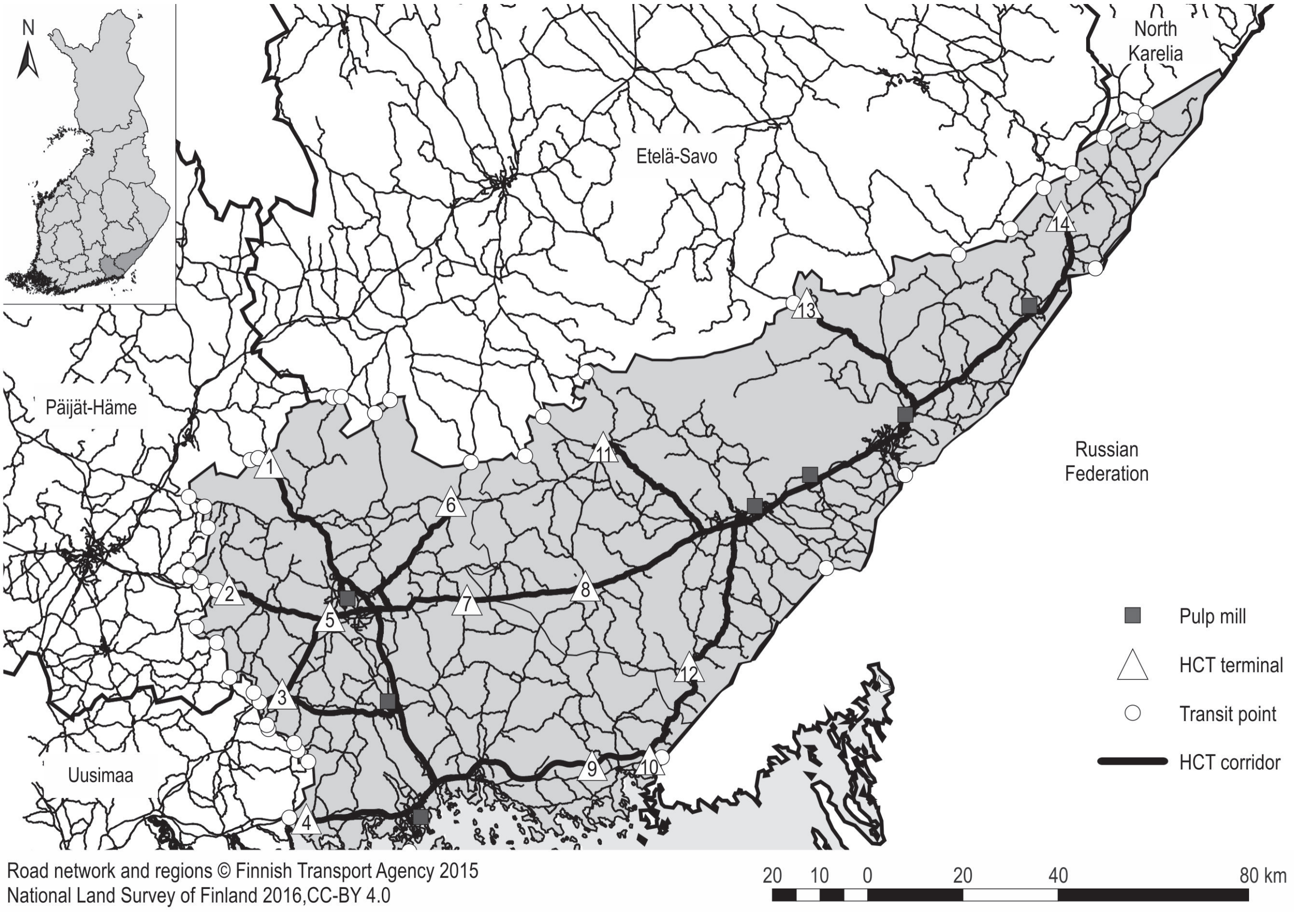
3.1 Case overview

The case study focused on pulpwood transportation in Southeast Finland. The area comprises ca. 4%

of the Finnish land area, but its seven pulp mill locations consume almost 40% of the industrial pulpwood used in Finland (Natural Resources Institute Finland 2016). The volume of ca. 15.0 Mm³ over bark, consisting of 5.7 Mm³ of pine (*Pinus sylvestris*), 3.6 Mm³ of spruce (*Picea abies*) and 5.6 Mm³ of hardwood (mostly *Betula pendula, Betula pubescens* and *Populus tremula*), corresponds to the total net weight of ca. 12.8 Mt in transportation. The pulpwood consumption is largely dependent on wood imports from neighbouring regions (Natural Resources Institute Finland 2015a, 2015b). Especially large amounts of hardwood are imported from Russia (Finnish Customs 2016). Roundwood exports from the studied area are mainly other than pulpwood and, therefore, outbound deliveries from the area were not considered in the study.

3.2 Spatial analyses

The input data with geographical references resulted from spatial analyses where QGIS Desktop 2.10.1 and ArcGIS 10.3.1 software were used. In the first analysis, Dataset 8 was created by calculating driving distances and times of the shortest routes between all locations in the system. Two transport networks were used: a network for regular trucks and a network for HCT corridors. The analysis was based on the digital road network data Digiroad (Finnish Transport Agency 2015), documentation about temporary overweight transports (ELY Centre Pirkanmaa 2015) considered as potential HCT corridors and location data from Datasets 1–3. Driving speeds of regular trucks were acquired from the speed limits of Digiroad (Finnish Transport Agency 2015). For roads without speed limits, e.g. forest roads, the allowed speed of 20 km/h was used. Considering the fact that a truck is unable to maintain the allowed maximum speed constantly, a driving speed of 75% of the allowed speed was applied for regular trucks. Based on the recent experiences about pulpwood HCT operations in the studied area, a constant driving speed of 60 km/h was applied.



Road network and regions © Finnish Transport Agency 2015
National Land Survey of Finland 2016,CC-BY 4.0

Fig. 3 The network of trunk roads in pulpwood transportation, pulp mills, potential HCT terminal locations and HCT corridors, and transit points between the studied area (grey) and the surrounding area

Table 2 Summary of location-specific input data used in the case study

Subject	Target Dataset (s)	Domain agent in SimPulp	Function in SimPulp	Data sources	Annual totals
Biomass availability	2, 5, 8	Supply Point	Represents wood supply at roadside storages and transit points	Estimated pulpwood harvest volumes in Finnish municipalities (Räsänen 2015) Biomass of growing stock per pulpwood type as 16×16 m grid (Natural Resources Institute Finland 2015c) Balance of industrial pulpwood removals and forest industries' pulpwood consumption by region in 2014 (Natural Resources Institute Finland 2015a, 2015b) Consumption of foreign pulpwood by region in 2014 (Natural Resources Institute Finland 2015a) Imported roundwood from Russia (Finnish Customs 2016) Border crossings of trucks (Finnish Customs 2016) Volumes of imported roundwood by transportation method in 2006–2015 (Strandström 2016)	Studied area: pine 0.8 Mt spruce 0.5 Mt hardwood 0.4 Mt Transit points: pine 1.2 Mt spruce 1.8 Mt hardwood 1.2 Mt Domestic 5.1 Mt transnational 0.7 Mt
Biomass demand	1, 3, 8	Demand Point	Represents pulpwood consumption at pulp mills	Industrial pulpwood consumption in 2015 (Natural Resources Institute Finland 2016)	Pine 4.9 Mt spruce 3.1 Mt hardwood 4.8 Mt
Transport networks	8	Main	Connect locations	Digital road network data, Digiroad (Finnish Transport Agency 2015) Network for overweight transports (ELY Centre Pirkanmaa 2015)	
Rail and waterway deliveries	6, 7	Demand Point	Affect truck transportation and stock levels at mills	Transport volumes of pulpwood deliveries by trains and vessels to mills (Finnish Transport Agency 2016, 2017, Finnish Customs 2016, Strandström 2016)	Pine 2.9 Mt spruce 0.8 Mt hardwood 3.2 Mt

Supply points (Dataset 2) included 491 centre points of a 5×5 km grid inside the studied area, representing roadside storages, and 41 transit points connecting the studied area to surrounding regions on the main road network. Four of the transit points were border-crossing points between Finland and Russia. An additional driving time of 80 min was assigned to the deliveries from transit points to represent the time consumption in neighbouring regions in Finland. For transit points between Finland and Russia, the extra time was 160 min. HCT terminals (Dataset 3) were positioned in 14 highway junctions attracting the majority of transport routes without HCT. This decision was based on visual examination of regular truck routes between supply and demand points in GIS. Fig. 3 presents the locations of HCT corridors, HCT terminals (Dataset 3), transit points and demand points (Dataset 1).

In the second analysis, Dataset 2 was accompanied by pulpwood volumes. The estimated annual supply in municipalities (Räsänen 2015) was allocated to the supply point grid in the studied area. The estimated pulpwood volume in the growing stock per wood type (Natural Resources Institute Finland 2015c) was used as a weighing factor for supply points located in the same municipality, and the disaggregation was conducted according to the method presented in previous studies about forest biomass availability and logistics (Jäppinen et al. 2013, Korpinen et al. 2013).

The assessment of the annual supply at transit points was based on the statistics about pulpwood removals and domestic pulpwood consumption in other regions of Finland (Natural Resources Institute Finland 2015a, 2015b, 2016), foreign pulpwood consumption in Southeast Finland (Natural Resources Institute Finland 2015a) and foreign trade and border traffic (Finnish Customs 2016). The estimation of train and vessel delivery volumes to the mills (Datasets 6 and 7) was based on information extracted from the Digitraffic database (Finnish Transport Agency 2016), foreign trade statistics (Finnish Customs 2016), waterway statistics (Finnish Transport Agency 2017) and a survey by Strandström (2016). The Digitraffic database was also used for assessing the train arrival intensity at the mills (Dataset 6). Vessels (Dataset 7) were assumed to arrive between April and November, and their arrival interval was constant at a monthly level but random within each month. The demand was assumed to be stable around the year (Dataset 4). Table 2 summarizes the datasets imported to SimPulp.

3.3 Cost data

The transportation cost data for Dataset 9 was based on the transport distance and time matrices of Dataset 8 and experimental cost-related data (e.g. fuel and wearing-part consumption, driving speeds and work shifts) that is being collected constantly from existing HCT trucks and their comparison trucks with regular weight. The following equations were fitted on the verified cost data from HCT trials between October 2014 and September 2017 (Poikela 2017):

$$CRT_{\mathrm{f\_mill}}=1.0816\,d^{0.957}+47.33\,t \quad (1)$$

$$CRT_{\mathrm{e\_mill}}=0.8127\,d^{0.943}+47.33\,t \quad (2)$$

$$CRT_{\mathrm{f\_term}}=1.0816\,d^{0.957}+47.65\,t \quad (3)$$

$$CRT_{\mathrm{e\_term}}=0.8127\,d^{0.942}+47.65\,t \quad (4)$$

$$CRT_{\mathrm{f\_mill}}=1.1833\,d^{0.961}+39.473\,d^{0.0283}\,t \;\big|\; d\geq 20 \quad (5)$$

$$CRT_{\mathrm{e\_mill}}=0.8176\,d^{0.944}+39.473\,d^{0.0283}\,t \;\big|\; d\geq 20 \quad (6)$$

Where:

CRT	represents transportation costs of regular trucks
CHT	transportation costs of HCT trucks
f_mill	transportation with a full load to the demand point
e_mill	return from the demand point with an empty load
f_term and *e_term*	transportation between the supply point and HCT terminal with full and empty loads
d	distance, km
t time (h)	of the trip between the origin and the destination.

Since HCT has not been used often for very short trips in the trials, it was determined that *CHT* is valid only for trips of 20 km or longer. The formulas return the cost as euros per truck per trip.

The routes were ranked in ascending order by unit costs (€/t) for each supply point. The unit costs were calculated as follows:

$$C_{\mathrm{direct}}=\frac{CRT_{\mathrm{f\_mill}}+CRT_{\mathrm{e\_mill}}}{52} \quad (7)$$

$$C_{\mathrm{via\_term}}=\frac{CRT_{\mathrm{f\_term}}+CRT_{\mathrm{e\_term}}}{52}+C_{\mathrm{term}}+\frac{CHT_{\mathrm{f\_mill}}+CHT_{\mathrm{e\_mill}}}{68} \quad (8)$$

Where:

C_{direct}	the cost on the direct route from the supply point to the demand point
$C_{\mathrm{via\_term}}$	the cost on the route via the HCT terminal
C_{term}	the cost of the use of the HCT terminal, €/t.

3.4 Sensitivity analysis

The case study included uncertain issues, whose impact on the system output was examined in a sensitivity analysis. Such issues were:

⇒ the ratio of HCT trucks to regular trucks in the system

⇒ the impact of terminal costs on HCT utilization

⇒ the impact of a transition to a sparser network of HCT terminals.

The sensitivity analysis focused principally on the economic output of the system, but attention was also paid to the utilization rates of regular and HCT trucks.

The impact of varying terminal service costs was studied, as there were very few references from similar pulpwood transportation systems available. In road-to-rail transshipment, an average transshipment cost of € 0.90/t was earlier reported (Iikkanen and Sirkiä 2011), but without any details about how much is based on truck drivers' labour costs and how much on the terminal fixed costs. The impact of truck visits (including loading and unloading) at terminals was included in the cost functions (Eqs. (3–6)), but the expenses from the maintenance of the terminal network were not. The cost of using an HCT terminal (i.e. C_{term} in Eq. (8)) was estimated at € 0.50/t as the baseline assumption. There are, however, several case-specific factors behind the economic basis of biomass terminals, such as land value or groundwork needs (e.g. Impola and Tiihonen 2011, Kühmaier et al. 2016, Virkkunen et al. 2016), and the cost impact on the logistics could also be higher. On the other hand, terminal costs can be compensated by possible benefits of HCT that were not considered in the study, such as lower organization costs or more efficient collection of roadside storage remainders (Venäläinen 2017b). To account for this uncertainty, two alternatives to the baseline value, € 0.00/t and € 1.00/t, were included in the analysis.

There are about 1300 timber trucks in Finland, and truck transportation of 5.8 Mt in the case corresponds with 13% of timber-truck transportation in the country (Strandström 2016). Based on the fact that SimPulp excludes depot time and supply area transfers, it was assumed that a suitable transport capacity would equal 100–150 regular trucks in the model. Three alternatives for the total transport capacity (TTC) were selected: a) 7800 t, b) 6500 t, and c) 5200 t. The alternatives correspond to the total payload of 150, 125 and 100 regular trucks, respectively.

Since regular trucks are needed to access the roadside storages in any case, it was estimated that HCT would be reasonable for less than 50% of the transport tasks, and HCT truck proportion of TTC was set to vary between 10% and 40%. Alternatives of 0, 20, 30 and 40 HCT trucks were applied to the scenarios of 7800 t TTC, and alternatives of 0, 10, 20 and 30 HCT trucks were applied to other TTC scenarios. The remaining TTC was complemented with regular trucks so that TTC was fully met (Fig. 4).

The impact of HCT terminal reduction was studied to determine the importance of terminal network coverage. This was done by removing terminals 1, 4, 5, 7, 8, 9, and 10 (Fig. 3) from the network. The selection was done with the same transport intensity based allocation method as the selection of the original 14-terminal network. Terminal utilization was recorded by the total volume of wood flown through the terminal, and the economic impact was assessed by comparing total costs with the cost output of the corresponding scenario with 14 terminals.

3.5 Scenario qualification

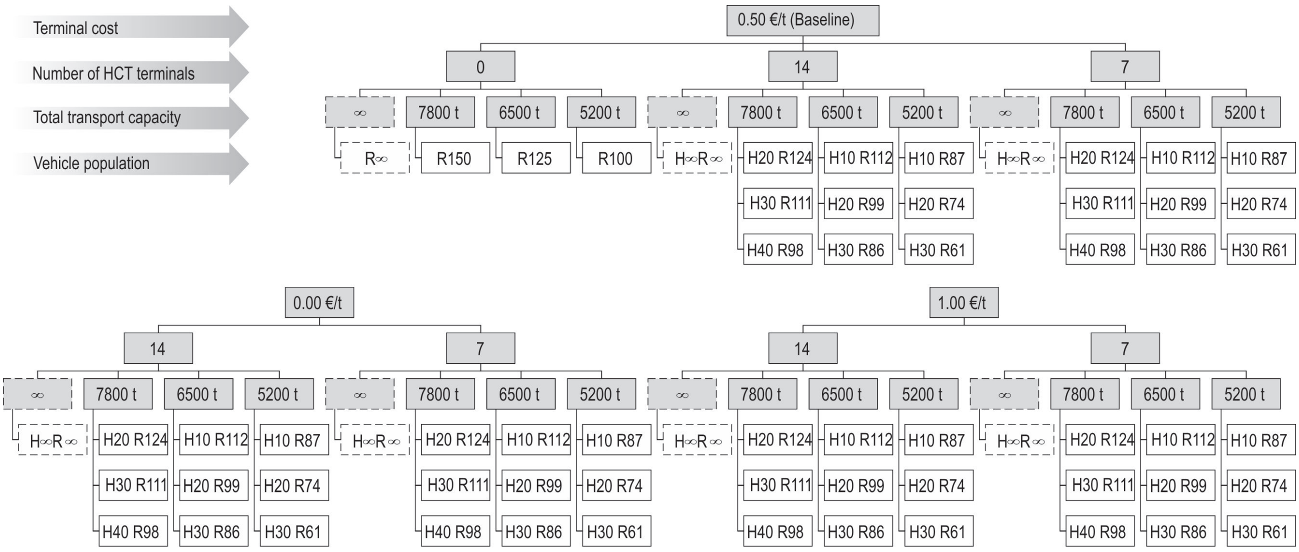
The scenarios were qualified or disqualified on the basis of accumulated wood shortage within the follow-up period. Due to the random events in the model, the follow-up period starting from a dynamic situation, and the fact that the model is just a generalization from the real world, a minor wood shortage was anticipated to be acceptable. Reference scenarios with an unlimited number of trucks were included to confirm that the unfulfilled demand in qualified scenarios was not caused by an insufficient number of trucks. If demand fulfilment was in accordance with the reference scenario, it was presumed that the system was sufficiently in balance to enable equitable comparison between the scenarios. The deviation from the reference scenario was indicated by rates of fulfilled total demand (FTD) and unfulfilled demand per wood type (UFD). It was determined that if the FTD of the scenario was over 0.5 percentage units smaller than the reference, or if the UFD of any wood type deviated more than 2 percentage units from the reference, the scenario was disqualified.

To make scenario outputs comparable, the transport distances and costs were readjusted by the difference between the targeted (i.e. 5.8 Mt) and simulated total haulage.

4. Results and discussion

4.1 Scenario qualifications

The scenario qualification returned 38 qualified scenarios corresponding to a TTC of 6500 t or 7800 t (Table 3). All 19 scenarios of a 5200 t TTC were disqualified based on their poor FTD and UFD ratings, indicating that the transport capacity corresponding to 100 regular trucks is inadequate against the transportation needs. In the qualified scenarios, the UFD principally consisted of hardwood shortage, while all wood types were represented in the UFD of the disqualified scenarios. The scenario of 150 regular trucks resulted in a slightly higher FTD (99.1%) than the scenario of 125 regular trucks (98.6%). In the corresponding HCT



Legend:
Fields with an unbroken outline indicate scenarios included in the qualification
Fields with a dashed outline indicate reference scenarios of an unlimited vehicle population
H – number of HCT trucks
R – number of regular trucks

Fig. 4 Configuration of simulation scenarios (white fields) scenarios, 7800 t scenarios produced an FTD of 98.1% and 6500 t scenarios an FTD of 97.9% on average.

The impact of terminal cost variation on the system balance was marginal. The average FTD was 98.0% in the scenarios with a terminal cost of € 0.50/t and 98.1% with costs of € 0.00/t and € 1.00/t. In contrast, the increase of the HCT proportion in the fleet seemed to decrease the average FTD slightly within the group of 6500 t. In this group, the average FTDs with 10, 20 and 30 HCT trucks were 98.2%, 97.9% and 97.7%, respectively.

4.2 Transport distances and costs

The total transport distances were shorter in all scenarios including 14 HCT terminals than in the corresponding scenario without HCT (Fig. 5 and 6). The greatest savings in total distances, i.e. 12.6–14.1%, were caused by the scenarios including the highest proportion of HCT trucks. Direct transportation to the mills represented at most 50% of the total distances in these scenarios. The group of 6500 t resulted in ca. 3% shorter transport distances on average than the TTC of 7800 t.

In the scenario group of 14 HCT terminals, transport costs were lower in 13 scenarios and higher in 5 scenarios than the costs of the corresponding scenario without HCT. The scenarios including 20 HCT trucks were the most profitable when no terminal cost was applied. When the terminal cost of € 0.50/t or € 1.00/t was applied, the most economic HCT scenarios had

Table 3 Fulfilled total demand (FTD) and unfulfilled demand (UFD) per wood type (pine–spruce–hardwood) in simulation scenarios

HCT terminals, n	HCT trucks, n	Regular trucks, n	HCT proportion of total transport capacity, %	Total transport capacity, t	€ 0.50/t (Baseline)		Terminal costs, € 0.00/t		€ 1.00/t	
					FTD, %	Wood type UFD, %	FTD, %	Wood type UFD, %	FTD, %	Wood type UFD, %
–	–	∞	–	∞	99.0*	0–0–3*	–	–	–	–
–	–	150	–	7800	99.1	0–0–3	–	–	–	–
–	–	125	–	6500	98.6	0–0–4	–	–	–	–
–	–	100	–	5200	96.1	5–3–4	–	–	–	–
14	∞	∞	–	∞	97.9*	0–1–6*	97.8*	1–1–6*	98.0*	1–1–5*
14	20	124	17	7808	98.1	1–1–5	98.2	0–1–5	98.1	0–1–5
14	30	111	26	7812	98.1	1–0–6	98.3	0–0–5	98.0	1–1–5
14	40	98	35	7816	97.7	1–1–6	98.4	0–1–5	98.1	1–1–5
14	10	112	10	6504	98.2	1–1–5	98.4	1–0–4	98.0	1–1–5
14	20	99	21	6508	98.0	1–1–5	97.9	1–1–6	98.5	0–0–5
14	30	86	31	6512	98.0	1–1–5	97.5	2–1–5	97.6	2–1–5
14	10	87	13	5204	95.1	6–3–5	95.6	6–3–4	94.9	7–3–6
14	20	74	26	5208	96.4	4–2–6	96.7	4–1–6	96.6	4–2–6
14	30	61	39	5212	90.4	10–9–10	91.2	9–8–10	88.0	13–12–11
7	∞	∞	–	∞	97.6*	2–1–6*	98.1*	1–1–5*	97.8*	0–1–6*
7	20	124	17	7808	98.3	0–1–5	98.1	1–1–5	98.0	1–1–5
7	30	111	26	7812	97.9	1–1–5	98.1	1–0–5	98.2	0–1–5
7	40	98	35	7816	98.2	0–1–5	98.0	1–0–6	98.4	0–0–5
7	10	112	10	6504	97.8	1–1–6	98.4	1–1–4	98.3	0–1–4
7	20	99	21	6508	98.0	1–1–5	97.6	1–1–6	97.6	2–1–6
7	30	86	31	6512	97.6	2–1–6	97.9	1–1–6	97.8	2–1–4
7	10	87	13	5204	95.6	6–2–5	95.1	7–3–6	95.5	6–2–5
7	20	74	26	5208	96.7	3–2–6	96.0	4–2–7	96.6	4–2–5
7	30	61	39	5212	88.9	9–12–13	90.3	10–9–12	86.5	13–13–15

* Reference scenario with unlimited transport capacity

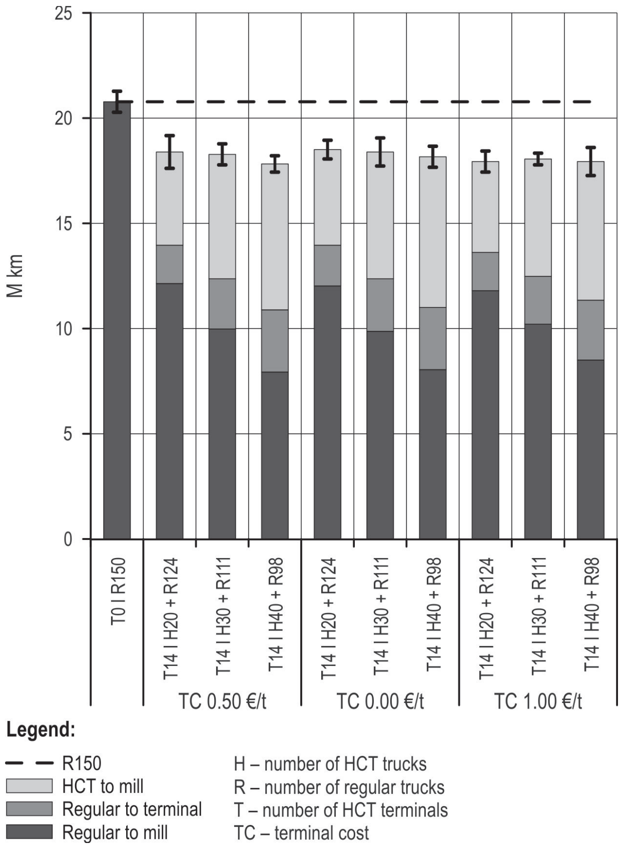


Fig. 5 Transport distances including empty returns according to transport modes in scenarios of 7800 t total transport capacity and 0 or 14 HCT terminals. Error bars represent the range of total transport distances in 8 reproduced simulation runs

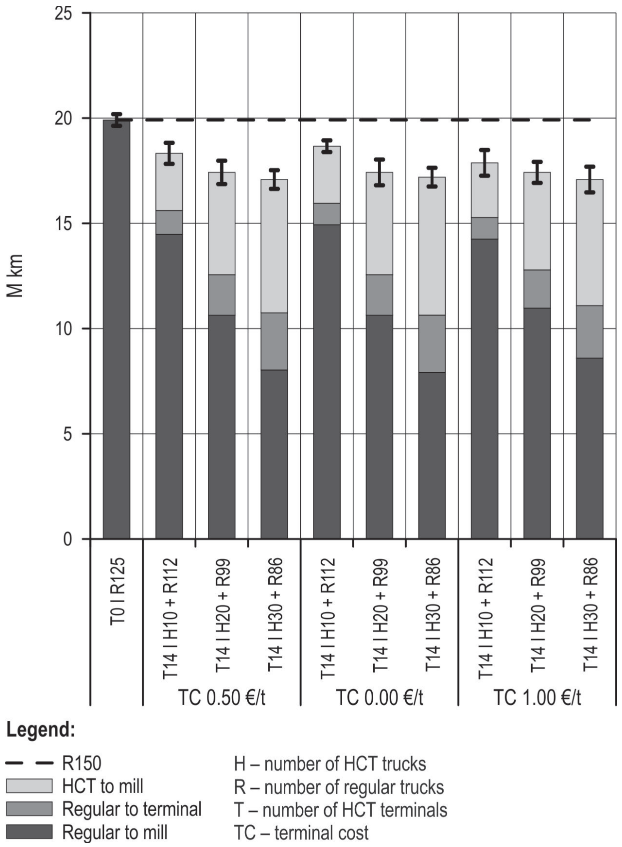


Fig. 6 Transport distances including empty returns according to transport modes in scenarios of 6500 t total transport capacity and 0 or 14 HCT terminals. Error bars represent the range of total transport distances in 8 reproduced simulation runs

the lowest possible number of HCT trucks. Out of the HCT scenarios producing less costs than the corresponding scenario without HCT, the TTC of 6500 t resulted in 2% lower costs than the TTC of 7800 t on average. With a cost level of € 0.50/t, terminal costs represented 1.4% of the total costs with 10 HCT trucks and 2.2% with 20 HCT trucks. With a cost level of € 1.00/t, the proportions were 2.6% and 4.3%, respectively.

The differences in total costs among all scenarios are small, considering the variation of eight reproduced simulation runs per scenario (denoted by error bars in Fig. 7 and 8). The smallest and the greatest records produced within the same scenario differed by ca. 0.6–2.6% from the average of the eight runs. However, none of the records in the most profitable HCT scenarios (i.e. scenarios of 20 HCT trucks and no terminal cost) exceeded the lowest record in the corresponding scenario without HCT (i.e. scenario of 150 or 125 regular trucks).

4.3 Utilization of HCT terminals

Within the most economic scenarios in each terminal cost category (Fig. 7 and 8), the proportion of wood routed through terminals was about 20% when 10 HCT trucks were used, and 34–39% when 20 HCT trucks were used. The change in terminal cost did not considerably influence the total volumes routed through terminals, but it affected terminal-specific volumes to some extent.

Fig. 9 presents the utilization of HCT terminals in scenarios of 10 and 20 HCT trucks. The most used terminals, i.e. 11, 13 and 14, were located near the transit points of abundant wood supply, and because of the attractive location, the terminals were also ranked high in the order of wood offers. The status of these terminals was nearly the same with 10 and 20 HCT trucks in traffic. When the network was condensed to seven terminals, the total throughput of terminals decreased only marginally. The use of terminals 11, 13 and 14 increased by ca. 10%. The use of terminal 6 increased by more than 100%, while the use of terminals remained the same as in the 14-terminal scenarios.

4.4 Sensitivity analysis

The ratio of HCT trucks to regular trucks was the most important factor affecting the total costs in the sensitivity analysis. As the best scenarios included 10 or 20 HCT trucks, they produced about 1.5–2.0% lower total costs than the scenarios of 30 or 40 HCT trucks or the scenarios without HCT. This impact has a strong correlation with the changes in the utilization of HCT trucks. While the utilization of HCT trucks was as high as 91% in the scenario including 10 HCT trucks, the rate dropped below 80% in the scenarios of 30 and 40 HCT trucks. In contrast, the intensified utilization of regular trucks did not improve the economic output of the system in these scenarios.

In the case of 20 HCT trucks, the exclusion of the terminal cost brought significantly greater savings than in the case of 10 HCT trucks. Based on the high utilization rate of the baseline scenario, it is assumable that the capacity of 10 HCT trucks was not enough to benefit from the increased number of more profitable routes via terminals. Fig. 10 presents the proportional impacts of the sensitivity analysis on the total costs and truck utilization rates.

5. Conclusions

The results of the case study indicate that partial replacement of the current pulpwood transport system with HCT would have a significant positive impact on traffic intensity (i.e. decreasing the total number of deliveries) and a small impact on transport economy in the studied area. In this holistic HCT sys-

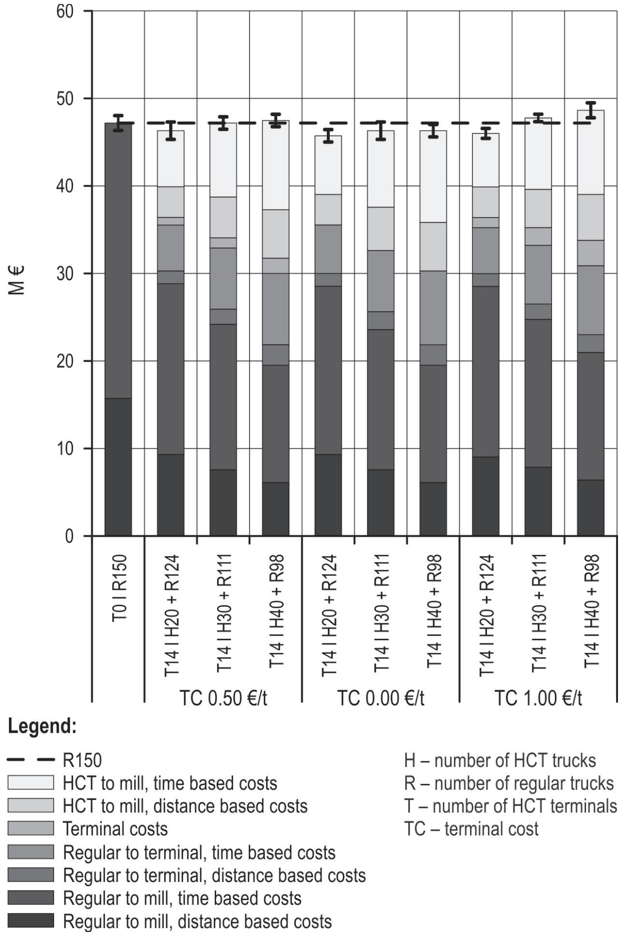


Fig. 7 Transport costs according to transport modes and their cost bases in scenarios of 7800 t total transport capacity and 0 or 14 HCT terminals. Error bars represent the range of total costs in 8 reproduced simulation runs

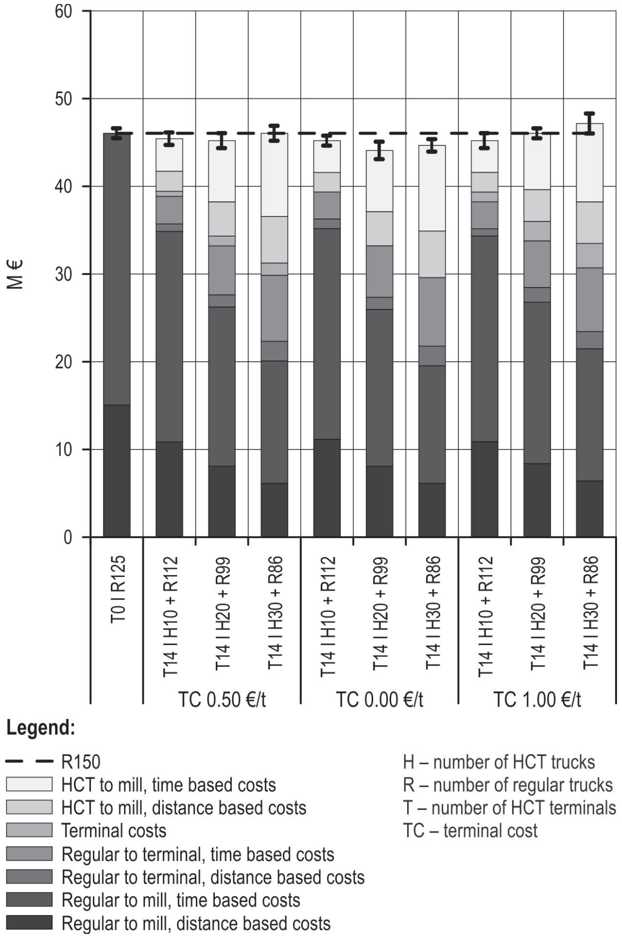
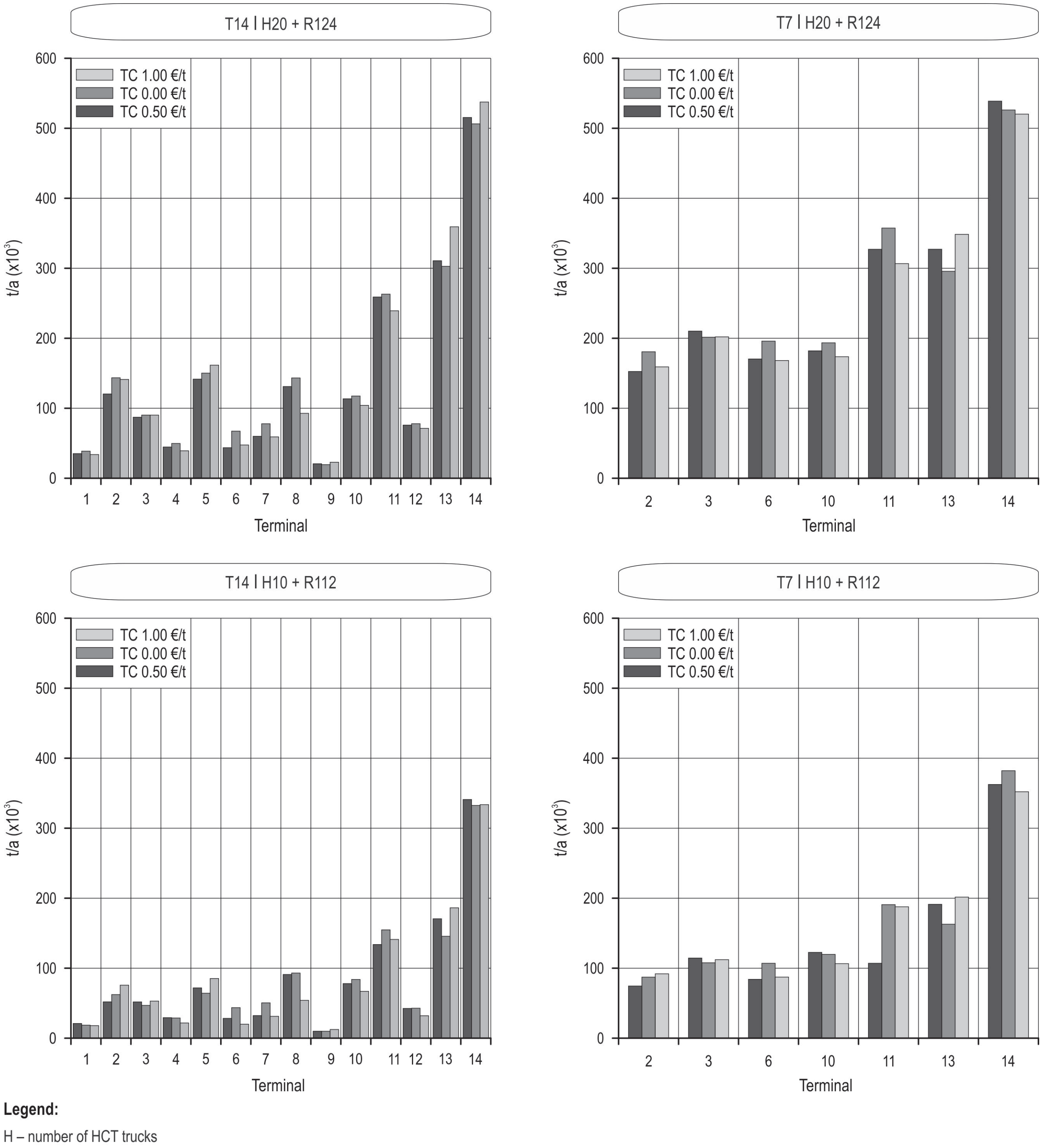


Fig. 8 Transport costs according to transport modes and their cost bases in scenarios of 6500 t total transport capacity and 0 or 14 HCT terminals. Error bars represent the range of total costs in 8 reproduced simulation runs



Legend:

H – number of HCT trucks
R – number of regular trucks
T – number of HCT terminals
TC – terminal cost

Fig. 9 Utilization of HCT terminals in 12 HCT scenarios

tem study, spatial (e.g. bidirectional transport of the same wood stack near terminals), temporal (e.g. additional loading times), and transport-modal (compulsory transshipment) factors together seemed to reduce the economic profitability found in the previous cost analyses of individual trucks or supply chains (e.g.

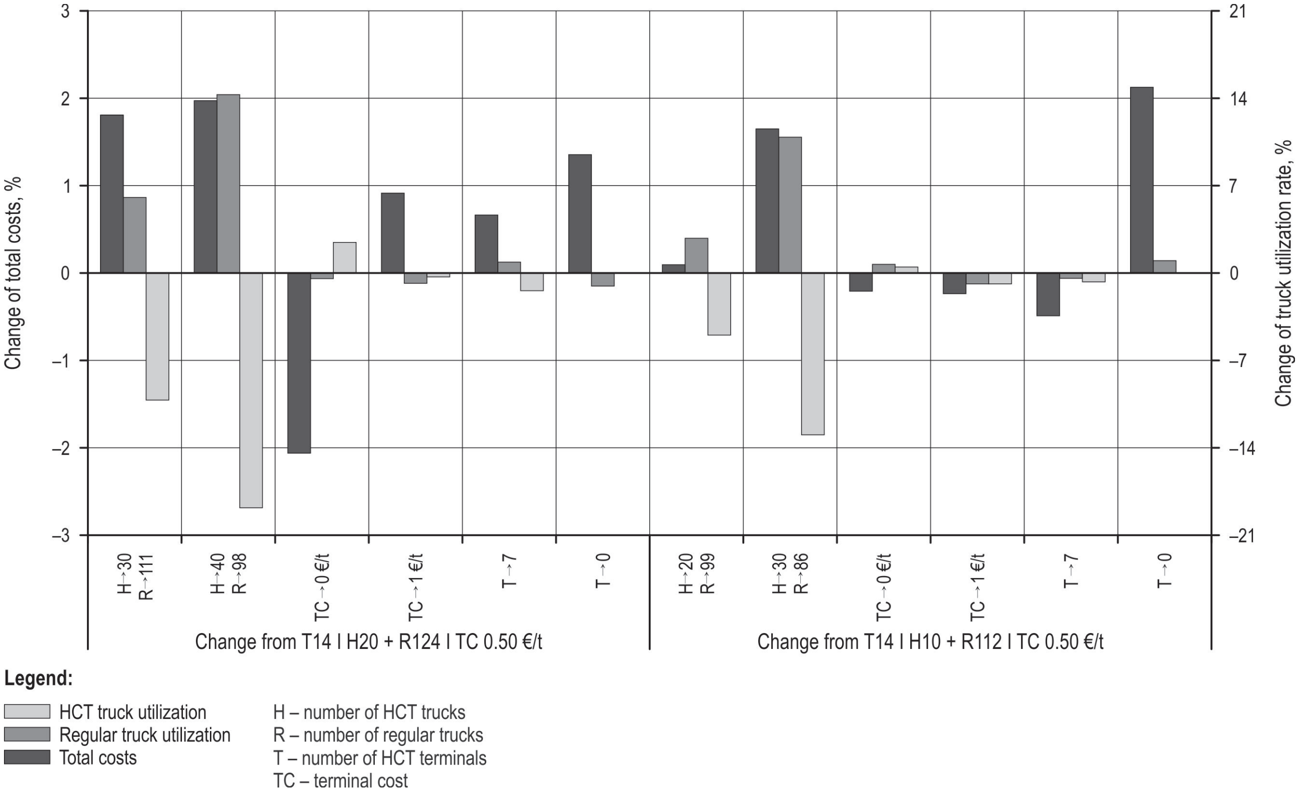


Fig. 10 Impacts of changes in truck number, terminal costs and terminal network on total costs and utilization rates of trucks

Fogdestam and Löfroth 2015, Venäläinen and Korpilahti 2015, Laitila et al. 2016).

The economic performance of HCT is largely dependent on the balance between HCT trucks and regular trucks that feed the HCT terminals. It can be conservatively concluded that a substitution of ca. 10% of the capacity by HCT trucks would cut the total cost by ca. € 1 million (i.e. ca. 2%) in the case. In practice, the transition to the HCT system would happen gradually because there are several transport companies with varying interests in fleet investments. The findings of the case study are promising in this aspect because positive system impacts are achieved already with a relatively small increase in the number of HCT trucks.

The most used HCT routes in the case study were shorter than 100 km, principally because the mills nearest to the HCT terminals were not further away. Extending the studied area would call for more spatial data collection from the neighbouring regions, and most likely, a sparser supply-point grid to keep the runtime performance of the model at a tolerable level. On the other hand, SimPulp could be developed with backhauling options, i.e. a procedure for HCT trucks to find the nearest terminal offering wood so as to minimize the return trip distances with empty loads from the mill for each truck.

Acknowledgements

The work was carried out in the project »Terminal Operations in Energy Efficient Timber Logistics« funded by the European Regional Development Fund. The authors want to give special thanks to Mr Asko Poikela for preparing and validating the cost data of HCT trucks, and to the steering group of the project for advising in the development work and verification of the SimPulp model.

6. References

Almeder, C., Preusser, M., Hartl, R.F., 2009: Simulation and optimization of supply chains: Alternative or complementary approaches. OR Spectrum 31(1): 95–119.

AnyLogic Company, 2017: Defining routes on GIS map.

Asmoarp, V., Enström, J., Bergqvist M., von Hofsten, H., 2018: Effektivare transporter på väg – Slutrapport för projekt ETT 2014–2016. Skogforsk, Arbetsrapport 962, 65 p.

Biswas, S., Narahari, Y., 2004: Object oriented modeling and decision support for supply chains. European Journal of Operational Research 153(3): 704–726.

Carlsson, D., Rönnqvist, M., 2007: Backhauling in forest transportation: models, methods and practical usage. Canadian Journal of Forest Research 37(12): 2612–2623.

ELY Centre Pirkanmaa, 2015: Liite lupapäätökseen Y120 Raskaat yhdistelmät.

Crooks, A.T., Castle, C., 2012: The integration of agent-based modelling and geographical information for geospatial simulation. In: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (eds.), Agent-based Models of Geographical Systems, Springer, New York, 219–252.

Finnish Customs, 2016: ULJAS – Statistical database.

Finnish Transport Agency, 2015: Digiroad.

Finnish Transport Agency, 2016: Digitraffic.

Finnish Transport Agency, 2017: Statistics on domestic waterborne traffic in Finland 2016. Statistics from the Finnish Transport Agency 2/2017.

Finnish Transport Safety Agency, 2017: HCT-rekat.

Fogdestam, N., Löfroth, C., 2015: ETTdemo 2011–2013: Slutrapport, demonstration av ETT- och ST-fordon. Skogforsk, Arbetsrapport 872, 40 p.

Government decree 407/2013: Valtioneuvoston asetus ajoneuvojen käytöstä tiellä.

Heinonen, T., 2016: High capacity transport – ajoneuvoyhdistelmien vaikutukset liikennevirtaan. Master's Thesis, Aalto University, School of Engineering, 134 p.

Iikkanen, P., Sirkiä, A., 2011: Rataverkon raakapuun terminaali- ja kuormauspaikkaverkon kehittäminen – Kaikki kuljetusmuodot kattava selvitys. Finnish Transport Agency, Transport System. Helsinki 2011. Research reports of the Finnish Transport Agency 31/2011.

Impola, R., Tiihonen, I., 2011: Biopolttoaineterminaalit – Ohjeistus terminaalien perustamiselle ja käytölle. Research report: VTT-R-08634-11, VTT, 38 p.

Jäppinen, E., Korpinen, O.J., Ranta, T., 2013: The effects of local biomass availability and possibilities for truck and train transportation on the greenhouse gas emissions of a small-diameter energy wood supply chain. BioEnergy Research 6(1): 166–177.

Korpinen, O.J., Jäppinen, E., Ranta, T., 2013: Geographical origin-destination model designed for cost-calculations of multimodal forest fuel transportation. Journal of Geographical Information Systems 5: 96–108.

Kühmaier, M., Erber, G., Kanzian, C., Holzleitner, H., Stampfer, K., 2016: Comparison of costs of different terminal layouts for fuel wood storage. Renewable Energy 87: 544–551.

Lahti, O., Tanttu, A., 2016: Report on summertime High Capacity Transport (HCT) 2015. Finnish Transport Safety Agency.

Laitila, J., Asikainen, A., Ranta, T., 2016: Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. Biomass and Bioenergy 90: 252–261.

Ministry of Employment and the Economy, 2012: Strategic programme for the forest sector.

Mooney, P., 2015: An outlook for OpenStreetMap. In: Arsanjani, J., Zipf, A., Mooney, P., Helbich, M. (eds.), OpenStreetMap in Geographic Information Science: Experiences, Research, and Applications. Springer International, 319–324.

Natural Resources Institute Finland, 2015a: Forest industries' wood consumption by region 1989–2014 (1000 m^3). Statistics database – Forest statistics – Economy – Forest industries' wood consumption.

Natural Resources Institute Finland, 2015b: Industrial roundwood removals by region. Statistics database – Forest statistics – Structure and production – Industrial roundwood removals by region.

Natural Resources Institute Finland, 2015c: MS-NFI Download Service: MS-NFI products from year 2013.

Natural Resources Institute Finland, 2016: Forest industries' wood consumption 2015. Statistics database – Forest statistics – Economy – Forest industries' wood consumption.

Palander, T., Väätäinen, J., 2005: Impacts of interenterprise collaboration and backhauling on wood procurement in Finland. Scandinavian Journal of Forest Research 20(2): 177–183.

Poikela, A., 2017: Personal communication 2 Oct 2017.

Räsänen, T., 2015: Estimated roundwood supply from municipalities. Unpublished.

Strandström, M., 2016: Timber harvesting and long-distance transportation of roundwood 2015. Metsätehon tuloskalvosarja 4b/2016.

Swedish Road Administration, 2018: BK4 – ny bärighetsklass effektiviserar industrins godstransporter.

Swedish Transport Agency, 2018: Lasta lagligt.

Venäläinen, P., Korpilahti, A., 2015: HCT-ajoneuvoyhdistelmien vaikutus puutavarakuljetusten tehostamisessa – Esiselvity MEE Publications, Corporate 30/2015.

Venäläinen, P., 2017a: Puuyhdistelmien kokojakauma. Unpublished.

Venäläinen, P. (Ed.), 2017b: Terminaalitoiminnot energiatehokkaassa puutavaralogistiikassa – Loppuraportti Metsätehon tuloskalvosarja 4/2017.

Virkkunen, M., Raitila, J., Korpinen, O.J., 2016: Cost analysis of a satellite terminal for forest fuel supply in Finland. Scandinavian Journal of Forest Research 31(2): 175–182.

Authors' addresses:

Olli-Jussi Korpinen, MSc *
e-mail: olli-jussi.korpinen@lut.fi
Mika Aalto, MSc
e-mail: mika.aalto@lut.fi
Prof. Tapio Ranta, PhD
e-mail: tapio.ranta@lut.fi
Lappeenranta – Lahti University of Technology LUT
LUT School of Energy Systems
Laboratory of Bioenergy
Lönnrotinkatu 7
50100 Mikkeli
FINLAND

Pirjo Venäläinen, MSc
e-mail: pirjo.venalainen@metsateho.fi
Metsäteho Oy
Vernissakatu 1
01300 Vantaa
FINLAND

* Corresponding author

Received: January 10, 2018
Accepted: July 9, 2018