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The Operational Efficiency of Waterway Transport of Forest Chips on Finland's Lake Saimaa

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New and cost-efficient methods for use in supply chains for energy wood should be found, to reach the targets of the renewable energy utilisation set by the European Union. The long-distance waterway transportation of forest fuels should be thoroughly investigated, especially in areas where the transport distance is long and waterways could provide a feasible method of conveying forest fuel. In comparison to transport of forest chips by truck, barge-based waterway transport shows a competitive advantage due to the larger loads and higher bulk density of chips it allows.

The cost-efficiency of waterway transportation operations related to forest chips in Finland's Lake Saimaa region was studied using practical demonstrations and discrete-event simulation. The varying demand for fuel wood in three separate bio-power plants on the Saimaa lakeside (near the cities of Varkaus, Mikkeli, and Savonlinna) was addressed in several barge transportation scenarios. Finally, the economy of barge transportation was compared to the economy of truck transportation as a function of transportation distance and in terms of the annual performance of the transportation methods examined.

The waterway supply chain of forest chips was cost-competitive to road transport by truck after 100–150 km. According to the simulation study, the most economical waterway transport options were based on fixed barge system and shift-independent harbor logistics where loading and unloading of barges were carried-out with a wheeled loader and a belt conveyor. Total supply chain costs including the best waterway logistics from road side storage to power plant ranged from €10.75 to €11.64/MWh in distances of 100–150 km by waterways. The energy-density of forest chips in the barge load was found to be, on average, 25% higher than that in truck hauling, because of the better compaction of chips. Waterway transport is a viable option for long-distance transportation of forest chips in Eastern Finland.

Keywords barges, discrete-event simulation, forest fuels, logistics, supply chains, tugboats
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1 Introduction

Climate change, exhausting of oil resources, and desire for self-sufficiency in energy supply are driving forces towards increasing the share of renewables in energy production (Nabuurs et al. 2007). Targets for increased use of renewable energy sources in the European Union are ambitious, aiming 20% of total energy consumption by 2020 in the EU as a whole (Renewable Energy Technology… 2007). The corresponding figure for Finland is 38% (Pitkän aikavälin… 2008). Biomass currently accounts for about 66% of the contribution of renewable energy sources in the EU (Renewable Energy Technology… 2007). Forest-derived fuel plays a major part in the supply of biomass for energy in the EU. Forest biomass can be used to substitute for fossil fuels, and its use has several positive effects on national and regional development, such as added economic growth through business earnings and employment, import substitution with direct and indirect effects on Gross Domestic Product (GDP) and balance of trade, contribution to local and national energy security, and support for traditional industries (Nabuurs et al. 2007, Renewable Energy Technology… 2007).

As a consequence of national and international targets, policies, and activities for boosting the energy use of biomass, the use of forest fuels has grown rapidly in Finland. In 2011, the use of forest fuel was 14 terawatt-hours (TWh) (Ylitalo 2012). The new target, for the end of 2020, has been at 13.5 million cubic metres, which corresponds 24 TWh (Työ- ja elinkeinoministeriö 2010). The national raw-material reserves are estimated to enable the reaching of these targets (Laitila et al. 2010).

The greater the competition and consumption of the fuel for the power plant, the longer the transport distance is. Nearly all forest biomass for energy use has been transported by truck from roadside storage to the end-use facilities or to fuel terminals near them (Kärhä 2010). In recent years, a small proportion of forest fuel has been transported by rail in Finland (Ranta et al. 2008).

Waterway transportation by barges has been used mainly inland lake areas in Finland. The simulation study of barge logistics from roundwood logging of islands was found that it would be reasonable to start using a barge system consisting of a tugboat and three barges in longer distances typical in Lake Saimaa region (Asikainen 2001). Fixed powered barge systems was found to be the cheapest alternative at transport distances shorter than 130 km, when only one logging system was working on the islands. If there were used two logging systems, a three barge system would be reasonable also at shorter transport distances. Two logging systems are not feasible onto relatively small islands in practice (Asikainen 2001).

Waterway and railway transport have used to keep cost- and energy-efficient methods over long distances. The average transportation distance by rail- and waterways is three times greater than that of truck transportation of domestic roundwood, and the cost per cubic metre per kilometre is almost 50% lower than that of truck transportation (Kariniemi 2011).

Roundwood transportation by road to mills cost 0.064 euros per solid cubic metres per kilometre (€/solid-m^{3}km), whereas the rail transportation sequence cost 0.033€/solid-m^{3}km and the water transportation chain came to, in total, 0.034€/solid-m^{3}km. Floating (0.028€/solid-m^{3}km) was less expensive than barge transportation (0.046€/solid-m^{3}km) (Kariniemi 2011). The benefit in cost- and energy-efficiency of water- and railway transport results from the multiple higher load capacity in comparison to truck transport. For example, one hopper barge (Europa IIa) can carry a load of forest chips equal to 34 chip-truck loads (Karttunen et al. 2008). One train transport unit with 15 railway wagons corresponds to 19 chip-truck loads (Tahvanainen and Anttila 2011). To be precise, rail- and waterway transportation also include hauling by truck from the forest to the nearest loading terminal. Therefore, truck transportation is an essential element of all forest fuel supply systems. In addition, rail and water transport systems require extra loading and unloading, which increase the total cost.

Forest fuel flow from roadside storage to energy-use facilities occurs predominantly as wood chips in Finland. Small-sized stems and whole trees from young stands and logging residues from final fellings are chipped at the roadside (60 to 80%), whereas stumps and roots are comminuted mostly at end-use facilities (70%) (Kärhä 2010). Trucks with separate trailers are the most common vehicles in chip transport. Because of the maximum weight limits for road vehicles (60 tonne), the payload has been roughly 35 tonnes, depending somewhat on the weight of the truck and on the moisture content of the forest chips (Ranta 2002, Ranta et al. 2011). The average payload of forest chips in chip-truck transportation corresponds to 85 megawatt-hours (MWh) per load (Ranta and Rinne 2006). The average energy density of forest chips has been 0.77 megawatt-hours per loose cubic metres (MWh/m^3) in truck transportation to the large-scale power plants and it stays under the average on winter when the fuel demand is the biggest (Impola 2002). The energy density of forest chips depends mainly on the moisture content, which has been 48.3% in the large-scale power plans and 38.4% in the small heat plants (Impola 2002).

In Finland, the largest untapped forest biomass resources are in Eastern and Northern Finland, whereas the biggest use of forest fuels is in Central Finland and coastal areas (Ranta et al. 2005). Growth of forest biomass consumption has increased the fuel supply radius of power plants by increasing the demand for cost- and energy-efficient long-distance transportation methods (Karttunen et al. 2008, Tahvanainen and Anttila 2011). In particular, larger power plants and production of biofuels in biorefineries will require a comprehensive fuel-supply system, including a range of transportation logistics and modes addressing various transport distances, in order to make supply chains more cost-efficient and environmentally friendly (Ranta et al. 2008). For both biofuels and traditional forest products, the importance of energy costs, energy-efficiency, and assessment of environmental impact is growing (Lindholm and Berg 2005), thus supporting the development of energy-efficient means of transportation such as railways and waterways.

The Lake Saimaa waterways of Eastern Finland provide a fairly good infrastructure (waterways, harbors, and roads next to waterways) for the logistics of forest fuel supply via waterways. Furthermore, cities such as Varkaus, Joensuu, Lappeenranta, Kuopio, Mikkeli, and Savonlinna are situated next to the waterways. Combined heat and power (CHP) plants and those cities' pulp and paper mills provide district heating to

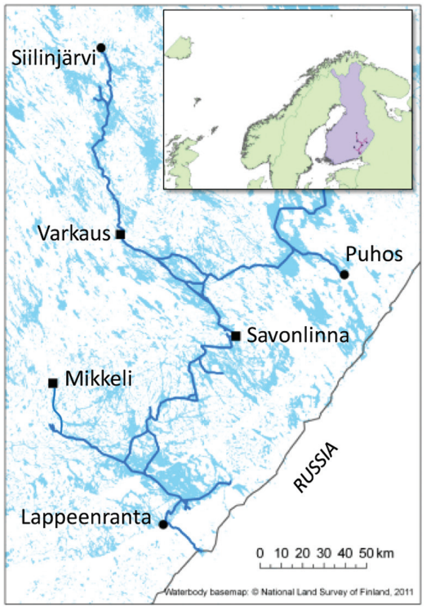

Fig. 1. The Lake Saimaa region, in Eastern Finland.

local residents and electricity to the national grid. Plans for building new biopower plants and biorefineries and to increase the operation capacity of the current power plants will increase the consumption of forest fuels considerably, calling for large-scale, constant forest biomass supply systems for the end users.

The main objective of the study was to determine the logistics and the operations efficiency of waterway transport of forest chips in the lake Saimaa by using practical demonstrations and discrete-event simulation as study methods. In closer, the objective was to clarify the most cost efficient options in waterway transport logistics of forest chips and ultimately to compare the cost-competitiveness of waterway transport to truck transport of forest chips. In order to attain the information needed for the simulations and to understand the functionality of the operations of waterway transports, practical demonstrations were arranged. The objectives of the demonstrations were to compare alternative chipping systems, to clarify the productivity of loading methods and to compare the energy densities of chip truck and barge loads. The study was organised in the Lake Saimaa region, the area for which the results are described (Fig. 1).

Table 1. Summary of the inland waterway supply chain demonstrations for forest fuels.

	Demonstration 1: Terminal chipping	Demonstration 2: Roadside chipping
Material	Logging residues	Logging residues
Cutting	Felling machine	Felling machine
Forwarding	Forwarder	Forwarder
Chipping	Chipper	Chipper
Truck transport		
Roadside to loading terminal	Loose truck-trailer and chip truck	Chip truck
Unloading terminal to plant	Chip truck	Chip truck
Loading and unloading	Material handling machine	Digger
Compaction		Bobcat
Waterway transport		
Tug-boat	Big tug-boat	Big tug-boat
Hopper barge	Europa IIa	Europa IIa

2 Material and Methods

2.1 Demonstration Studies

Research data from the demonstrations were collected in the Inland Waterway Transport of Forest Fuels project (2006–2008), co-ordinated and carried out by Lappeenranta University of Technology. A few practices/options were tested in demonstrations of transporting forest chips and small trees via inland waterways. Demonstrations were carried out in 2007. During the demonstrations, time studies for the waterway supply chain were performed also. Additionally, phases of loading and unloading of forest chips were timed and recorded.

Demonstrations constituted the first ever transport of forest chips by tugboat and barge. Both the roadside and terminal chipping systems were tested and completed before the transportation by waterways (Table 1).

The barge's frame capacity is the main constraint in transport of light materials such as forest chips. The carrying capacity of barges and the draught of waterways would allow heavier loads. Barges are used mainly for round wood transportation, which allows a possibility to utilise barges' frame and weight capacity to its full extent with the aid of side poles, unlike in transport of loose material.

The size of vessels and barges in transporting material via inland waterways is restricted mainly by dimensions of general waterway routes (i.e., widths and depths) and the canals (locks). In terms of traffic for trade use and the length of negotiable waterways, the Lake Saimaa region is Finland's most significant inland water area. The catchment of these waters covers nearly the whole Eastern Finland (most of the cities in the area) and has a canal connection to the Baltic Sea. The draught of waterways (up to 4.35 metre) allows ships of maritime competency with a maximum payload of 2540 tonnes on the Lake Saimaa waterways.

Both roadside and terminal chipping systems for logging residues were demonstrated before long-distance transport of forest chips by a combination of a large pusher/tug boat and a hopper barge. The hopper barge chosen was the Europa IIa, which is most often used in European inland waterway transport. The standard Europa IIa barge's (76.5 m × 11.4 m × 3.7 m) frame load holding capacity was 2650 m^3 (without ramp). It is possible to heap the load of loose material such as forest chips above the hold capacity level of the hopper barge. In addition to that, large amount of forest chips will compact by itself or through additional mechanical compaction. The mechanical compaction effect was tested with a small machine (Bobcat, 4.7 tonnes). Barges, without their own source of power, have been steered with pushers or tugboats of various sizes in Finnish inland waters.

The maximum weight limit for trucks is 60 tonnes in Finland. Smaller chip trucks (120 m^3 of frame volume) were used for transportation at the beginning of the supply chain from the forest to the loading terminal in the roadside chipping demonstration. Smaller trucks could be driven on the forest roads, and loading was done by a chipper. Truck-trailers (140 m^3 of frame volume) for uncomminuted forest biomass were used to transport logging residues in the terminal chipping demonstration. To get information about the density of forest chips, extra transport from the terminal to the quay was done by smaller chip trucks. Large chip trucks (140 m^3) were used for transportation at the end of the supply chain from the unloading terminal to the power plant. Large trucks are normally used for transport of pulp chips, and loading was done by a material handling machine, a digger or a wheeled front loader.

The combination of a small tugboat and a large hopper barge was also demonstrated on a waterway that had a low draught and a narrow waterway. A belt conveyor for loose materials was tested as a loading method. Use of these methods was organised and paid for by a private company and not included in this demonstration study. Nonetheless, it was chosen as a scenario for the simulation study.

The productivity of various loading and unloading methods was studied via the demonstrations. The time study focused on the lift-on/lift-off (LO/LO) demonstrations, which could be used for the loading of forest chips as well as round wood. Productivity in terms of operating hours was affected by delays (each shorter than 15 minutes), so the results were announced primarily in green tonnes per operating hour.

In the first demonstration, the loading of forest chips into the hopper barge by a material handling machine used a machine with a scoop size of 7.0 m^3 and 360 kilowatt (kW) engine power. The unloading of forest chips by material handling machine involved a machine with scoop size of 4.5 m^3 and 194 kW power. The second demonstration used the same machine for the loading and unloading of forest chips, a digger whose scoop size was 3.0 m^3 and whose power was 123 kW. There was a special automatic platform for the digger on the barge.

The moisture content of the forest chips used in the demonstrations varied between 32–46% (with end samples averaging 39%) in the first and between 37 and 51% (end samples averaging 39%) in the second demonstration. The forest chips used were based on samples from separate stands. The forest chips were received from 11 individual forest stands for each demonstration.

2.2 System Environment of the Discrete-Event Simulations

The discrete-event simulation model was constructed with the WITNESS simulation software, which is designed mainly for the modeling of industrial production systems (Witness 1996). The simulation environment consisted of shipping routes from fuel terminals at harbors to end-use facilities next to cities, and vice versa, at the Lake Saimaa waters (Fig. 2). Furthermore, the model included both the fleet of barges and powered vessels and the fleet of harbors' loading and unloading machines in the system environment. Transportation logistics and interactions before the fuel terminal in the loading phase and after the unloading phase were excluded from the simulation environment. Information on the waterway transport fleet was collected from watercraft manufacturers and from shipping contractors then operating in the Lake Saimaa region. Corresponding information for fuel terminal operations at harbors was collected from interviews and the literature. The model has later been used as a study method in the developing projects of biomass logistics in Eastern Finland (Karttunen et al. 2008, Korpinen et al. 2011).

Three sizes of end-use facilities were chosen for the study, from the cities of Varkaus, Mikkeli, and Savonlinna (Fig. 1). Cities' end-use facilities met the criteria of a central location at Lake Saimaa waters and end-use facilities right next to easily negotiable shipping routes. Respectively, three fuel terminals (in Siilinjärvi, Puhos, and Lappeenranta) were strategically chosen to meet the fuel demand for the waterway-based supply system from the surrounding areas with good biomass reserves (Fig. 1). Furthermore, the fuel terminals' locations were widely dispersed over the Lake Saimaa water area. Distances between loading and unloading terminals ranged from 102 to 338 km. The demand estimate for forest fuels at end-use facilities was based on the needs predicted for 2015 (Karttunen et al. 2008).

The fuel consumption of forest biomass esti-

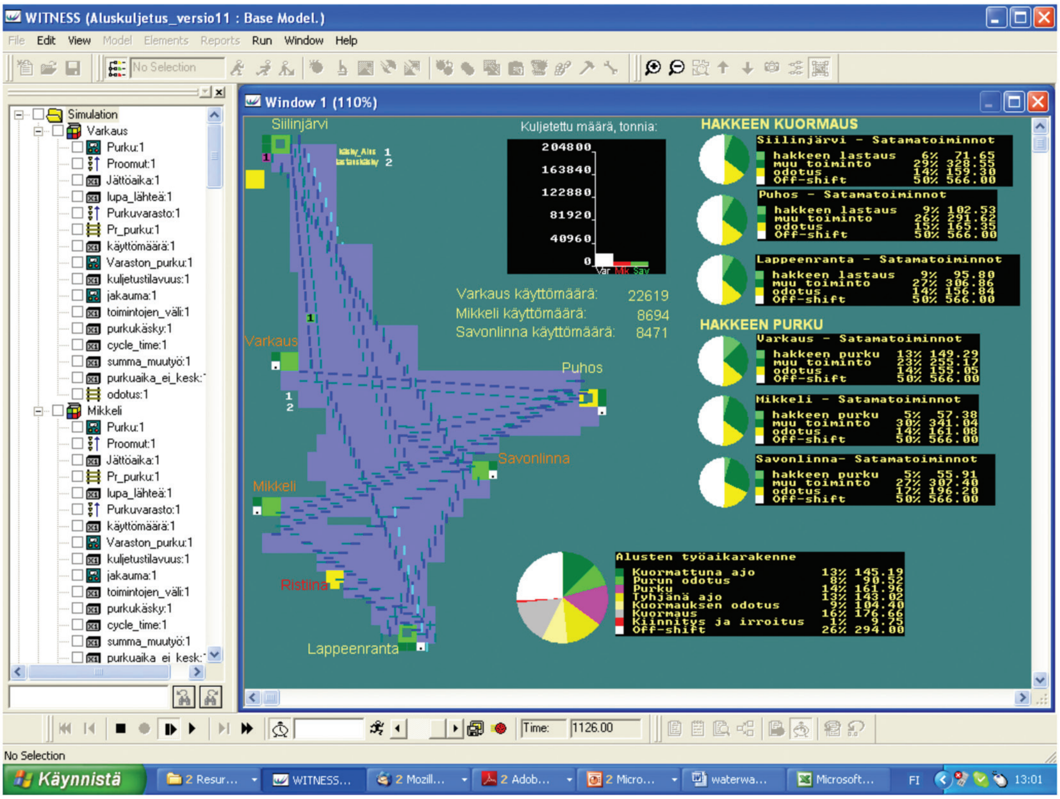

Fig. 2. A screen shot from the display of the simulation model used in the study.

mates for biopower plants supplying district heating to citizens in Mikkeli and Savonlinna were set 500 gigawatt-hour (GWh) and 120 GWh per annum. The sizeable investment of establishing a big biorefinery in Varkaus would require a large proportion of the available forest fuel. The estimated consumption of forest biomass at the biorefinery for 2015 was set 2000 GWh. In the model, forest fuel transport via waterways closely followed consumption at end-use facilities; the distribution of fuel was Savonlinna 10%, Mikkeli 30%, Varkaus 60%. By the rules of the model, fuel-supply terminals were utilised evenly, with the assumption that each terminal can supply the same, sufficient quantity of forest chips for the waterway supply system. In the simulation, vessels transported material one way only, without return hauling of other material, such as roundwood.

The tugboats used in the simulation model were of two sizes: small tugboats with engine power of 350 kW and big tugboats with 750 kW engine power. In addition, two types and three sizes of barges were used in the simulation. The smaller, deck-barge type had a 500-tonne capacity, while the hopper barge could carry 1200 tonnes. The third barge used in the study was a hopper barge and its modification to have side edges. This could carry 1800 tonnes. In transport of forest biomass, the volume of the barge, not the carrying capacity, is the limiting factor. The maximum load weight, given the draught of the inland waterways, is 2540 tonnes. To get closer to this, forest chips can be loaded on the barges as heaped piles, increasing the volumetric capacity considerably. In the simulations, the unit used for the material transported was a green tonne.

Two methods were used for loading and unload-

Table 2. Average speeds of vessels-barge combinations and landing and departure times of harbor logistics in the simulation scenarios.

Vessel type & Load size	Speed, km/h	Transport logistics	Times at harbors, min Landing	Departure
A: SMALL TUGBOAT				
A1: 500 tonnes	11.9	A1a: Fixed barge	30	30
		A1b: Interchangeable barge	60	60
A2: 1200 tonnes	9.8	A2a: Fixed barge	30	30
A3: 1000 tonnes	11.4	A3a: Fixed with two 500-tonne barges	96	150
B: BIG TUGBOAT				
B1: 1200 tonnes	13.7	B1a: Fixed barge	30	30
		B1b: Interchangeable barge	60	60
B2: 1800 tonnes	13.6	B2a: Fixed barge	30	30
B3: 2400 tonnes	13.4	B3a: Fixed with two 1200-tonne barges	96	150

ing operations at fuel terminals. At the biggest inland harbors, efficient long-boomed material handling machines are used. A 90-tonne material handling machine able to load/unload loose material via a scoop with 7 m³ capacity was chosen as one type of handling machine for the study. This efficient handling method is usable for on-shift work at harbors. An alternative method involves a wheeled loader and a belt conveyor for loose materials. This method is not dependent on the work shifts of the harbor system; the machines could be operated by the vessels' crew during harbors' off-shift time.

For each shipping route from one harbor to another, the routes and distances were fixed. The speeds of the shipping units changed in function of shipping route characteristics, vessel and barge type, and total barge weight. The speed function was formulated from the data collected from the demonstrations of forest chip waterway transportations. In order to take to account the influence of weather changes, speed correction was done to the speed function's result value by using normal distribution (Table 4). For the small tugboat unit, the speed ranges were 9.3–12.8 kilometer per hour (km/h) loaded and 10.5–14.0 km/h unloaded. Shipping speeds for the big tugboat were 9.9–15.7 km/h loaded and 11.4–16.7 km/h unloaded. Towing of a loaded barge (small tugboat and 1200 tonnes barge) because of visibility limitations decreased speeds by 2 km/h on all shipping routes. Landing and departure times of shipping units depended on barge logistics. (Table 2)

The operation time per year was set to nine months, excluding the winter months (January–March) in which most waterways in the Lake Saimaa region are closed because of the ice cover. During the active shipping season, waterway supply of forest chips ran day and night all week, 24 hours per day. Therefore, the members of a vessel's crew included the workers in action and those resting. The small tugboat had a two man crew, and the big tugboat had a five. In harbor operations, the crew onshore at harbors worked in shifts from 7am to 11pm on weekdays (off-shift at weekends).

2.3 Simulation Experiments

Two main scenarios, with respect to the size of the vessel in use, were set up in the simulation study. Main scenarios were divided into three subscenario lines addressed 1) load size, 2) transport logistics, and 3) harbor logistics (Table 3).

The scenario line of "load size" contained three load size alternatives for each vessel. The subscenario line of transport logistics included three experiments: fixed-barge, interchangeable-barge, and fixed with two barges. In the first of these, one barge was attached to the tugboat at all times and there was only one barge in the system. The

Table 3. Scenarios and experiments in the simulation.

Vessel type & Load size	Scenarios and experiments: Transport logistics	Harbor logistics[1]
A: SMALL TUGBOAT		
A1: 500 tonnes	A1a: Fixed barge[2]	A1a1: Shift-dependent
		A1a2: Shift-dependent in unloading
		A1a3: Shift-independent
	A1b: Interchangeable barge[2]	A1b1: Shift-dependent
A2: 1200 tonnes	A2a: Fixed barge[3]	A2a1: Shift-dependent
		A2a2: Shift-dependent in unloading
		A2a3: Shift-independent
A3: 1000 tonnes	A3a: Fixed with two 500-tonne barges[2]	A3a1: Shift-dependent
B: BIG TUGBOAT		
B1: 1200 tonnes	B1a: Fixed barge[3]	B1a1: Shift-dependent
		B1a2: Shift-dependent in unloading
		B1a3: Shift-independent
	B1b: Interchangeable barge[3]	B1b1: Shift-dependent
B2: 1800 tonnes	B2a: Fixed barge[3]	B2a1: Shift-dependent
		B2a2: Shift-dependent in unloading
		B2a3: Shift-independent
B3: 2400 tonnes	B3a: Fixed with two 1200-tonne barges[3]	B3a1: Shift-dependent

[1] Harbor logistics:
Shift-dependent: Loading and unloading depended on harbor work shifts. Long-boomed material handling machine were used in loading and unloading.
Shift-dependent in unloading: Loading was performed via a wheeled loader and belt conveyor operated by the vessels' crew. Unloading was dependent on harbor work shifts (material handling machine).
Shift-independent: Loading and unloading were independent of harbor work shifts, while loading and unloading were carried out via a wheeled loader and belt conveyor operated by the crew of the vessels.
[2] Deck barge, capacity 500 tonnes.
[3] Hopper barge, capacity either 1200 tonnes (normal) or 1800 tonnes (modified with side walls).

experiment of "interchangeable-barge transport logistics" included seven barges; one for each harbor and one for the tugboat. In a simulation run, there was always one loaded or unloaded barge to replace the one arriving at the harbor. The experiment of "fixed with two barges" included two barges attached at all times to the tugboat.

Harbor logistics scenario line included three experiments: shift-dependent, shift-dependent in unloading, and shift-independent. In shift-dependent experiment, loading and unloading were depended on harbor's work shifts, in which long-boomed material handling machines were used in loading and unloading. With "shift-dependent in unloading" -experiment, loading was carried out by a wheeled loader and a belt conveyor operated by vessels' crew while unloading was depended on harbor's work shifts (using a material handling machine). Shift-independent work meant that both the loading and unloading were independent of harbor's work shifts and were carried out by a wheeled loader and belt conveyor operated by the crew.

The total number of experiments in the study was 16. Each experiment was repeated five times, and the duration for each replication was nine months. In every replication, initial values of model parameters were kept constant, whereas random number streams varied between the replications having stochasticity in each simulation run. The results of each experiment were announced as in average of five replications.

With the use of stochasticity in the model, the results of each experiment replication were different. Stochasticity was introduced by random distribution of certain occurrences or events in the model. The randomised occurrences in the model were the speed correction of the vessel-barge

Table 4. Theoretical distributions used and their parameters used in the simulation model.

	Distribution	Average, tonnes/hour	SD	Min. tonnes/hour	Max. tonnes/hour
Speed correction	normal	0	0.5		
Load size	normal				
500 tonnes		500	15		
1200 tonnes		1200	30		
1800 tonnes		1800	55		
Loading					
Material handling machine	truncated normaltruncated	175	10	160	190
Wheeled loader + conveyor	normal	120	10	100	140
Unloading					
Material handling machine	truncated normal	165	10	150	180
Wheeled loader + conveyor	truncated normal	75	10	55	95

combination, loading and unloading events, and determination of the load size of the barge for each load (Table 4).

2.4 Cost Calculations

The cost- and consumption factors for the vessels, barges and material handling machines at harbors were either self-reported by the entrepreneurs or surveyed from other sources. Costs were booked via a cost-accounting calculator. Unit costs were obtained by dividing the total simulation volume by the year's total cost. Run-time costs included capital costs, salary costs, and fixed overhead costs in addition to operating costs. Fixed costs for the in-port period included capital costs, salaries, and other fixed overhead costs. Total unit costs were converted from mass units to energy units. The rate corresponding to the energy content of forest chips with a moisture content of 39% (average of demonstration). Net calorific value of dry matter was based on average of normal range of wood chips, 18.5–20 MJ/kg (Alakangas 2000). Net colorific value as received was calculated as follows (Alakangas 2000):

$$Qnet,ar = Qnet,d \times \frac{100 - Mar}{100} - 0.02441 \times Mar = 10.82 \qquad (1)$$

$Q_{net,\,ar}$ = Net calorific heating value as received (MJ/kg)
$Q_{net,\,d}$ = Net calorific value of dry matter (MJ/kg): 19.3
M_{ar} = Total moisture content of fuel as received (%): 39
0.02441 (MJ/kg) = Evaporation of water reaching the amount of heat (+ 25°C).

And further delivered amount of energy (MWh) was calculated as follows (Alakangas 2000):

$$\text{MWH} = \frac{Qnet,ar}{3.6} \times m = 3.0 \qquad (2)$$

m = Fuel mass delivered: 1 tonne
$Q_{net,\,ar}$ = Net colorific heating value as received: 10.82

The unit cost of waterway transport for forest chips varied with the equipment, the operating hours, and the water route choices. The time consumption and output figures generated in the simulation were calculated with the aid of cost data received from cost accounting calculators built purposely for each of the separate machine of device unit (Table 5).

For comparing the cost-competitiveness of waterway transport of forest chips to the costs of road transport, the transporting costs for the chip truck was explored. The cost calculation scenario involved the operations in which the truck was filled at the roadside, travelled to the power plant and returned back to the roadside storage as empty. The chip truck had a payload of 34 tonnes resulting 102 MWh energy content in one full

Table 5. Average annual operation and cost of machines according to the simulation and machine costing models. Prices and costs are presented without value added tax.

Cost element	Purchase price, €	Operating hours / year	Annual cost, €	Hourly cost, €
Small tugboat	900 000	3642	395 000	108
Big tugboat	3 800 000	2505	885 000	353
Deck barge	600 000	3642	51 000	14
Hopper barge	1 000 000	2505	80 000	32
Modified hopper barge	1 400 000	2259	110 000	49
Hydraulic boom loader, 67 tonnes	600 000	2100	200 000	95
Wheeled front loader, 20 tonnes	195 000	2100	112 000	53
Belt conveyor (30 m)	30 000	2100	10 000	5
Chip truck (34-tonne payload, 100 km driving distance)	222 000	3000	198 000	60

load. The other cost of the road transport chain addressed the roadside price of logging residues and the cost of roadside chipping. The operations' management costs were not taken into account.

For calculating the consumed time for the transport cycle of the chip truck, earlier time and follow up study information of chip truck transports were used. Speed functions for driving unloaded and loaded were adopted from the study of Halonen and Vesisenaho (2002). By using the speed functions, the time durations for driving empty and loaded were derived in function of driving distance. Terminal time in loading place in road side storage area as well as unloading time and auxiliary time were set as constant values added to the cycle time. Terminal times were taken from the publications of Asikainen et al. (2001) and Laitila (2008).

For calculating the unit costs for the chip truck transport of forest chips the cost accounting calculator received from the Finnish Transport and Logistics association (SKAL) and total time durations of transporting cycle times were used. Unit costs presented as Euros per megawatt-hours (€/MWh) were expressed in function of driving distance varying between 50 and 250 km.

The cost parameters were kept as constant before long-distance transportation of road and waterway transport supply chain scenarios (Table 6). The loading and unloading operation costs at harbors were based on the simulation results of the waterway supply chain scenarios.

The cost of waterway transport included the loading and unloading of loads as well as fixed and variable costs of tugboats and barges, based on both the annual transport performance in MWh's and total costs of each simulation scenarios. Cost structure and unit cost comparisons of waterway transport scenarios were presented for the waterway distance of 178.5 km representing the waterway route of "Siilinjärvi-Savonlinna". Unit cost comparisons (€/MWh) among waterway transport scenarios were performed also in function of waterway distance ranging from 100 km to 350 km.

Table 6. Cost division of road- and water-transport supply chain of forest chips before the long distance transport (either by road or by waterways).

	Road transport, €/MWh	Waterway transport, €/MWh
Roadside price	3.5	3.5
Chipping	3.5	3.5
Road transport, 30 km	–	2.2
Pilling and storage	–	0.3
Loading and unloading at harbors	–	0.3–0.6

Ship personnel's had average hourly wages of €16.40/h, which included intensive working of overtime (6+6 h/day). The smaller tugboat had a two-person crew, and the larger one was worked by, in total, five people, including a chef for one shift as in the demonstration study. Automatic piloting could be used in the marked waterway routes. Indirect salary costs were assumed to be 54% of the average hourly wage.

Ships used a motor fuel the price of which was set at €0.63/liter, the average price of light fuel oil in 2007 (Oil and Gas Federation 2008). The

Table 7. The energy-density (MWh/m^3) with the truck and barge transport options in the demonstrations.

	1. Demonstration (MWh/m^3)	2. Demonstration (MWh/m^3)	3. Average (MWh/m^3)
Truck (120 m^3)	0.76	0.77	0.76
Truck (140 m^3)	0.87	0.83	0.85
Barge (Europe IIa)	0.95	1.03	0.99

Table 8. Forest chip load capacity (tonnes) for a Europa IIa standard hopper barge (data based on test of hold capacity without compaction).

	Dry material, Tonnes	Moisture, tonnes	Green material, tonnes
Hold capacity (2650 m^3)	489	306	795
Max. capacity (4000 m^3)	738	461	1199
Modified capacity (6000 m^3)	1107	692	1799

Table 9. Loading and unloading productivity and used machines for forest chips in the barge demonstrations 1 and 2 (tonnes per hour, E_{15}).

Demonstration	Machine type	Machine power, kW	Size of scoop, m^3	Productivity, tonnes/h (E_{15})
1. Loading	Mantsinen 100	360	7	177
1. Unloading	Fuchs 360	194	4.5	124
2. Loading	CAT 325	123	3	126
2. Unloading	CAT 325	123	3	103

other machines used diesel oil, which had an average price of €0.92/liter in 2007 (with 10% of the entrepreneurs' discount taken into account).

3 Results

3.1 Demonstration Study

In energy-density comparison of forest chip loads between barges and chip trucks showed 25% higher energy density in barge loads than in loads of chip trucks. The energy-density of forest chips was 0.95 MWh/m^3 in barges without compaction. The maximum heaped load capacity and compaction test increased the energy-density of forest chips in barges by nine per cent, for a total energy-density of 1.03 MWh/m^3. The energy-density for truck loads averaged 0.81 MWh/m^3 and varied according from the average of smaller loads (120 m^3) 0.76 MWh/m^3 to bigger loads (140 m^3) 0.85 MWh/m^3 (Table 7).

The demonstration showed that the large hopper barge can be loaded with a heaped load of forest chips (1200 tonnes) for a 50% greater load capacity than the barge's hold capacity alone allows (800 tonnes) (Table 8). The barge could be modified with side walls to carry a load of 1800 tonnes. The compaction effect for forest chips was a result of the hold capacity (800 tonnes), and the compaction effect with larger capacities was not analysed separately in this case.

The productivity of loading and unloading a hopper barge's forest chips by alternative methods varied from 103 to 177 tonnes per hour (E_{15}) (Table 9). The most efficient method was loading by the machine with the biggest scoop and greatest power.

3.2 Cost Reduction Potential of Waterway Transport

The most economical transport option (A2a3) proved to be a small tugboat with a large barge

(1200 tonnes) fixed to the tugboat including harbor operation, where loading and unloading were independent of harbor work shifts. The most advantageous loading method was the combination of a conveyor belt and a wheeled front loader. The cost of the most economical scenario with a small tugboat was €1.71/MWh for a 178.5-kilometre distance (corresponds the average waterway route). The costs in small-tugboat scenarios varied between €1.71 and €3.45 per megawatt-hour (178.5 km distance) (Fig. 3).

The most profitable scenarios with the big-tugboat option were both B2a3; with a fixed barge of 1800-tonne load size and shift-independent loading and unloading (wheeled loader and belt conveyor), and B3a1, a fixed combination of two 1200 tonne-capacity barges where loading and unloading were shift-dependent (material handling machine). The cost of these scenarios with a big tugboat was €2.26/MWh (178.5 km journey). The cost of big-tugboat scenarios varied between €2.26 and €3.34/MWh (for a 178.5 km journey) (Fig. 4).

Operations costs of tugboats had the highest shares in costs of waterway transport representing 57 to 75 % of all waterway costs for the smaller tugboat and 57 to 78 % for the bigger tugboat. Biggest impact in cost reduction in waterway transport costs was achieved by using bigger barges and load sizes. In scenario comparisons of small tugboat, while the barge type changed from deck barge to hopper barge and the load size increased from 500 to 1200 tonnes, the cost of waterway transport of forest chips decreased by a bit over 30 % (Fig. 3). By increasing the load weight from 1200 tonnes to 1800 tonnes with the bigger tugboat scenarios, the impact in cost decrease was 17–21 % (Fig. 4).

In comparing harbor logistics, the best logistics was to use a wheeled front loader and conveyor belt in loading and unloading phases. Depending on the size of barge and the size of tugboat in compared scenarios, the best harbor logistics returned 15 to 19 percent lower waterway transport costs than the scenario of harbor shift dependent logistics with the use of material handling machines in loading and unloading. Cost savings were achieved due to the cheaper harbor logistics involved and the decrease of idling times of vessel units. In harbor shift dependent scenarios (A1a1, A2a1, B1a1 and B2a1), if tugboat-barge system was arriving to harbor just before the start of the week-end, transport system had to wait over the week-end before starting to load or unload. Interchangeable barge system had the lowest idling times of tugboats, but in turn, the high number of barges involved in the logistics increased the total transportation costs in a notable high level.

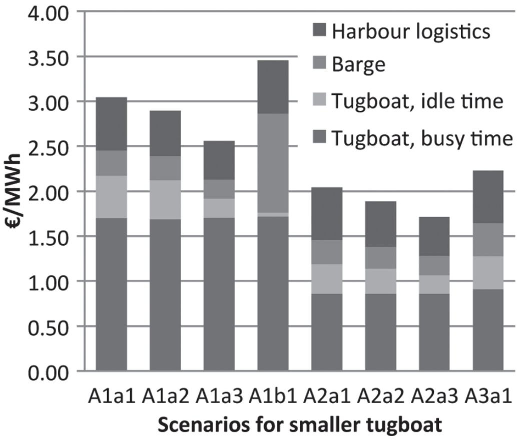

Fig. 3. Waterway transport costs in simulation scenarios with a smaller vessel (based on a 178.5 km journey).

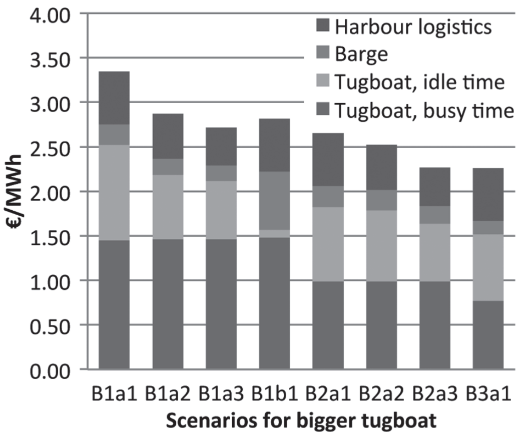

Fig. 4. Waterway transport costs in simulation scenarios with a bigger vessel (based on a 178.5 km journey).

The cost of the most economical scenario (A2a3) with a small tugboat was €1.25/MWh for a 100 km journey and was still the most economical for a 300 km journey, at €2.80/MWh (Fig. 5).

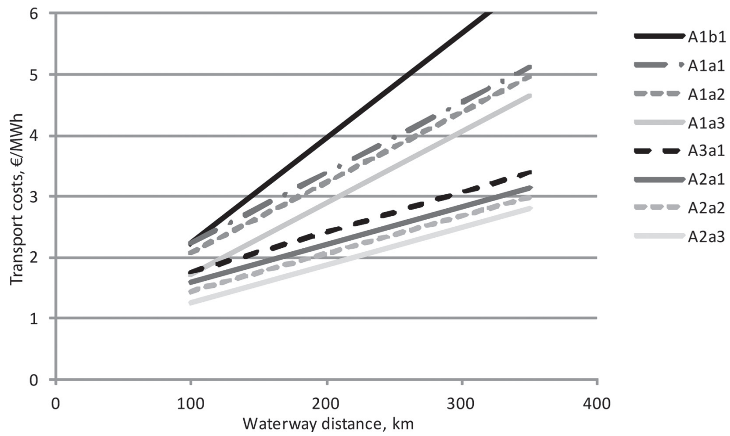

Fig. 5. Waterway transport costs in simulation scenarios with a smaller vessel, by waterway distance (loading and unloading costs included).

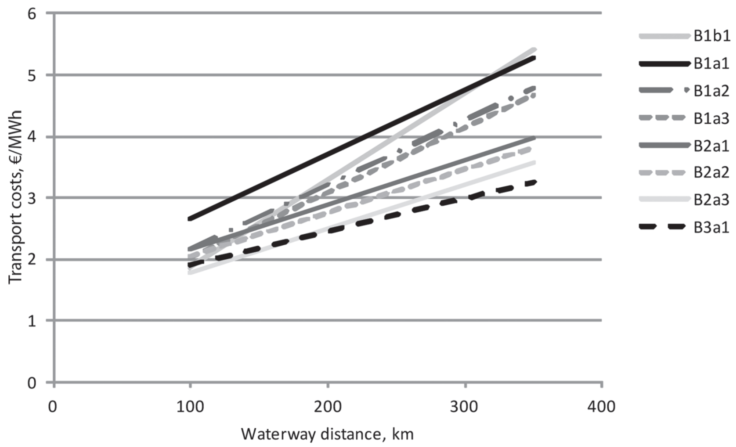

Fig. 6. Waterway transport costs in simulation scenarios with a bigger vessel, plotted against waterway distance (loading and unloading costs included).

The most profitable big-tugboat scenario (B2a3) cost €1.78/MWh for a 100 km journey but lost its profitability in the longer waterway distances in favour of scenario B3a1, which was more economical for a 300 km journey, at €3.25/MWh (Fig. 6). For the both vessel sizes, transport costs of smaller load size options were more sensitively increased by the increase of water way distances.

3.3 Road vs. Waterway Supply Chain

For the annual operating of 3000 hours, truck transport cost per megawatt-hour ranged from €2.06 to 6.85 while transport distance varied from 50 km to 250 km. When the operating hours per year were 4000, transport cost ranged from €1.81 to 6.31 per megawatt-hour. The cost reduction potential of truck hauling was on average 10% if the operational hours could be increased from 3000 to 4000. (Fig. 7)

The best waterway transport scenarios, extracted from the both vessel size scenario-lines, were compared to truck transportation of forest chips (Fig. 8). In comparison, supply chain costs for both transport modes included all cost divisions of supply chains presented in table 6. Chip truck oriented supply chain was more cost-competitive than water way supply chain in shorter distances and distances up to 100 to 150 km,

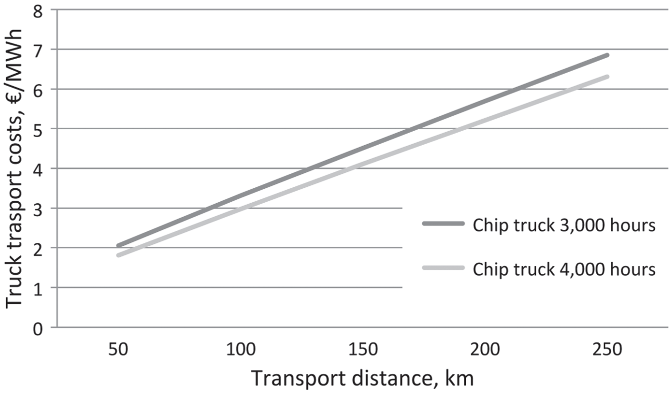

Fig. 7. Truck transportation costs of forest chips in function of transport distance (one way) with two different annual operating hours (3000 and 4000 operating hours per year).

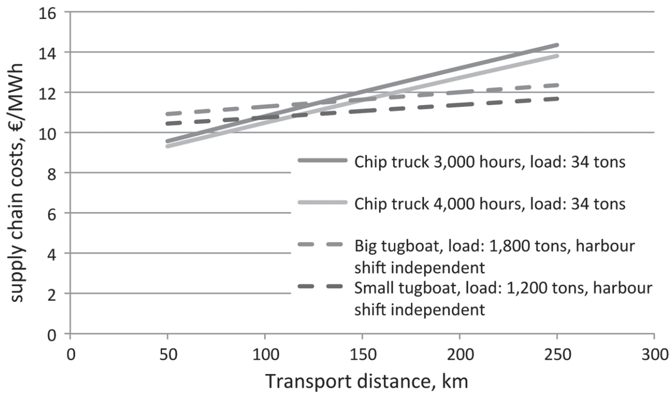

Fig. 8. Cost comparison between road and waterway supply chain options (A2a3 and B2a3). Supply chain costs include the costs presented in Table 6.

depending on the transport options in comparison. The best supply option in truck transportation of chips resulted 9.3 €/MWh and 13.8 €/MWh of supply costs with the transport distances of 50 km and 250 km, whereas best water way supply option resulted 10.4 €/MWh and 11.7 €/MWh with the same distance comparisons. Barge transport, with loading and unloading, represented 12–23% (€1.29–€2.64/MWh) of the total cost in the most economical scenarios, while hauling by truck represented a third (€3.48–€3.81/MWh) of the total cost of the road transport supply chain (Fig.8).

3.4 Annual Transport Performances

The biggest annual performance for smaller-tugboat experiments was achieved with a small tugboat and large barge (1200 tonnes) combination (A2a3), consisting of a fixed barge-tugboat system and a harbor logistics, where loading and unloading were independent of harbor work shifts (Fig. 9). This showed potential to transport forest chips up to 123 132 tonnes (= 369 GWh) of forest chips. The lowest annual performance (57 974 tonnes = 174 GWh) was found with the fixed deck barge-tugboat (500 tonnes) combination depended on harbor shifts (A1a1).

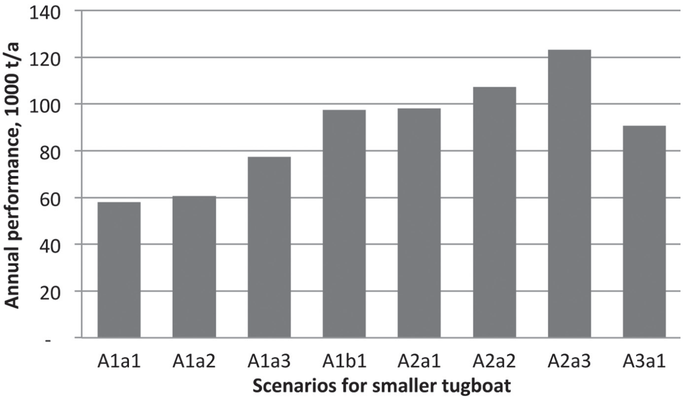

Fig. 9. Annual transport performance with alternative experiments for the smaller tugboat-barge unit.

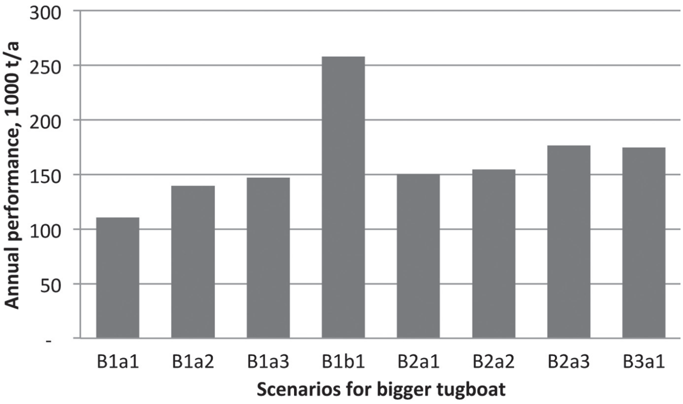

Fig. 10. Annual transport performance with alternative experiments for the bigger tugboat-barge unit.

The highest annual performance within the bigger tugboat experiments was achieved by a big tugboat and a 1200-tonne-load barge (B1b1) with the use of interchangeable barge transport logistics and shift-dependent harbor logistics (Fig. 10). The annual transport performance was relatively high: 257 956 tonnes of forest chips (=774 GWh), compared to the other scenarios' having annual performances from 110 810 to 176 654 tonnes.

4 Discussion

Simulation study of waterway transport logistics of forest chips in the lake Saimaa revealed new cost-competitive alternatives for long distance transporting of forest chips in Eastern Finland. While the demand of forest chips is high in cities' power plants located at the southern shores of the lake Saimaa, and the balance of forest biomass resources is highly positive in the northern areas of the water system, the flow and supply of forest chips from the north to the south via waterways would be a feasible solution. Moreover, the studied waterway transport fleet is currently in use in Saimaa waterways; tugboats and barges are used for transporting round wood mainly for pulp mills (Karttunen et al. 2008).

Discrete-event simulation was chosen as a study method, in order to take into account all important logistics interactions and their impacts in waterway supply of forest chips. Essential was to understand the behavior of the waterway supply system of forest chips in different supply scenarios. Simulation is a proper method while the system includes idle times in element interactions and while having uncertainty and randomness in the system. These aspects were included in the studied waterway supply system. Furthermore simulation is the appropriate tool for making sensitivity analyses and evaluating the functionality of studied operation environment (Taha 1992, Thesen and Travis 1992).

The variation of five repetitions in each simulation experiment was insignificantly small. The share of calculated 95% confidence levels from the total waterway supply costs varied 0.4 to 1.0 % within the experiments of the smaller tugboat scenarios and 0.4 to 0.8% of the bigger tugboat scenarios. Since the differences of each experiment result, as in averages from five repetitions, were clearly distinguishable, there was no need to highlight the fluctuation of experiment replications in the results.

Simulation model did not include separate breakdown or failure factors for the vessel units and for the harbor operations. However, smaller failure times were determined to include in the variation of productivities of harbor operations and speeds of vessel units. Vessels unexpected engine breakdowns or sudden groundings during transports are minuscule and, then again, the vessel unit's maintenance was expected to do at times, when they were idling or loading/unloading at harbors. However, model did not take into account the possible queuing time of vessel units, while loading or unloading systems could have been occupied at harbors. Practically, with the aid of transport scheduling, the queuing problems in inland waterways have been mostly tackled.

According to Enström (2008), the competitive advantage potential of long distance transport methods, such as waterway and railway transports, will be often lost due to insufficient arrangements and inefficient execution of loading and unloading at mid-point terminals. Even though harbors or terminals already exists for the waterway supply of forest chips, some additional investments and costs should be added to total waterway supply costs. All in all, referring to these arguments, system productivities for all simulation scenarios are slightly overestimations, and therefore presented waterway transport costs are underestimated.

Practical demonstrations revealed new information of the energy-density differences of forest chips due to the changes of the load size. The difference in energy density, such as in megawatts per cubic meter (MWh/m^3), between the loads of barges and trucks, was caused by the compacting effect of the material at bigger loads, the hold form of the hopper barge and the loading and compaction methods used in demonstrations. These factors improved the economy of waterway transports by barges in comparison to chip truck transports. The average energy density of forest chips has been 0.77 MWh/m^3 (48% moisture content) in chip truck transportations to the large-scale power plants (Impola 2002). According to the study demonstrations, transporting of chips by truck the average energy density was 0.8 MWh/m^3, whereas in barge transport it was 0.99 MWh/m^3.

While comparing supply chain cost-competitiveness between waterway and road transportation, certain assumptions and constraints, which do not correspond to the practice in all cases, must be highlighted. For the both supply chains, transporting only for one way was used. This is quite often the case for truck transports of forest chips, whereas in barge transport system, back hauling of other bulk material could be possible in practice. Waterway transport of forest chips by barges through the season of low fuel demand of power plants (i.e. summer season) is not a feasible solution. An exception for the traditional fluctuating demand of forest chips would make a biorefinery, which was the case of Varkaus demand of forest chips in the simulation study. Moreover, chip trucks, which operate 4000 hours annually, are rare in practice. For the use of forest chip transportation, 3000 hours of annual operation will be close the maximum. In the previous study of Laitila and Väätäinen (2011), 2600 hours were used in cost calculations for the annual operation for the chip truck in transporting forest chips to power plants. Therefore, the total supply costs of both transport methods are underestimations while comparing to practice.

The average consumer fuel price has increased dramatically in recent years. Fuel price increase has affected to the cost structure of logistics alternatives; truck options more negatively than waterway options. Simulation used prices of diesel fuel from the 2007. Diesel prices were quite low (0.92 €/l) when compared to prices of previous year 2011 (1.37 €/l on average 2011) (Oil and Gas Federation 2008 and 2011).

Harbor logistics and the productivity of loading and unloading operations could be still improved. In handling of low density material, such as forest chips (250–330 kg/loose-m³ in 40 % moisture cont.), loading and unloading of barges can be improved through the use of bigger scoops in traditional lift-on/lift-off (LO/LO) material handling methods. The loading of forest chips is a bit faster than unloading, because of the delay due to cleaning the bottom of the barge at the end. Forest chips as a wood fuel is a competent material for barge transportation because of its good compaction and easy handling. Other loading and unloading methods for the forest chips should be examined, such as more efficient belt conveyors and pneumatic systems (Karttunen et al. 2008). On the other hand, barge loading and unloading at harbors is not a decisive factor for the waterway transport productivity, if there are interchangeable barges available at harbors.

Large variation was found in annual transport performances within the waterway transport experiments. In most of the experiment cases, the bigger the annual transport performance was, the lower the transport cost was. An exception was the experiment of interchangeable barges having relatively high capital costs due to the high number of barges in use. While comparing the annual transport performances of waterway supply options to the total demand of studied three end use facilities of forest chips, the share remains still relatively low. The lowest and the highest transport performances of one transport unit were 174 GWh and 774 GWh per annum, whereas the total consumption of biomass or other fuel was 2620 GWh with all three end use facilities together. To compare to road transport, achieving 540 GWh of annual transport performance with the chip trucks in average procurement distance of 80 kilometres around the plant, it requires at least 12 chip trucks with high annual operating action and full payload capacity (35 tonnes) in every hauling (Lättilä 2012).

Worth noticing is that the biomass need of a biorefinery is so great, that the procurement areas must be extended beyond the normal supply area handled with trucks (Ranta et al. 2008). Therefore, long distance transport options, such as waterways and railways, are essentials for fullfilling the high demand of biomass.

4 Conclusions

Forest fuels especially forest chips can be transported along inland waterways by barges. If the harbor and barge logistics are managed well and barge structures are fit to match the efficient forest chip transportation waterway supply chain of forest chips may be cost-competitive to the conventional supply chain along roads by chip truck in transport distances after 100–150 km. A winter season (3–4 months) with ice-covered lake areas decreases the efficiency of waterway systems. A fuel supply business model based on an inland waterway supply chain including satellite terminals next to waterways may be cost-competitive for the power plants which are close or next to waterways and, which require forest chips more than truck transports could cost-efficiently supply.

All in all, fuel supply system by barge transportation is a complex logistical system with many phases and interactions included. Waterway supply chain must be well-organized to achieve the cost-competency compared to the truck transportation. Even if the barge transportation itself is not expensive in long-distance transports, there may exist some additional overhead costs, unexpected fuel supply failures and route problems causing increased expenses. The capacity of truck fleet in Finland is high, whereas the number of tugboats and barges used in inland waterways is limited. This may have an influence on the competition causing a decrease in practical prices of truck hauling. Finally, due to the increase of transportation in the future more environmentally sustainable and energy efficient transportation method such as waterway transports should be favored in places where they are feasible.

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