Developing forest chips supply chains by redesigning supply operations and logistics

Kari Väätäinen

School of Forest Sciences
Faculty of Science and Forestry
University of Eastern Finland

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Author: Kari Väätäinen

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Thesis supervisors:
Professor Antti Asikainen
Natural Resources Institute Finland, Joensuu, Finland

Doctor Jukka Malinen
Department Faculty of Science and Forestry, School of Forest Sciences

Doctor Lauri Sikanen
Natural Resources Institute Finland, Joensuu, Finland

Pre-examiners:
Associate professor Lars Eliasson
Skogforsk, Uppsala Science Park, Uppsala, Sweden

Doctor Bruce Talbot
Norwegian Institute of Bioeconomy Research, Ås, Norway

Opponent:
Professor Rolf Björheden
Skogforsk, Uppsala Science Park, Uppsala, Sweden

ABSTRACT

The overall aim of the thesis was to design efficient supply chain setups in the selected supply environments by enhancing overall supply system performance, decreasing supply costs and improving year-round working opportunities by taking fuel properties through the supply chain into account. The supply chain re-engineering approach has been used with a narrowed focus, where logistics and inventory, material handling and delivery of forest chips to heat and power plant as well as the customer's desideratum have been considered. The studied supply chains were all based on the transportation of forest biomass as chipped from roadside storage locations either directly to power plant or via terminal or inland waterway harbour to power plant by chip truck or a combination of barge and chip truck.

Discrete event simulation was selected as a study method due to the characteristics of the forest chip supply chains including the high level of interactions between system elements and the specific characteristics of the supply environment. The data required for the model development and models' parameter input values were acquired from the available data of the real system and from the literature.

To enhance the performance of the forest chip supply chain from roadside storage locations to end-use facilities, the following results and conclusions were obtained: 1) Rearrangements in the set-up of fuel reception stations and the logistics of fuel truck reception at the power plant as well as adaptive shift scheduling of trucks resulted in a notable decrease in the waiting times of fuel trucks at the power plant's fuel reception. 2) Forest chip supply from roadside storage locations highly encourages the use of storage area location and quality information for smart material allocation to achieve a higher energy output with lower supply costs, especially when the demand for fuel is at its highest. 3) By introducing a feed-in terminal for forest chip supply, cost compensation for additional terminal-driven costs can be gained through a higher annual capacity utilisation of a fuel supply fleet and more secured fuel supply to power plants by decreasing the need for supplemental fuel, which can be more expensive at times when fuel demand is at its highest. Terminal-aided forest chip supply facilitates smoother working throughout the year in the chipping and transporting of forest chips, thus offering more stable working opportunities than a conventional direct supply of forest chips. 4) Inland waterway areas with existing waterway infrastructure and close connections to biomass resources and end-use facilities can offer a cost-competitive and supplemental method for the long distance transport of forest chips. Reshaping the conventional fleet used for waterway transport and restructuring the logistics of waterway transportation together with harbour operations can improve the cost-competitiveness of the transport method.

The cost-efficiency of forest chip supply for heat and energy generation can be further enhanced with the support of research and technology development.

Keywords: Discrete-event simulation, supply chain re-engineering, logistics, forest chips, terminal, chipper, chip-truck, waterway transport

ACKNOWLEDGEMENTS

LIST OF ORIGINAL ARTICLES

This dissertation consists of a summary and the following four articles, which are referred to by Roman numerals I–IV. All articles (I, II, III and IV) are reprints of previously published articles reprinted with the permission of the publisher.

I   Väätäinen K., Asikainen, A., Eronen, J. (2005). Improving the Logistics of Biofuel Reception at the Power Plant of Kuopio City. International Journal of Forest Engineering 16(1): 51-64.
https://journals.lib.unb.ca/index.php/ijfe/article/view/9840/9971

II   Windisch J., Väätäinen K., Anttila P., Nivala M., Laitila J., Asikainen A., Sikanen L. (2015). Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain. Applied Energy 149: 315–325. https://doi.org/10.1016/j.apenergy.2015.03.122

III   Väätäinen K., Prinz R., Malinen J., Laitila J., Sikanen L. (2017). Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant. Global Change Biology Bioenergy 9(11): 1657–1673.
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IV   Karttunen K., Väätäinen K., Asikainen A., Ranta T. (2012). The operational efficiency of waterway transport of forest chips on Finland's Lake Saimaa. Silva Fennica 46(3): 395–413. https://doi.org/10.14214/sf.49

Article I: Kari Väätäinen and Antti Asikainen carried out the data collection and study design. The author had the responsibility of structuring the simulation model, running the simulations and analysing the result data of simulations. The author took the main responsibility for writing the article with the help of co-authors.

Article II: Johannes Windisch and the author shared responsibility for the method selection, study design, data analysis, interpretation of results and writing of the article. The author was responsible for data collection and Johannes Windisch for data preparation and development of the simulation model. The co-authors improved the article by commenting on the study setup and the manuscript.

Article III: The author, Lauri Sikanen and Robert Prinz completed the study design. The author developed the simulation model, run the simulations and made the analysis of simulation output data. The author and Robert Prinz wrote the first sketch of the article. The other co-authors contributed to the writing of the article.

Article IV: Kalle Karttunen took the main responsibility for data collection and data analysis. The author designed the simulation model, made the simulations and interpretation of simulation results. Kalle Karttunen and the author wrote the first sketch of the article. The co-authors took part in the study design and reshaping the article.

CONTENTS

1. INTRODUCTION

1.1 Background

In EU-28 countries, wood and wood products accounted for 5.9% of the total energy consumed in 2015 (Eurostat 2017). The share of wood fuels of total energy consumption in Finland was 26% in 2016 (Luke stats 2017), the biggest share in European countries after Latvia (Eurostat 2017). Of total wood fuel use, forest chips represented around 20% in Finland (Torvelainen et al. 2014). The use of forest chips for producing heat and power increased in Finland during the last few decades though there was a decrease in use in the year 2014 (Ylitalo 2017). In 2016, total consumption of forest chips for heat and energy generation totalled 7.39 million solid-m³ (Ylitalo 2017). Around 80% of forest chips are consumed in heat and power plants and the rest is used on a small scale for heating real estate and farm buildings (Ylitalo 2017).

The wood components or stems which do not fulfil the dimensional or quality requirements of industrial roundwood are utilized for heat and energy generation (Hakkila 2004). Commonly, in early thinning or pre-commercial thinning of young stands, small sized or poor quality whole trees and delimbed stems are used for energy purposes. From regeneration cuttings interlinked to stemwood harvesting, the biomass components rejected for industrial use (including stem tops, living and dead branches, foliage, off-cuts of stems, stumps and roots) are utilized. Depending on the price levels of forest chips, competing fuels and industrial pulp wood, competition can increase in regard to small sized pulp wood dimensions. In addition, the price levels and supply chain costs of energy wood may affect the decision whether to utilize it or not.

In Finland, forest chips are produced mainly from small sized roundwood (52% in 2016), which consists of small sized whole trees, delimbed stem wood and pulp wood (Strandström 2017). Other forest chip sources and shares were logging residues 34%, stump wood 10% and big sized defect (e.g. rotten) stem wood 4% (Strandström 2017). Harvesting of small sized roundwood for energy purposes has increased rapidly within the last ten years, being less than 2 TWh in 2005 and increasing to over 7 TWh in 2015.

There are many reasons for utilizing forest chips for heat and energy purposes. The total wood volume in Finnish forests has increased steadily from the beginning of the first national inventory, in spite of increased harvesting amounts of industrial roundwood and energy wood. Sustainable and efficient forest management with regeneration, tending of seedlings and young forests, forest fertilization and intermediate felling as well as forest tree breeding have enhanced wood production in forest land areas. Young forests which require tending and treatment to ensure efficient wood production might require treatments where the extraction small sized stems can be seen as a source of energy. In addition, logging residues from spruce-dominated regeneration cuttings are forwarded with low extraction costs to the roadside storage locations using the same base machinery as in roundwood harvesting. Moreover, recovery of logging residues eases regeneration work, improving its quality and lowering its costs (Saksa et al. 2002, Harstela 2006). To conclude, energy wood extraction from forests can be seen as a part of effective forest management which is in line and in parallel with the procurement of industrial roundwood.

Forest chips from the forests of Finland are a local energy source, thus providing business and work opportunities to local people in the procurement chain from harvesting to transport, storing and comminution of woody biomass for energy. Many heating and power plants are designed to combust forest chips as a mixed fuel, thus setting the demand

for forest chips and other locally produced solid based fuels such as peat, bark and sawdust. The number of heating and power plants using forest chips has increased from 365 to 860 within the ten year period of 2002–2012 (Hakkila 2004, Ylitalo 2013). In addition, according to the National Energy and Climate Strategy for 2030 conducted by the Ministry of Economic Affairs and Employment of Finland in 2017, the target is for the share of transport biofuels to be increased to 30% and 10% of bioliquids will be blended into light fuel oil used in machinery and heating (Huttunen 2017).

Forest chips made from early thinning wood and logging residues is defined as a quickly decomposing renewable energy source. Comparably, the substitute fuel in combined heat and power plants is fossil fuel such as charcoal, heavy oil or peat. The demand for stump wood has decreased during the last years partly due to it being classed as a slowly decomposing CO_2 source (Repo et al. 2011).

Finland has been committed to the EU's climate strategy goal of increasing the use of renewable energy up to 38% by 2020 (Pitkän aikavälin ilmasto ja energiastrategia 2008, Huttunen 2017). On a national level, Finland has set a goal to increase the use of forest chips to reach 29TWh by 2030 in combined heat and energy generation, representing 18% of total renewable energy use (Huttunen 2017). Furthermore, the Finnish province of North Karelia has set the ambitious target of being a fossil-fuel-free region in terms of heat generation by the year 2020 and transport fuels by the year 2030 (Farewell to … 2015). To respond to the EU, national and regional targets, the work for sustainable and cost-efficient production and delivery of forest chips has to be done with cautious planning and with feasible and cost-efficient investments.

1.2 Supply chains of forest chips for heat and energy production

Supplying forest chips from the forest to their user (customer) is quite the opposite of traditional goods supply by roads from manufacturer and distributors to wholesalers and customers, where material from one or few locations is supplied to several locations next to customers. Material is collected and distributed from several small roadside storage locations either directly or via terminal(s) to plants for generating heat and/or energy or refining upgraded liquid fuels. Moreover, in goods supply, the points of supply and demand places are nearly always static in location, whereas the multiple supply points in forest chip supply are constantly replaced by new ones. Dispersed and constantly varying small supply points with widely varying quality affected by the weather makes great demands on supply logistics and are the reasons for the relatively high logistics costs for forest chip supply (Andersson et al. 2002, Hakkila 2004, Routa et al. 2013).

The control and management of timber supply has the same type of challenges but are more advanced than forest chip supply mostly due to its longer history, bigger business and higher impact on the national economy. In timber transportation, sophisticated routing and transport control systems help to keep track of the roadside storage locations with the demanded timber to be transported to the designated mills with prioritized orders. These applications also give suggestions to the drivers on the shortest routes to complete the transport cycles. To have reliable operator support in routing, the applications used require real time data from the road network, roadside storage locations, timber volumes, timber demand of mills, locations of trucks and their driving status (Tokola & Kalliovirta 2003, Väätäinen et al. 2012). Similar developments have taken place during the last decade in forest chip supply management for managing fuel supply particularly for large consumers of chips, yet many smaller suppliers have not started using such systems. Nowadays, there

are more providers offering moderately priced supply and fleet management applications for small sized companies.

Variation of heat production through the year in heat plants in boreal conditions can be manyfold, with the demand of fuel at the high heating season being up to seven to eightfold that of the lowest heating season (Windisch 2015). Due to this, there is also high seasonal variation in forest chip supply for heat generation, which causes problems for the efficient use of the forest chip supply fleet and personnel operating them. The capacity of the supply fleet has to be adequate to cope with the highest fuel demand, thus having low machine and personnel utilization of capacity during the mid and low heating seasons results in difficulties in keeping the skilled workforce committed to their posts throughout the year (Laitila et al. 2010). In addition, the capacity of the fuel receiving stations at the heat and power plants has to be designed to follow the highest fuel demand (Väätäinen et al. 2002). Under-sized fuel receiving stations causes extra waiting times for trucks at times when transport should operate at its highest efficiency within the working day (Väätäinen et al. 2002). Challenges arise in forest chip supply due to variations in fuel quality and moisture during storage. The moisture content of stored biomass is lowest during summer, when the demand for heat and power are lowest and highest during winter, when the heat and power demand peaks. To increase the burden of chip supply difficulties caused by the winter season, milder winters together with declined quality of forest road conditions force forest chip supply operations into areas with weather sensitive road connections (Gautam et al. 2017). Moreover, traditional winters with snow cover require ploughing of forest roads to access remote fuel storage locations during the winter.

The composition of the supply chain of forest biomass depends strongly on the type and form of the material (whole trees, delimbed stems, logging residues or stumps, comminuted or uncomminuted), the transportation distances from feedstock to plant, the scale and the infrastructure of the end-use facility, and in which phase of the supply chain comminution takes place (Laitila et al. 2010). Centralized comminution is conducted next to the end-use facility or in the terminal, whereas decentralized or distributed comminution is usually carried out by mobile chippers next to feedstocks (Laitila et al. 2010).

According to research results and practical experience, in most of the cases, loose logging residues, small sized whole trees and stumps are most cost-competitive to comminute next to the roadside storage locations with mobile chippers and then transported by chip truck to the place of use. The main reason for decentralized comminution has been the low transport payload and therefore high transport costs of uncomminuted material. Centralized comminution, on the other hand, allows high chipping/crushing production, high supply volumes, use of electricity in comminution, and therefore low comminution costs. In order to increase the use of centralized comminution, the focus in development has been in the transportation of uncomminuted material. The payload of transport vehicles remains much lower than the maximum allowed capacity in mass if transporting loose logging residues, for example. According to the studies of Laitila et al. (2010), Tahvanainen & Anttila (2011) and Laitila et al. (2017), truck transport costs of forest chips from roadside landing has been 4-5.5 €/solid-m³ and chipping at the roadside landing 5.5-7.5 €/solid-m³ depending on the average transport distance used in the studies.

Traditionally, Finland has been a place for decentralized comminution representing a 54% share of all forest chips for heating and energy generation (Strandström 2016). While the use of terminals has increased in forest chip supply, comminution of forest biomass at terminals has also increased drastically having a 31% share in 2015 (Strandström 2016). In

2015, chipping at the roadside has the highest share in logging residue chipping (77%) and the lowest in stump wood chipping (24%) (Strandström 2016).

The level of roads, railway and waterway network connections and transport distances determine the transport mode or modes used in forest chip supply. For shorter distances, truck transport is used as the only transport method. According to Anttila et al. (2007), Karttunen et al. (2008), Laitila et al. (2010) and Iikkanen et al. (2014), if the transport distance exceeds 150 km, railways and/or shipping become competitive to chip supply by road in terms of supply costs. Long distance transport methods are justified when there is a high demand for fuel and there are not enough biomass resources available for energy use at shorter distances optimal for truck transport. Transport by railway and waterway are always linked to truck transport from feedstock to loading terminals/harbours and often truck transports are needed after long distance transports.

In Finland, domestic forest biomass for energy is transported by trucks, whereas in Sweden, for example, train transport is also used, particularly when the transport distance is very long (Enström 2008, Enström & Winberg 2009). The most common combination of forest chip supply unit is a mobile chipper and two, sometimes even three chip trucks (Ranta 2002, Asikainen 2010, Laitila 2012, Eriksson et al. 2014a). Few simulation studies of supply of forest chips have considered the effect of the number of trucks in the supply unit on supply costs. In the supply of logging residue chips, depending on the truck's payload, trailer setup and the chipper's productivity, operating with chipper and two trucks has been more cost competitive in transport distances of 60–100 km, and after that a three-truck unit has had lower costs (Asikainen 1995, Zamora-Cristales et al. 2013). Respectively, in the case of transporting comminuted material of stump wood, the breakeven point in transport distance has been a bit less than for logging residue chips (40–60 km) (Asikainen 2010, Eriksson et al. 2014a). With shorter distances, the chipper has less idling time, whereas for longer distances the idling time increases. The influence of the distance on idling time is the opposite for trucks.

As with industrial wood transport by truck, the majority of truck transports (85%) of forest chips make their return trip empty (Venäläinen & Poikela 2016). The rest of transports were back-haulage, circular routes or multi-point pick up routes. The ways to increase back-hauling has had interest, once there is clear evidence of its cost-competitiveness (Venäläinen & Poikela 2016).

As a result of changes in traffic legislation in Finland (Valtioneuvoston asetus, 2013), bigger dimensions and masses of trucks were allowed for truck transports on Finnish roads starting from 1 October 2013. Compared to the earlier law allowing truck-trailer units with a maximum gross vehicle weight (GVW) of 60 tons, the new law enables trucks with 64, 68 and 76 ton GVW depending on the amount of axles in the truck-trailer unit. New maximal dimensions of truck-trailer combination are 25.25 m in length, 2.55 m in width, and 4.4 m in height. Before the law reform, 84% of chip trucks' load spaces were a maximum of 140 in frame-m³ and 60 GVW in total weight (Karttunen et al. 2012, Korpilahti 2010). A change in the truck fleet is in progress towards trucks with higher maximum total weights and larger load spaces (Venäläinen & Poikela 2016), as the changes have been seen already in timber truck sizes. Nevertheless, the question of transporting full loads of forest chips in energy content is related to the moisture of chips and the compaction of chips (Ranta & Rinne 2006, Laitila et al. 2017). The loading density ratio in solid-m³/loose-m³ has been 0.36–0.41 while comminuting logging residues to chip truck containers (Verkasalo 1988, Karttunen et al. 2008). For wetter material, the maximum allowed weight of the transport unit is reached first, whereas for the dryer material the frame volume is reached before the

maximum weight. Therefore, for enhancing transport efficiency, it is really essential to have material that is sufficiently dry, good compaction of material as well as a high volume/gross weight relationship of the truck unit.

Terminals have become more common in the forest fuel supply chain, especially in countries which use a lot of forest fuels for heating and energy (Raitila & Korpinen 2016, Raitila & Virkkunen 2016). The share of terminal delivered forest fuels to heating and power plants of all forest fuel deliveries has increased steadily in Finland and Sweden and now stands at roughly 45% and 55%, respectively (Kons et al. 2014, Raitila & Virkkunen 2016). According to Kons et al. (2014), terminals under 2 ha are dominant in Sweden having three or four wood assortments in average and most often having comminution activities at the terminal (90% of cases). In Finland, terminals of a size 1-3 ha supply two thirds of the forest fuel from all terminals (Virkkunen et al. 2015).

Though terminals add costs to the supply chain due to additional phases and operations of the supply chain, this is often accepted in order to secure the supply of forest fuel to end-use points throughout the year in all conditions (Ranta et al. 2012, Ranta et al. 2014). Andersson et al. (2002), Hakkila (2004), Ranta et al. (2012), Karttunen et al. (2012), Enström et al. (2013), Karttunen et al. (2013), Kons et al. (2014), Virkkunen et al.(2015), Anerud et al. (2016), Raitila & Korpinen (2016) and Gautam et al. (2017) have stated other factors, which support the introduction of terminals to the fuel supply.

Weather changes have an effect both on energy demand and on the progress of supply operations of forest fuel (Kons et al. 2014). During the thaw seasons in particular, the accessibility of remote feedstock is limited due to the low carrying capacity of forest roads thus making the use of terminals for securing the fuel supply beneficial (Ranta et al. 2014, Gautam et al. 2017). Moreover, the need and the costs of road maintenance of secondary and tertiary roads could be reduced, if some of the forest fuel could be delivered to terminals during the time of good road connections (Anerud et al. 2016, Gautam et al. 2017). When the procurement volumes are large and transport distances long, terminals are essential for the efficient supply operations for fuel consumption facilities and where different transport modes are connected (Karttunen et al. 2012, Karttunen et al. 2013, Enström et al. 2013)

Raitila & Korpinen (2016) introduced the concept of rescaling the supply fleet; with less resources (machines, vehicles, workforce) it is possible to achieve the same desired output with a terminal than a supply chain without one. This is because terminals enable balancing the utilization of the supply fleet over the year. Increased machine utilization of the fleet has a decreasing effect on supply costs (Virkkunen et al. 2015, Anerud et al. 2016). Simultaneously year-round working opportunities raise the social factor into account; the workforce is more motivated and the work is more secure and less recruitment activities are needed (Kärhä & Peltola 2004, Väätäinen et al. 2008). Terminals can be utilized for controlling, managing and upgrading the quality of stored biomass as well as mixing different fuels and sieving the fuel material to meet the correct blend and homogeneity for combustion (Kons et al. 2014, Raitila & Korpinen 2016, Gautam et al. 2016). Synergetic aspects can be highlighted in terms of utilizing terminals for other business purposes during the low season of biomass storing (Raitila & Korpinen 2016). Moreover, terminals are inevitable to have in cases when end-use facilities with a lack of storage space are next to cities and settlements and with limitations on traffic and chipping due to noise and air pollution considerations (Wolfsmayr & Rauch 2014).

The layout of fuel reception and the fuel reception capacity at the power plant are decisive factors for efficient fuel arrivals, as well as the unloading and short lead-times of

chip trucks at the end-use facility (Väätäinen et al. 2002, Hakkila 2004, Laitila et al. 2010, Ranta et al. 2002). Fuel reception has to work efficiently especially during the period when fuel demand is at its highest, when truck arrivals can be over 100 per day for the large CHP plants (Väätäinen et al. 2002). Upgrading of existing power plants to increased heat and power production also require modifications to fuel reception: fuel receiving, weighing, handling, storing and feeding systems (Impola 2001). Fuel reception has to cope with varieties of fuels, unloading methods of trucks, intermittent and high number of truck arrivals with little disturbance to the supply chain (Impola 2001, Hakkila 2004).

1.3 Fuel quality aspects

Since the quality of the forest fuel is of great importance in energy conversion efficiency of the supplied biomass, a lot of effort has been addressed to improve the quality of forest biomass for energy (Andersson et al. 2002, Hakkila 2004, Pettersson & Nordfjell 2007, Routa et al. 2016). The characteristic most influencing quality regarding the efficiency of the whole supply chain of forest chips is moisture content (Hakkila 2004, Röser et al. 2011, Routa et al. 2016). According to Hakkila (2004), moisture has a negative impact in regard to transport efficiency and its costs, heat value of fuel, combustion efficiency, combustion emissions, dry matter losses during storage as well as handling functionality especially during the frost period in winter. The methods of enhancing fuel quality have to be taken into account when defining the supply chain and storage of harvested biomass (Röser et al. 2011) such as utilizing best natural drying seasons during spring and summer (Nurmi 1999, Nurmi & Hillebrand 2007, Pettersson & Nordfjell 2007, Erber et al. 2012), having a drying period for loose logging residues on site (Jirjis 1995, Nurmi 1999), selecting feasible locations for roadside storage (Nurmi 1999, Nordfjell & Liss 2000, Nurmi & Hillebrand 2007, Fillback et al. 2011) and for covering forest biomass piles at roadsides (Jirjis 1995, Nurmi & Hillebrand 2007, Röser et al. 2011). With the use of these methods, the drying potential can be 20–30 percent points from the initial moisture content after harvesting. For enhancing the influence of natural drying, various methods for stem treatment have been studied, such as partial debarking or scarifying of stems during harvesting (Röser et al. 2011).

Smaller heating plants require drier fuel material than larger combined heat and power plants (Hakkila 2004, Röser et al. 2011). Principally, for smaller heating plants roundwood chips from young stands are the most desired forest chips, whereas combined heat and power (CHP) plants can use logging residues from tops and branches for combustion. Bigger plants usually mix forest chips with peat, bark, sawdust or coal to control combustion. In particular, controlling the moisture content of arrived fuel at CHP plants can be done by regulating truck arrivals and by mixing fuels such as peat and forest chips (Hakkila 2004, Ranta et al. 2002). In addition to moisture, other important quality factors are heat value, energy density, share of green particles (needles), share of impurities, share of ash and particle size (Hakkila 2004, Routa et al. 2013). For example, impurities in forest biomass for energy causes additional breakdowns in chippers, causes difficulties during combustion and increases the ash content of the material (Laitila et al. 2010). This is particularly prevalent with stump fuel wood (Laitila & Nuutinen 2014). According to Holzleitner et al. (2013), reducing moisture content from 45% to 37% improves the productivity of chip trucks by 9% at a transport distance of 55 km.

A better understanding of material dissipation during storage in terms of microbial activity or spillage of material due to handling and storing (Routa et al. 2015, Routa et al.

2016) and the influence of dry matter loss on the forest chip supply efficiency (Kinnunen 2016, Sikanen 2016) has raised the importance of monitoring and controlling material losses within the supply chain of forest chips. For example, according to Kinnunen (2016), the use of a "fast-track approach" with minimized storage times for forest chips, supply costs could be decreased by 8–13% compared with conventional chip supply depending on the speed of decomposing. Benefits in supply resulted from the decreased dry matter loss. Progression of decomposing and dry matter loss (DML) are closely connected to the moisture of forest biomass, to the share of green material (composting material) and to the particle size of the stored fuel material (Jirjis 1995, Nurmi 1999, Pettersson & Nordfjell 2007).

1.4 Supply chain management and re-engineering

As a combined definition by Mentzer et al. (2001), Blanchart (2010) and Christopher (2016) a *supply chain* is a network of organizations, where organizations, people, activities, information and resources are involved in moving a product or service from supplier to customer. *Supply chain management* (SCM) is an approach, which then coordinates and manages supply chain activities to maximize customer value and gain a competitive advantage in the marketplace (Surbhi 2015, Christopher 2016). The multi-dimensional approach of SCM can be seen as a unity, which strategically manages and coordinates the flow of raw materials and works in progress (semi-finished goods) within the organization and the end product outside the organization till it reaches the hands of the final consumer with a complete emphasis on the customer requirement (Surbhi 2015).

Logistics or *logistics management*, on the other hand is a part of supply chain management. According to Surbhi (2015), the process of integrating the movement and maintenance of goods in and out of an organization is logistics. The main objective in the logistics management process is to provide the right product with the right quality and quantity at the right time in the right place at the right price to the end customer (Surbhi 2015, Christopher 2016). To compare, the main aim of *logistics* is full customer satisfaction, conversely, the main aim behind *SCM* is to gain a substantial competitive advantage (Surbhi 2015). Rushton et al. (2014) have categorized *supply chain* and *logistics* as follows; *Logistics* is formed by materials management and distribution, whereas *supply chain* includes suppliers and customers. According to Hugos (2003), *logistics* typically refers to activities that occur within the boundaries of a single organization and *supply chain* refers to networks of companies that work together and coordinate their actions to deliver a product to market.

To improve the supply chain and logistics in it by enhancing customer satisfaction, minimizing supply costs and reducing inventories, for example, various methods or approaches have been presented in literature and performed in research and practice. *Business Process Re-engineering (BPR)* has had success among researchers and companies since it was introduced in the early 1990s (Hammer 1990, Groznik & Maslaric 2009). In BPR, a business process is understood as a set of methods, where business processes are mapped, the flow of activities are understood and alternative sets of processes are identified and created (Grover & Malhotra 1997). BPR is based on fundamental rethinking and redesigning of business processes to achieve improvements in quality, cost, service, lead times, outcomes and innovation (Groznik & Maslaric 2009). BPR reinforces the importance of IT and its efficient use in managing redesigned business (Grover & Malhotra 1997). *Supply chain re-engineering* (SCR) is a holistic approach for company business and

its chain of suppliers and customers, taking into account improvements in materials management, manufacturing, marketing, distribution and logistics processes (Flickingen & Baker 1995, Leenders & Fearton 1997, Handfield & Nichols 1999). According to Sweeney (2000), SCR consists of analysis of the existing configuration of a supply chain, defining improvements to the existing supply chain and finally putting these improvements into practice. The third approach presented here is called *logistics (process) re-engineering,* which is basically a redesign of logistics processes such as customer order to deliver, inbound logistics, third party provider selection, facility location network design and inventory deployment (Crosby 1994).

From the perspective of the forest chip supply chain, it consists of main activities and operations like pre-procurement activities of forest biomass, harvesting of biomass at forest sites and extraction to roadsides, storing as uncomminuted, comminution and transport of forest biomass to terminals or to heating and power plants as well as fuel receiving, storing and feeding on chips to the burning process to generate heat and/or energy or the refining process to produce fuel and/or other components, for example. Forest biomass producers can be private forest owners, state, municipalities and forest industry corporations. Target customers are households, business sectors and the sector of transport and traffic. While observing the supply chain of forest chips in detail with the aid of business process mapping, high number of business processes and activities can be detected from behind the actual operations (Windisch et al. 2013, Windisch 2015).

The logistics approach is controversial when comparing forest chip supply to conventional supply and distribution of goods and products. Instead of managing, transporting and distributing products/goods from one of a few points to several end users, forest fuel needs to be collected from various points of origin to one or a few places of end use. This is similar to the supply logistics of agriproducts, such as meat, milk, grain, from individual farms to refining facilities, for example. In this respect, logistics is delineated to inbound logistics, which is the movement of goods and raw materials from suppliers to your company (Ballou 2004).

As expressed earlier, there are various options of supply chains for forest chips and within each main supply chain method several approaches with operational specialties have been used in practice. In addition, depending on the use, the scale of business, characteristics of forest biomass resources, procurement environment, level and available options of transport connections as well as characteristics of biomass utilization facilities, the number of supply chain concepts in use can be multifold.

1.5 Discrete-event simulation as a study method

1.5.1 Simulation as a part of Operations Research

Today, a great variety of analysis methods are available for studying optimal solutions to a specific problem. The discipline called Operations Research (OR) consists of various analytical methods for decision support wherein simulation belongs together with the set of other analysis methods, such as Linear Programming, Network Optimization, Dynamic Programming, Integer Programing, Nonlinear Programming, Metaheuristics, Game Theory, Queuing Theory, Decision Analysis, Markov Chains, Queuing Theory, Inventory Theory and Markov Decision Processes (Taha 2007, Lättilä 2012). By using the methods within OR, the decision maker is provided a scientific basis for solving the problems and for finding a solution which is in the best interest of the organization as a whole (Murthy

2007). The terms quantitative approach, operations research, management science, system analysis and system science have often been used interchangeably (Murthy 2007).

Simulation is OR technique often used in analysing complex systems, which cannot be presented by a mathematical model due to the stochastic nature of the system and its behaviour (Murthy 2007). The importance of simulation has increased over time due to the recent advances in simulation methodologies, technical development and increased availability of software (Murthy 2007). Today, in various fields of business, simulation has been incorporated in their everyday operations and decision making processes. Today simulation software allows improved visualizations to illustrate system behaviour efficiently and compactly. Simulation models can be used for training purposes, decision support, understanding, education and learning and entertainment (Sokolowski & Banks 2009). Simulation can be used for comparison, optimization, prediction and investigation (Rossetti 2016).

To shorten and sum up the definitions of simulation from the literature, simulation is an imitation of a real system from the nature or field of practice, or it can be a representation of virtual reality or fully theoretical system. More closely, simulation has had the following definitions over time, for example: According to Malcolm (1958), a simulation model can be defined as one which illustrates the working of a large scale system of men, machines, materials and information operating over a period of time in a simulated environment of actual real world conditions. According to Naylor et al. (1966), simulation is a numerical technique for conducting experiments on a digital computer, which involves certain types of mathematical and logical relationships necessary to describe the behaviour and structure of a complex real world system over an extended period of time. Hillier and Liebermann (1974) have stated that simulation is an "experimental arm" of Operations Research. "To simulate is to try to duplicate the features, appearance and characteristics of a real system" (Render & Stair 1992). According to Taha (1992), simulation is a model entity, which is an abstraction of a system, resulting in a theory. "Simulation refers to the application of computational models to the study and prediction of physical events or the behaviour of engineered systems" (Simulation-Based… 2006) "Simulation is a representation of reality through the use of a model or other device, which will react in the same manner as reality under a given set of conditions." (Murthy 2007). "A simulation is the imitation of the operation of a real-world process of a system over time. (Banks et al. 2010). "A simulation is only a model (representation) of the real thing" (Rossetti 2016).

1.5.2 Discrete event simulation

Discrete Event Simulation, as the name implies, models the activities or operations of a system as discrete events in time. In DES, the components of the system are modelled as objects with specific attributes (White & Ingalls 2009, Banks et al. 2010). The basic structural components in the DES model are presented in table 1 according to While & Ingalls (2009).

Table 1. Basic components in DES adopted from White & Ingalls (2009).

Component	Description
Inputs	Actions of the environment causing changes in the system
Outputs	Measured quantities derived from system state
State	Internal condition of the system
Entities/items	Dynamic elements which flow through the system
Attributes	Unique characteristics of an entity/item
Activities	Processes and logic in the simulation model, such as delays, queues and logic
Events	Conditions occurring during the simulation, causing a change in the state of the system
Resources	Elements, which have a constrained capacity, such as workers, machines, nodes etc.
Global variables	Variables containing information about the system
Random number generator	Generates randomized values to be used during the simulation
Statistics collector	Collects statistics on the conditions, values of global variables or performance data based on attributes of the entity
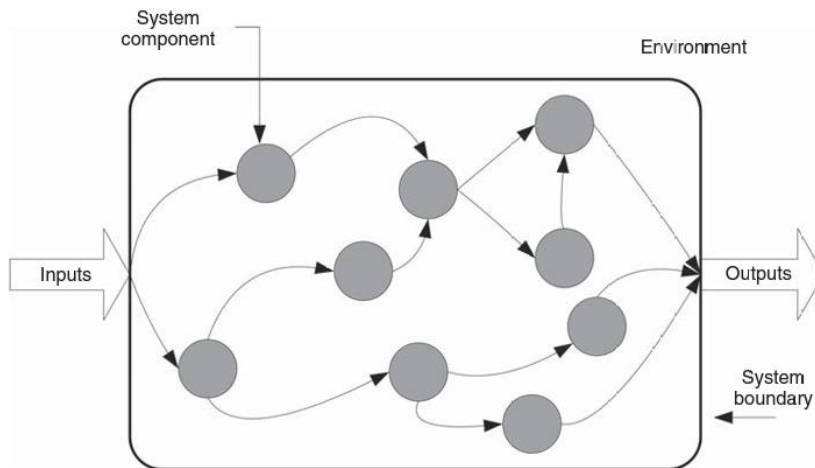
Figure 1. A conceptualization of a system according to Rossetti (2016).

As Rossetti (2016) states, the main purpose of a simulation model is to enable observations about a particular system to be collected as a function of time (Figure 1). According to Blanchard and Fabrycky (2011), a system is a set of interrelated components working together towards a common objective. A broader definition of a system is, "Any object which has some action to perform and is dependent on a number of objects called entities, is a system" (Singh 2009). Like all modelling environments, at the beginning of the model construction in discrete event simulation (DES) also, the content and outline of the studied system has to be defined.

Systems, system modelling and simulation can be classified into separate types depending on the nature of the system and whether or not it changes with respect to time. If the system changes with respect to time it is dynamic, otherwise it is called static. In dynamic systems, the changes of the system can take place at discrete points in time or continuously with time. DES is usually categorized as dynamic simulation including stochasticity.

Different approaches have been stated in the branch of simulation, DES being the most widely used study method within peer-reviewed articles in 1997-2006 (Jahangirian et al. 2010). Other widely used simulation approaches have been System Dynamics (SD) and

Hybrid models (combining two or more approaches in one model) Other used approaches have been Agent-Based Modelling (ABS), Monte Carlo Simulation and Intelligent simulation, for example (Jahangirian et al. 2010).

A general methodology for solving problems also follows in simulation studies as in other OR studies (Taha 2007, Murthy 2007). In principle, the structure of simulation study resembles the conventional study experimentation carried out in real life with the explicit exception that instead of making observations from reality, the simulation software makes observations of the operations of the system. Everything starts from the problem definition, which actually describes in detail the objectives of the study, the desired outputs from the model and the types of scenarios to be examined (Rossetti 2016). After formulating the study problem and setting the overall project plan with objectives of the study, the model conceptualization and construction takes place (Banks et al. 2010, Rossetti 2016) (Figure 2).
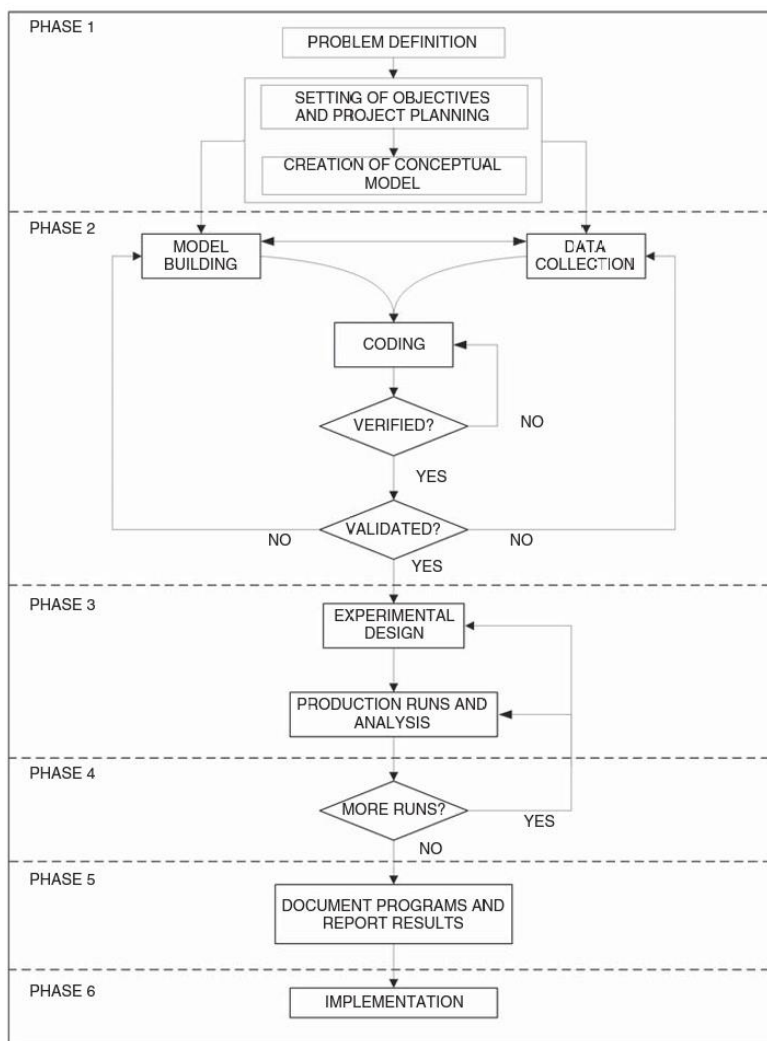
Figure 2. The structure of the simulation project (Rossetti 2016).

According to Banks et al. (2010), it is better to start with a simple model and to increase the complexity for fulfilling the study purposes and requirements. Furthermore, this approach helps the verification of the model along with the model development phase. The level of model complexity should also follow the quality of the input data and the defined objectives of the study (Banks et al. 2010, Rossetti 2016).

Comprehensive knowledge of the system and operations to be studied is essential, therefore the data used for model construction and simulations is of high importance. Moreover, the better you have assimilated the study problem, the better you can outline and define the model structure together with the required data. According to Shannon (1975), there is a continual interplay between the construction of the model and the collection of the needed input data. Data can consist of performance, capacity and other operational characteristics of elements; parameters and attributes from buffers, tracks, vehicles, machines, labour etc. For example, a mobile chipper for a forest chip supply system has special parameters such as cycle time for producing one cubic meter of forest chips, breakdown parameters, set up times before the start of chipping in a new storage location. Parameter data can be either fixed values or in the form of mathematical formulas or theoretical distributions. Today, a large volume of comprehensive data is available more and more for problem solving (Fey et al. 2008). Referring to this, simulation modelling is data-friendly, allowing the handling of a large amount of data in different forms; as variables, parameters and functions or in forms of multidimensional matrices and distributions with theoretical or empirical base (Ojala 1992). With the help of developed data collection, handling and computer science, the time effort for input data acquisition and utilization in the simulation study process has decreased. Actually, many scientific fields have become highly data-driven, thus encouraging the use of data intensive applications (Chen & Zhang 2014). In some situations, it is not possible to collect data; in these cases usually time is very limited and/or the studied system or process does not yet exist, thus encouraging the use of expert knowledge and educated guesses for the study (Banks et al. 2010).

Along with model development, model verification (building the model correctly) and validation (building the correct model) comes hand in hand and it is an iterative process (Carson 2002, Banks et al. 2010, Sargent 2011). The importance of the verification and validation of the simulation model cannot be overplayed, because decisions will be made on the basis of results derived from the simulation model (Banks et al. 2010). As Carson (2002) has stated, the model verification and validation process improves the model's credibility among decision makers. According to Sargent (2011), verification and validation procedures are conducted until sufficient accuracy and confidence in the simulation model is obtained.

Model verification comprises implementation of the correct model from conceptual model into the simulation software comprising finding and fixing modelling errors (Carson 2002, Sargent 2011). Model review by an expert, logic flow diagram presentations of model actions, inspection of input parameter specifications, conducting model documentation to verify model logic, tracing technique to compare variety of input parameter influence on model output and interactive debugger tests are techniques to verify the model (Banks et al. 2010). For example, sophisticated simulation software have inbuilt functions for model debugging to locate any errors in the simulation code itself (Rossetti 2016). To conclude, the objective of model verification is to confirm that the implementation of the model is correct.

The validation of the simulation model practically reviews the accuracy of the model's representation of the real system. Some approaches are used to validate a simulation model (e.g. Naylor & Finger 1967, Carson 2002, Banks et al. 2010, Sargent 2011). According to (Sargent 2011), validation can be divided into conceptual model validation, operational validation and data validity. If the data to be used for i) building the conceptual model, ii) validating the model and iii) performing experiments with a validated model, has shortcomings in quality and sufficiency, it has direct impacts on the validity of the model. The validity test process with three steps formulated by Naylor & Finger (1967) has been widely followed. As a first step, a face facility embodies model testing done by users and experts with a good knowledge of the real world system. Model assumption validation includes a structural assumption review about the correctness of system operations with the given assumptions and data assumption review about data accuracy, quality and reliability. In input-output transformation validation, the model's accuracy level in predicting the outcomes of various circumstances comparable to the real system will be carried out. In addition, there are a range of approaches from subjective reviews to objective statistical validity tests (Sargent 2011). In practice, during model development, comparing the model to reality must be done all the time to calibrate and correct the model (Banks et al. 2010).

1.5.3 DES method in modelling forest chip supply chain and logistics

DES has been proven to be reliable method for studying complex supply chains with multiple internal interactions (e.g. Asikainen 1995, Asikainen 2010, Banks et al. 2010, Spinelli et al. 2014). According to Talbot & Suadicani (2005) and Asikainen (2010), deterministic models of forest chip supply chains are much less realistic than proper stochastic models. The dynamic simulation model can reliably describe the behaviour of such systems as the supply of forest chips represents. As discovered in several DES studies of forest chip supply, machine or sub-system interactions can cause substantial idling times for the machines (Asikainen 1995, Asikainen 2001, Asikainen 2010, Karttunen et al. 2013, Belbo & Talbot 2014, Eriksson et al. 2014a, Eriksson et al. 2014b, Eliasson et al. 2017). According to Asikainen (2010), if using a deterministic and static study approach instead of dynamic ones as DES is in the forest chip supply chain of a chipper and chip trucks, there is a tendency to significantly overestimate system performance and underestimate waiting times and supply.

Several studies consisting of the modelling and analysis of the entire chain or sub-chain of the forest chip supply have applied the DES approach as the main study method. Asikainen (1995) introduced the DES method in the modelling and analysis of energy-wood harvesting and transport in his doctoral thesis, where he revealed that machine interactions that cause waiting have to be taken into account in the system analysis. The DES approach was applied later in the study of Asikainen (1998), where alternatives for crushing, loading and transport logistics for supplying forest chips from terminal to power plant were analysed. With the DES approach, Talbot & Suadicani (2005) analysed and compared two forest chip supply systems based on terrain-going chip harvesters either co-operating with a separate bin forwarder for transporting loaded bins to the roadside or chipping to the bins and forwarding them using a chip harvester at the site without an additional shuttle. In the study of Asikainen (2010), the optimal number of trucks in a supply system of stump crushing and truck transport of chips from a landing to a district heating plant with varying transportation distances was analysed by DES. Also, Zamora-

Cristales et al. (2013) applied DES for analysing the cost-efficiency of forest chip supply by mobile chipper and chip trucks.

Karttunen et al. (2013) introduced a combination of agent-based modelling and DES for constructing the simulation model, which was utilized for comparing the cost-efficiency of an intermodal container supply chain and a traditional multi-modal supply chain with corresponding direct truck logistics for long-distance transportation of forest chips by road and rail. Belbo & Talbot (2014) compared the supply of small trees from landing to plant or terminal by varying the transportation of biomass as loose, as chipped and as baled. Spinelli et al. (2014) studied the cost-efficiency and fuel economy of forest chip supply systems in mountain conditions as a function of transport distance and number of trucks.

Eriksson (2016) compiled his doctoral thesis by analysing forest fuel supply chains in four separate articles by having DES as the main study method. In Eriksson et al. (2014a), the comparison of stump fuel supply was conducted from roadsides to heat and energy generation by varying the comminution method, timing of comminution and number of trucks in scenarios. In contrast to the previous study, the whole supply chain including harvesting and forwarding of stumps from the sites were modelled in the Eriksson et al. (2014b) study, where fuel quality and site characteristics, for example, were taken as the main focus in the scenario analysis. In the study of Eliasson et al. (2017), analysis of forest chip supply included an option to forward filled chip containers from a landing to a reloading point where they could be loaded onto container trucks. The DES modelling took the work scheduling approach into account. A holistic DES model for forest chip supply was conducted by Eriksson et al. (2017), where quality changes of forest fuel material during storage were included into the model as a weather-driven method.

1.6 Structure of the thesis

This thesis investigates supply chain efficiency of forest chip supply chains having different objectives and fuel supply cases in each article. All articles in the thesis are focused on practical situations in supply chains of forest biomass and exploring alternative system setups to find economically, environmentally or socially better solutions. The first article concentrates on finding an efficient setup for fuel reception at the CHP plant in order to enhance the supply of peat and a variety of woody biomass by truck. In the second article, the aim was to quantify the benefits on the efficiency of forest chip supply chain of utilizing accurate biomass storage characteristics in the selection of storage locations and fuel allocation in time. The third article investigated the efficient use of terminals as a part of conventional direct forest chip supply. As an alternative long distance transport option, waterway transport logistics in Lake Saimaa waterways was studied to magnify the cost-competitiveness of barge transport logistic alternatives for forest chips compared to road transports.

The supply chain reengineering approach has been used in the thesis with narrowed focus, where logistics and inventory, material handling and fuel delivery as well as the customer's desideratum have been in consideration. Business processes in the sense of human to human, human to IT, IT to human interactions and processes have been neglected, whereas the focus has been on events and time consumption occurring in material storage, flow and handling, i.e. operations and actions related to material flow in the supply chain have been under study. In addition, the influence of the quality changes of forest chips has been taken into consideration in articles II and III. The fuel property

requirements of the customer, here meaning the end-use facility, has been introduced as in energy content of the forest chips delivered to the plant.

The studied supply chains were all based on logistics of comminuted forest biomass next to roadsides or at terminals before the main transport either by chip truck or a combination of barge and chip truck (Figure 3). All supply chains were "hot chains", where idling times occur due to machine-to-machine interactions, i.e. one has to wait for the other to finish the task. With the exception of article IV, the transport mode of solid fuel is road transport with container truck-trailer units. Article IV covered waterway transport of forest chips by barge.
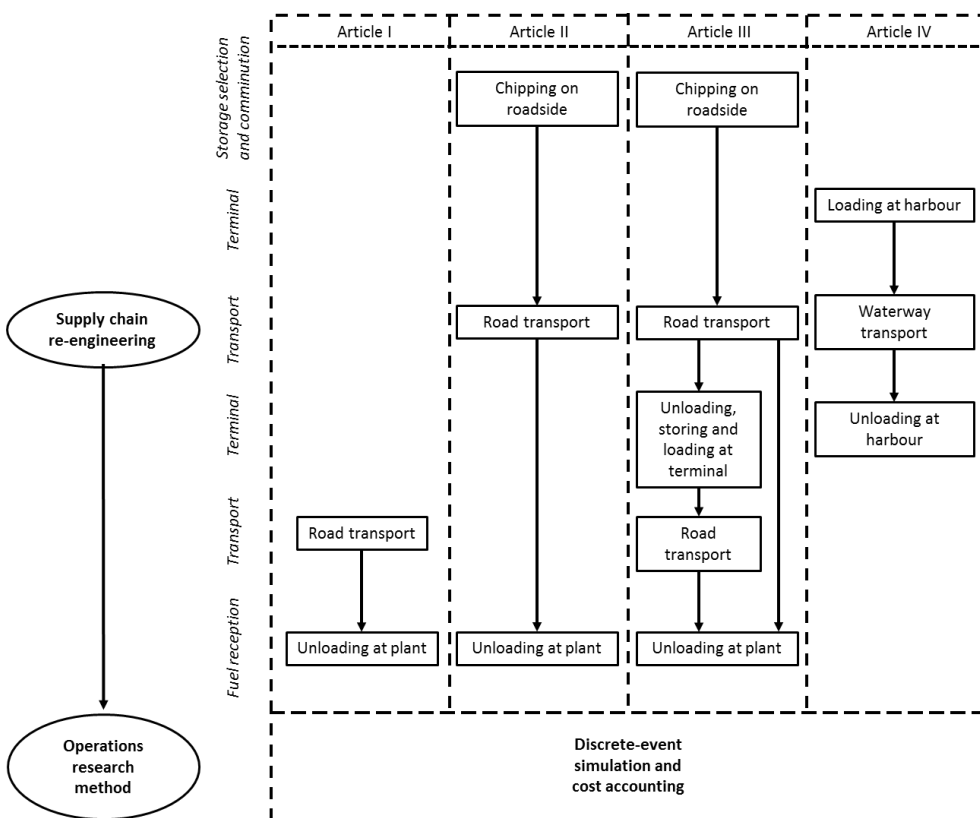
Figure 3. Framework of the thesis. Articles are expressed by system definition with the main operations expressed. The supply chain re-engineering approach with the discrete-event simulation study method has been used for analysing the holistic efficiency of forest chip supply.

Studied supply chains do not cover the whole supply chain of forest chips, instead, depending on the article, the focus is on either the analysis of operational efficiency of the sub-system or the sequence of sub-systems and therein efficient logistics. The trading actions of forest chip purchase between owner and buyer has been neglected. Also, harvesting and extractions of uncomminuted forest fuel is not included in any analysis in the articles. Lastly, the monitor of material flow through the supply chain is the prerequisite of incorporated analysis related to operational efficiency, supply costs, fuel quality, timing of deliveries and social and environmental aspects (Figure 4).
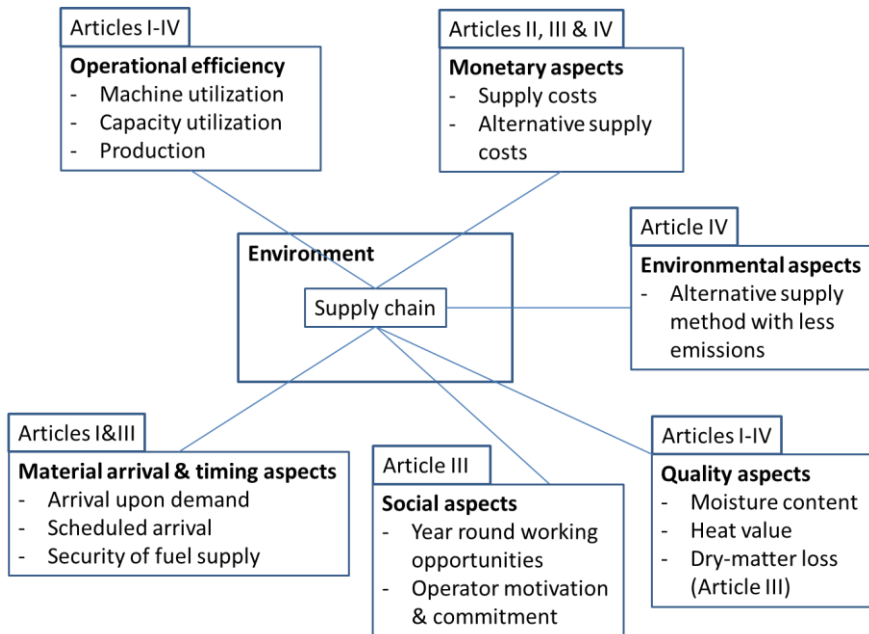
Figure 4. Schematic chart presenting the aspects and its indicators which have been included in articles.

1.7 Objectives of the thesis

The overall aim of the thesis was to design efficient supply chain setups in the selected supply environments by enhancing overall supply system performance, decreasing supply costs and improving working opportunities by taking the fuel properties through the supply chain into account. Moreover, special attention was paid to the selection and allocation process of forest chips and terminal use as part of fuel supply to the end-use facility.

The specific objectives were to:

1) Evaluate the influence of truck arrival procedures and fuel reception set ups at the combined heat and power (CHP) plant to improve the efficiency of fuel supply to heat and energy generation. (Article I)

2) Quantify the impact of raw material selection based on fuel characteristics at roadside storage locations on the efficiency of forest chip supply logistics. (Article II)

3) Analyse the differences in supply costs and performance indicators between direct forest chip supply and terminal based chip supply. (Article III)

4) Evaluate the influence of terminal specific characteristics and quality changes of forest chips in terminal based forest chip supply. (Article III)

5) Evaluate the cost efficient logistic set ups in waterway transport of forest chips by barge on Lake Saimaa. (Article IV)

2. MATERIAL AND METHODS

The scenario analysis of forest chips supply chains with machine interdependencies and stochasticity included called for simulation as a study method. In all articles, discrete-event simulation has been used to study the problems. In each article, areal fuel supply system or sub-system has been modelled to the simulation environment with predefined system boundaries and model simplifications. Witness simulation software (Witness 1996, Lanner 2017) was used for building the models and examining the defined scenarios. Separate simulation models were designed for each study in each article. Due to the models' stochasticity and system sensitivity in varying conditions and machine interdependencies, each determined scenario was simulated several times to reach the desired confidence interval of decision variables, thus improving the comparability of studied scenarios.

Most of the data required for the development of the model and the models' parameter input values were acquired from the available information of the real system. In addition, machine characteristics of conventional forest chip supply chains were obtained from the literature, whereas the waterway supply chain was demonstrated and time studied to derive the required data for parametrization of the system. In the following chapters, material and methods are described briefly for each article separately.

2.1. Re-engineering the fuel reception at the CHP-power plant (Article I)

2.1.1 Description of the case study

The base model scenario was made to describe the initial situation of the truck arrivals and functions of the fuel receiving station at the Kuopio power plant during the winter of 2000. The simulations of alternative logistic solutions were compared to the base scenario. The simulation study focused on the winter period, which is the period when energy production is at its highest and the bottlenecks of the operation at the receiving station were easier to detect. The main result parameter was the queuing time, which was automatically registered by the model. Additionally, the model calculated the degrees of utilization of the delivery bays.

2.1.2 Material for the study

Initial data for the simulation models was derived from the plant's fuel receiving station's database, which was collected during the year 2000 by an automatic data collection system. The data included truck arrival times to the weighing station, starting and ending times of unloading and departure times from the weighing station. The data also included information regarding unloading technique, fuel suppliers, supplied fuel, the fuel's calorific value, volume and mass of the load. In the data of one year, the number of truck arrivals was 13,479 and the total delivered fuel mass was approximately 500,000 tons. The total annual number of rear end unloading (presented as RU) truck arrivals was 10,832 and side tipper unloading (presented as ST) trucks 2,647. There were 30 trucks delivering the fuel.

2.1.3 Modelling the system environment of the case

Basic elements for the simulation model were 30 fuel trucks, one fuel-loading bay, roads from/to loading place to/from fuel receiving station, weighing station, roads from/to

weighing station to/from DP1 and DP2, and two delivery (unloading) bays (delivery bay 1 = DP1 and delivery bay 2 = DP2) and their fuel hoppers.

In the base scenario, the timing of truck departures from the fuel stores was done so that trucks arrived at the power station in a manner resembling the arrivals in the current situation. For other scenarios, changes to the base model were made in the truck controlling unit, in guiding rules of trucks after weighing and in the speed of fuel flow from delivery bay 1's hopper to combustion.

The parameters of the simulated week correspond to an average week, which was built up from the winter season data (October – April). Moreover, three different truck arrival sets (wintertime, coldest month and coldest week) were used in the simulation experiments. Truck type as RU or ST, fuel supplier, fuel type, fuel quality and load amount of 110 loose-m³ were determined for each departing truck. The number of departing trucks for every hour was estimated by a theoretical Poisson distribution and the expectation values, λ (trucks per hour) were taken from the analysed database in the base model. The procedure of the actions of trucks and fuel reception station as well as the model input parameters in simulations are presented more detailed in Väätäinen et al. (2006).

2.1.4 Study scenarios

Four main scenario set ups with a varying set of sub-scenarios were conducted. In scenario A, the target was to detect the influence of upgrading options at fuel reception on the queuing times of fuel trucks and utilization levels of unloading stations. In scenario B, predefined time-schedules for truck arrivals were simulated to reveal its impact on morning arrivals and queuing times of trucks. The effects of a cold winter season were examined in scenario C and the effect of the increased use of forest chips to replace the use of peat on queuing times was examined in scenario D.

2.2 Smart biomass storage allocation for enhanced forest chip supply (Article II)

2.2.1 Description of the case study

The case study was based on the operations of a forest entrepreneur supplying forest chips from roadside storage locations of logging residues to a large-scale CHP plant providing heat and power to the city of Joensuu, located in the region of North Karelia (Figure 5). A new approach was designed for information-based decision making in the allocation process using the criteria transportation distance, moisture content and storage volume with the aim of increasing the efficiency of the chipping and transport of forest chips during peak periods in particular. The effects on the productivity and cost-efficiency of a supply chain from roadside storage to plant were investigated.

2.2.2 Material for the study

For defining and validating the model structure, expert interviews were held with four entrepreneurs engaged in forest biomass supply in the study area. The questions at the interviews were related to the characteristics of forest biomass supply operations, such as size of operating area, pile sizes, transport distances, fleet size, work shifts and shift arrangements.

The storage data used in the simulations was derived from a larger data set of the timber logging operations provided by a forest enterprise operating in North Karelia. The data set from the year 2008 to 2012 involved spatial coordinates, logging date, seasonal accessibility, unique identification number and the volume in terms of solid m³ for every storage location. The theoretical occurrence of logging residues in volume from spruce (Picea abies) final fellings was calculated by a biomass expansion factor of 0.44 and the volume of extractable logging residues was then estimated by converting the available amount with the value of 0.70 (Laitila 2008). The final data set consisted of 328 separate storage locations with a total volume of 57,166 solid m³.

The drying curves by Sikanen et al. (2013) were used to estimate the moisture content of the storage locations for every month of the year. The storage locations were then grouped into spatial clusters so that driving distances between the locations remained short. From this data pool the supply chain was assigned clusters of storage locations according to criteria described further.

2.2.3 Modelling the system environment of the case

The simulation model was build based on current knowledge of the behaviour and structure of the forest biomass supply system. The model consisted of one truck-mounted mobile chipper and two truck-trailer combinations and involved detailed machine interactions, set-up and breakdown parameters as well as productivity, driving speed, loading/unloading, load capacity and working shift parameters presented in Windisch et al. (2015).

The maximum transport distance to the plant was 110 km. The contractor's business premises were located in the city of Ilomantsi, 65 km from the power plant (Figure 5). The operations of the supply chain were simulated over a period of one year divided into four supply periods according to the variation of demand of the CHP plant in different seasons; Peak period-high demand (Peak): December to February, Interim period 1 –medium demand (Interim1): from March to May, Summer-low demand (Summer): from June to August, Interim period 2-medium demand (Interim2): from September to November.
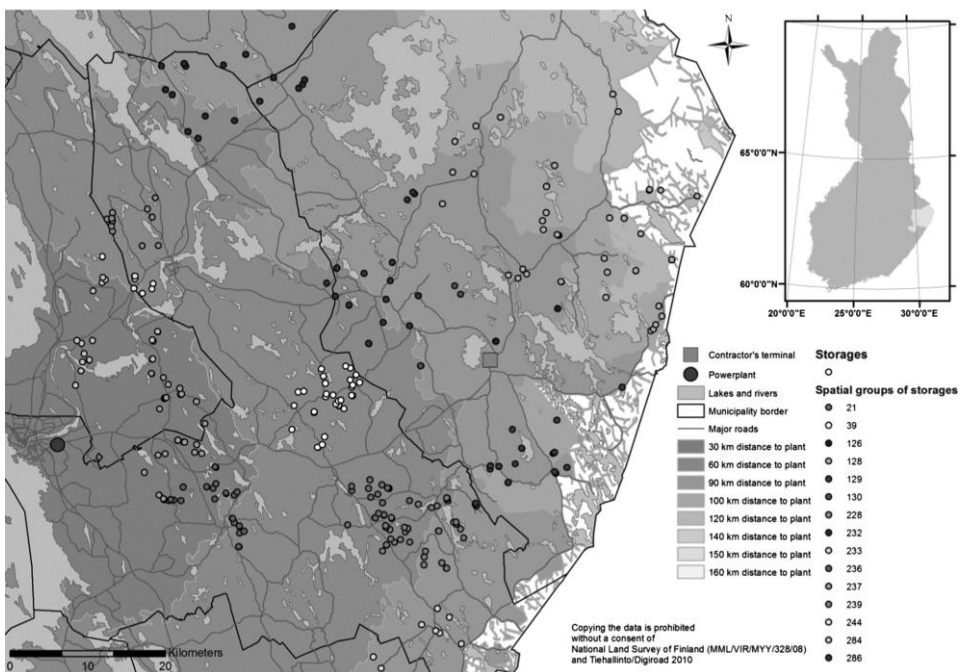
Figure 5. Map of the entrepreneur's operational area. The dots are the individual storage locations. The square denotes the location of the entrepreneur's business premises, the circle the location of the plant he supplies. The distances to the plant shown in the legend refer to driving distances on public roads.

The model used the driving distances from the contractor's business premises to each storage locations and from each storage locations to the plant determined by an analysis with ESRI ArcGIS for Desktop version 10.0. The loading capacity of the trucks was limited either by the load volume or the load mass. A dry matter density of 445 kg/solid m^3 was used, which is the average of the dry matter densities of spruce logging residues with and without needles according to Hakkila (1978).

2.2.4 Study scenarios

A total of seven scenarios were defined for the simulations (Table 2). The information-based raw material allocation process was named *precision supply* (PS) which was divided to five scenarios. Three criteria were defined: average transportation distance to the plant, average volume per storage and average estimated seasonal moisture content. PS scenarios 2 and 5 had combination criteria with different weightings in each index (Table 2). Criteria are presented in more detail in Windisch et al. (2015).

Table 2. Overview of the scenarios investigated by discrete-event simulation (Td = transportation distance, Vol = volume, Mc = moisture content).

Scenarios	Description	Spatial clusters in use	Abbreviation	Weighting		
				Td	Vol	Mc
1	Business as usual	Yes	BAU	–	–	–
2	Precision supply 1	Yes	TdMcVol	0.33	0.33	0.33
3	Precision supply 2	Yes	Td	1	0	0
4	Precision supply 3	Yes	Vol	0	1	0
5	Precision supply 4	Yes	Mc	0	0	1
6	Precision supply 5	Yes	TdMc	0.5	0.5	0
7	Random supply	No	RAND	–	–	–

In the seventh scenario, storage locations were processed randomly. In all scenarios, logging residues stayed on the cutovers for one month during the drying season. Each scenario was simulated with seven repetitions, each using different random number streams.

For calculating the costs of chipping, the key figures were effective machine work hours (E_0h), driving time, other work time and annual production in terms of solid m^3 and MWh. Costing parameters were given by the Finnish Machine Contractor Association. The key figures for the cost calculation for the chip truck were average transport distance per truck load, average time consumption per truck load, average number of truck loads per day and average amount of MWh and solid m^3 per truck load. The values of the costing parameters corresponded to the average price levels of the year 2013 and the key factors of machine cost calculations are presented in Windisch et al. (2015).

2.3 Efficient use of feed-in terminal as a part of forest chip supply (Article III)

2.3.1 Description of the case study

The aim of the study was to compare the costs of the conventional direct forest chip supply to an alternative fuel supply with the use of a feed-in terminal using discrete-event simulation method. A combined heat and power plant (CHP plant) using 517GWh of forest chips supplied by four supply chains within a 100 km operation radius was selected as a case environment for the study. The forest chip supply environment was defined to begin from the roadside storage locations of forest biomass and to end at the power plant. A feed-in terminal for the storing and supplying of forest chips was introduced into conventional direct forest chip supply as a balancing and securing option for the fuel supply to the CHP plant.

2.3.2 Material for the study

The sizes of the roadside storage locations of logging residues corresponded to the real situation of spruce-dominated final fellings located in North Karelia, Eastern Finland. Unlike in Windisch et al. (2015), the data and the parameters of logging residue storage locations were defined by theoretical distributions.

The monthly demand for the forest chips used in simulations was derived from the local CHP plant in the city of Joensuu and corresponded to the typical fuel demand of an average year (Figure 6). Moisture in the forest chips from roadside storage locations was determined by the theoretical distribution following the moisture data of fuel received by a large scale CHP plant. Monthly mean values for the moisture in forest chips were derived from Hakkila (2004) (Figure 6).
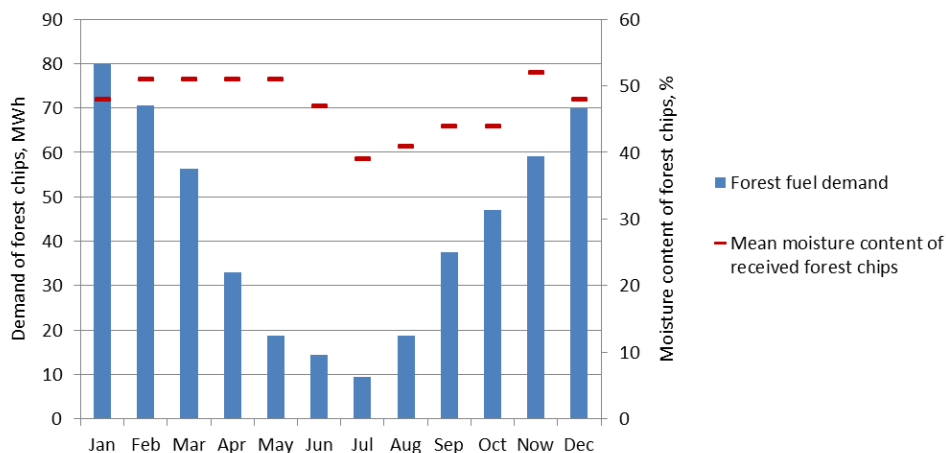
Figure 6. Monthly mean moisture content of received forest chips and monthly forest fuel demand of the CHP plant in the simulation in GWh.

2.3.3 Modelling the system environment of the case

The simulation model consisted of four forest chip suppliers operating with one truck-mounted chipper and two chip trucks. The fuel suppliers operated with a one-shift weekly working schedule having Sundays off from work. The material for the chipping was logging residues (tops and branches) from spruce-dominated final felling. The dry net calorific value of forest chips was 19.2 MJ/kg (Alakangas et al. 2016) and the dry matter weight of forest chips was 445 kg/solid-m³ (Hakkila 1985). In addition to the monthly demand variation, the daily demand had a variation determined by the truncated normal distribution varying ± 20% from the monthly mean demand. Storage size of forest chips at fuel reception was set to 6,000 MWh.

The chip trucks in use were conventional container-based truck and trailer units with seven axles allowing a vehicle of a maximum of 64 tons providing 50 solid-m³ of load capacity (130 m³ frame volume of containers). A shuttle truck with a total weight of 76 tons and 60 solid-m³ of load capacity (160 m³ frame volume of containers) was used in the terminal scenario, where outbound terminal transports were carried out with a higher capacity truck and trailer unit. The mobile chipper was a truck-mounted drum chipper typically used in chipping at roadside storage locations. The machine interactions, the distribution parameters of breakdown, set-up, loading/unloading and productivity as well as of speed functions, shift schedules, the actions of the fleet and other fixed parameters are presented in more detail in Väätäinen et al. (2017).

The supply of forest chips from spruce dominated logging residue roadside storage locations was distance oriented i.e. the higher the fuel demand of power plant was, the closer storage locations and shorter distances were stressed on the selection of roadside storage locations. Average transport distance was 60–64km depending on the study scenario. Inbound and outbound terminal transports were controlled by the defined alarm levels of the power plant's buffer size. If the supply of forest chips by the contractors did not meet the demand of the power plant, a supplement fuel was introduced to fill the missing part of energy demand.

The size of the feed-in terminal was not pre-determined, thus the terminal area was defined after simulations. Consequently, the area was 4.7 ha having a 50 GWh capacity of forest chips. One operator managed terminal activities and had the responsibility of establishing the heaps of chips, loading trucks and maintaining the terminal area. Other cost parameters for defining the investment cost of terminal, following the values used in Virkkunen et al.'s (2015) study, are introduced in Väätäinen et al. (2017).

2.3.4 Study scenarios

Four main simulation scenarios were examined. At first, conventional direct fuel supply (Scenarios 1A1 and 1A2) was compared to terminal aided fuel supply (Scenarios 1B and 1C). Both the supply of contractors' own chip trucks and a separate shuttle truck to conduct outbound terminal transports were compared. In addition, the location of feed-in terminal, dry matter loss of terminal stored material as well as moisture changes of terminal stored chips were examined (Table 3). The studied scenarios are explained in more detail in Väätäinen et al. (2017).

For each scenario simulation, seven replications with varying seed numbers for determining unique random number streams were applied. In addition to the terminal scenario runs, sensitivity analyses for the operating hours of the shuttle truck and the investment level of the terminal were investigated. The main cost parameters accounting for the mobile chipper, the chip truck and the shuttle truck were presented in Väätäinen et al. (2017). To specify, supply costs in this study included chipping, truck transports and terminal costs (investment and operations).

Table 3. Simulation scenarios used in the study. (pp = percentage point)

| Main scenario	Abbreviation	Terminal in use	Definitions	Equals to
1: Business as usual (BAU) vs. terminal	1A1	no	BAU - one shift; 2+2 months off-shift at summer	
	1A2	no	BAU - 1 to 2 shifts; 2+2 months off-shift at summer	
	1B	yes	Suppliers' chip trucks used for terminal transports	
	1C	yes	Separate shuttle truck for terminal transports	
2: Terminal location	2B1	yes	terminal 5 km from CHP-plant, Suppliers' trucks	1B
	2B2	yes	terminal 10 km from CHP-plant, Suppliers' trucks	
	2B3	yes	terminal 20 km from CHP-plant, Suppliers' trucks	
	2B4	yes	terminal 30 km from CHP-plant, Suppliers' trucks	
	2C1	yes	terminal 5 km from CHP-plant, Shuttle truck	1C
	2C2	yes	terminal 10 km from CHP-plant, Shuttle truck	
	2C3	yes	terminal 20 km from CHP-plant, Shuttle truck	
	2C4	yes	terminal 30 km from CHP-plant, Shuttle truck	
3: Dry matter loss (DML)	3C1	yes	Moisture and DML equal with BAU	
	3C2	yes	Moisture equal, DML 1 pp higher than BAU	1C
	3C3	yes	Moisture equal, DML 2 pp higher than BAU	
4: Moisture change	4C1	yes	Moisture 3 pp lower, DML 1 pp higher than BAU	
	4C2	yes	Moisture 3 pp higher, DML 1 pp higher than BAU	
	4C3	yes	Moisture 6 pp higher, DML 1 pp higher than BAU	
	4C4	yes	Moisture 6 pp higher, DML 2 pp higher than BAU	
	4C5	yes	Moisture 10 pp higher, DML 2 pp higher than BAU	

2.4 Efficient logistics for waterway transports of forest chips (Article IV)

2.4.1 Description of the case study

Barge transportation as a long distance transport method for forest chips was investigated as a substitutive method for truck transports. Logistic efficiency of waterway transports of forest chips was studied in Lake Saimaa waterways in Eastern Finland (Figure 7). The varying demand for forest chips in three separate biopower plants on the Saimaa lakeside near the cities of Varkaus, Mikkeli, and Savonlinna was addressed in several barge transportation scenarios. Scenario comparisons were analysed by discrete-event simulation with Witness simulation software.

2.4.2 Material for the study

The waterways and the distances of the waterways used in simulations were conducted from the Finnish Transport Agency. Research data for the simulations were collected by the demonstrations conducted in the project called Inland Waterway Transport of Forest Fuels (2006-2008). A few options were tested in demonstrations of transporting forest chips and small trees via inland waterways. During the demonstrations, time studies for the waterway supply chain including the phases of loading and unloading of forest chips were performed (Karttunen et al. 2012). Information on the waterway transport fleet was collected from watercraft manufacturers and from shipping contractors operating in the Lake Saimaa region. Corresponding information for fuel terminal operations at harbours was collected by interviews and from the literature.
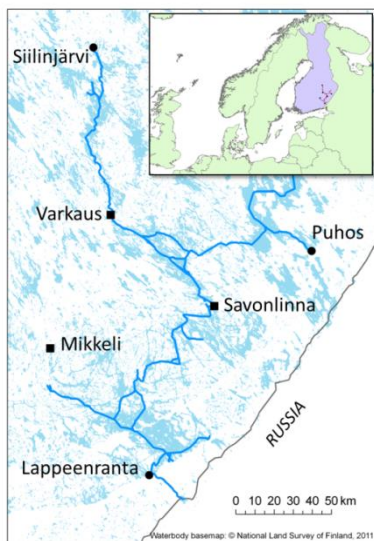
Figure 7. Waterways of the Lake Saimaa region. Loading harbours for forest chips presented as dots and biopower plants receiving forest chips transported by waterways presented as squares.

2.4.3 Modelling the system environment of the case

The simulation environment consisted of shipping routes from fuel terminals at harbours to end-use facilities next to cities, and vice versa, at the Lake Saimaa waters (Figure 7). Furthermore, the model included both the fleet of barges and powered vessels and the fleet of harbours' loading and unloading machines in the system environment. The transported material was forest chips having an item entity of one green ton. Transportation logistics and interactions before the fuel terminal in the loading phase and after the unloading phase were excluded from the simulation environment.

Three end-use facilities were chosen for the study located in the cities of Varkaus, Mikkeli, and Savonlinna. Three fuel terminals were strategically chosen to meet the fuel demand for the waterway-based supply system from the surrounding areas with good biomass reserves. 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).

In the model, forest fuel transport via waterways followed the consumption of end-use facilities; the distribution of fuel was Savonlinna 10%, Mikkeli 30% and Varkaus 60%. In the simulation, vessels transported forest chips one way only, without return hauling other material, such as roundwood.

Small and large-sized tugboats were used in the simulation scenarios. In addition, two types and three sizes of barges were used in the simulation with the mean pay load varying from 500 tons to 1,800 tons. The frame volume of the barge was the limiting factor, not the pay load in mass. The barges and their loading capacities are described in more detail in Karttunen et al. (2012). The speeds of the shipping units changed in function of shipping route characteristics, vessel and barge type, as well as total barge weight. The speed function was formulated from the data collected from the demonstrations of forest chip waterway transportation.

Two methods were used for loading and unloading operations at fuel terminals. At the biggest inland harbours, efficient long-boomed material handling machines were used. An alternative method involved a wheeled loader and a belt conveyor for loose materials. The latter method was not dependent on the work shifts of the harbour system, thus the machines could be operated by the vessels' crew during harbours' off-shift time.

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. The small tugboat had a two man crew, and the big tugboat five. In harbour operations, the crew onshore at harbours worked in shifts from 7am to 11pm on weekdays (off-shift at weekends).

2.4.4 Study scenarios

Two main scenarios, with respect to the size of the vessel in use, were set up in the simulation study. The main scenarios were divided into three sub-scenario lines: i) load size, ii) transport barge logistics, and iii) harbour logistics.

The scenario line of "load size" contained three load size alternatives for each vessel. The sub-scenario 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

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

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

With the use of stochasticity in the model, the results of each experiment replication were different. The results of each experiment were announced as in average of five replications. The randomized occurrences in the model were the speed correction of the vessel–barge combination, loading and unloading events, and determination of the load size of the barge for each load.

3. RESULTS

3.1 Re-engineering the fuel reception at the CHP-power plant (Article I)

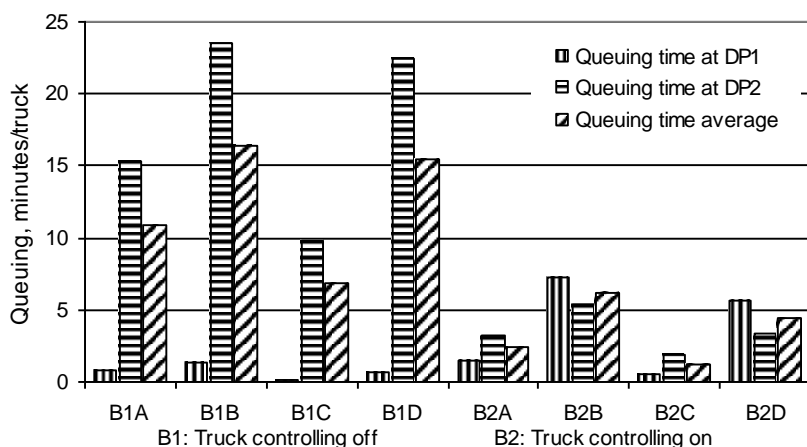### 3.1.1 Truck control at the receiving station

Acceleration of the hopper's fuel flow at DB1 had only a minor effect on queuing times and practically no change on the use of delivery bays was detected (Figure 8). When the main fuel supplier's RU trucks were directed to the shorter queue i.e. having the truck controlling system on, the queuing times decreased considerably (experiments A2A-A2C). The fuel flow speed of 110m³/hour at DB1 was not fast enough to enable shorter queuing times, when the truck controlling was on. In this situation, many trucks had to wait for hopper 1 to be empty, before they could unload. While comparing the scenarios of A1A and A2C, both the directing of the RU trucks to the shortest queue and the increment of fuel flow speed of DB1's hopper increased the utilization rate of DB1 from 14.9% to 25.3%. Compared to the base scenario (A1A), increasing the speed of fuel flow of hopper 1 from 110m³/h to 200m³/h and the use of truck control diminished average truck queuing time from 19.9 minutes to 5.8 minutes.

3.1.2 The effect of scheduling the truck arrivals

In experiments B1A-B1D, the queuing varied significantly (Figure 9). Time-schedule option 1, where two trucks were set to arrive every hour, decreased the average queuing time by 45% compared to the basic situation. Concerning queuing, the best alternative among B scenarios was B2C, where the trucks were set to arrive uniformly with truck controlling at the plant and with time-schedule 1. On the other hand, in the experiments B2A-B2D queuing times were very short and also the degree of utilization of DB1 almost doubled compared to experiments B1A-B1D. In the experiments of scenario C with the high fuel use at the plant, time-scheduling of truck arrivals had a drastic impact on queuing. Compared to truck arrivals received from practice (scenario C1A), average queuing time dropped down from 18.5 min to 2.5 min if time-scheduling option 3 was in use (scenario C1E).
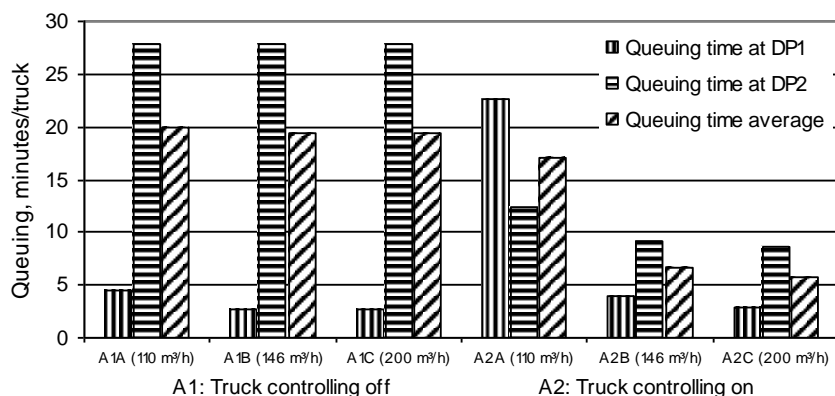
Figure 8. Average queuing times of fuel trucks at the receiving station and its delivery bay in simulation scenario A (Increasing the use of DB1). Values in parentheses are DB1 hopper's fuel flow speeds.

Figure 9. Average queuing times of fuel trucks at the receiving station and its delivery bays, when scenario B (time-scheduling of arriving trucks) was used in simulations.

3.1.3 Improved fuel flow in plant's delivery bay 1

When the use of fuel was high in the power plant, more trucks were queuing at the receiving station even if truck controlling was applied (Figure 10). Increase of the fuel flow at DB1's hopper from 146m³/h to 200m³/h would shorten the queuing remarkably. An additional increase to 300m³/h did not greatly affect queuing times. At peak truck arrivals (72 trucks/day), the current maximum fuel flow speed (146m³/h) with truck controlling at the station resulted in an average queuing time of 65.5 minutes per truck. Increasing the hopper's fuel flow speed to 200m³/h diminished queuing time to 19.5 minutes/truck.

Figure 10. Average queuing times of fuel trucks at the receiving station and its delivery bays, when scenario C with 57 and 72 truck arrivals per day was used in simulations. Values in parentheses are DB1 hopper's fuel flow speeds.
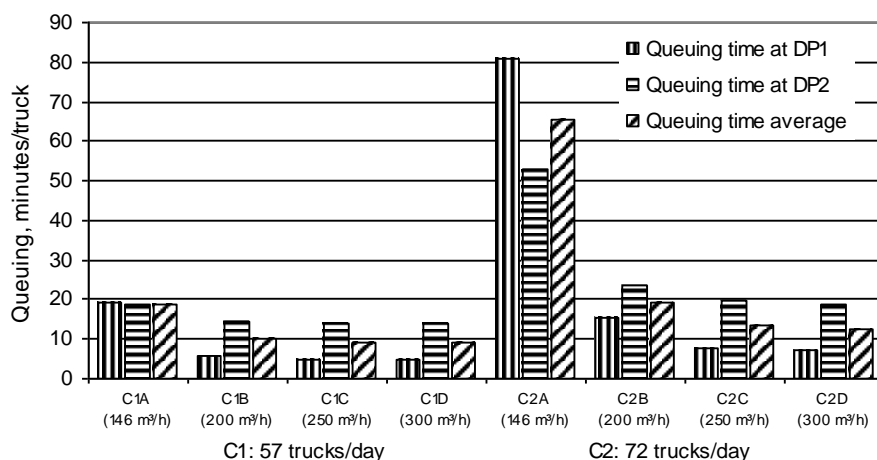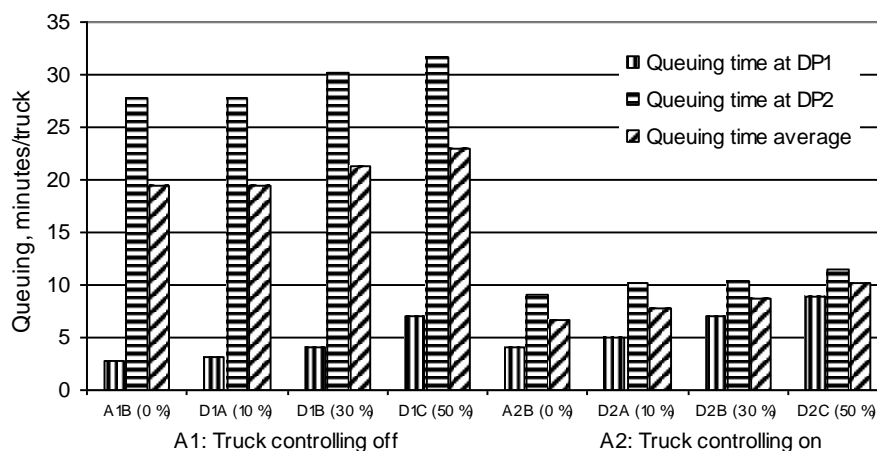

Figure 11. Average queuing times of fuel trucks at the receiving station and its delivery bays, when scenario D (increased use of forest chips) was used in simulations. Values in parentheses are the proportions of forest chips of total fuel use.

3.1.4 Increased use of forest chips

The transported volume increases, if peat is replaced by forest chips. Replacing 10 % of the peat with forest chips increases the transport volume and truck arrivals by 1.3 %. However, in the simulations the change in queuing time and degree of utilization of both delivery bays compared to the current situation was insignificant (figure 11). If 50 % of the fuel is forest chips, fuel transportation increases by 6.3 % and queuing times increase by 3.5 minutes per truck compared to the base situation. Implementing truck controls at the fuel receiving station has a greater effect on queuing than the increased use of forest chips.

3.2 Smart biomass storage allocation for enhanced forest chip supply (Article II)

3.2.1 Impact of the control of forest fuel storage parameters on fuel supply efficiency

The energy density of the logging residues varied over the year and differed notably among the scenarios (Figure 12). BAU and RAND showed the strongest variance and exceeded the PS scenarios in the Summer period, while the energy density of the material supplied during the Peak period was low.

The comparison of the annual energy content delivered to plant (Figure 13) proved that all PS scenarios outperformed the BAU approach. TdMcVol, Td and TdMc showed the largest increase in total energy output per annum (7%, 8% and 7%) (Figure 13). During the Peak period the benefit of the PS approach was evident. The increase amounted to 23%, 27% and 29%. Compared to BAU, these scenarios increased the energy output of the supply chain also during the Interim2 period (13%, 10% and 10%). The increase in Peak and Interim2 periods led to a decrease of supplied energy content in the other periods because then material from lower ranking storage locations had to be processed and delivered.
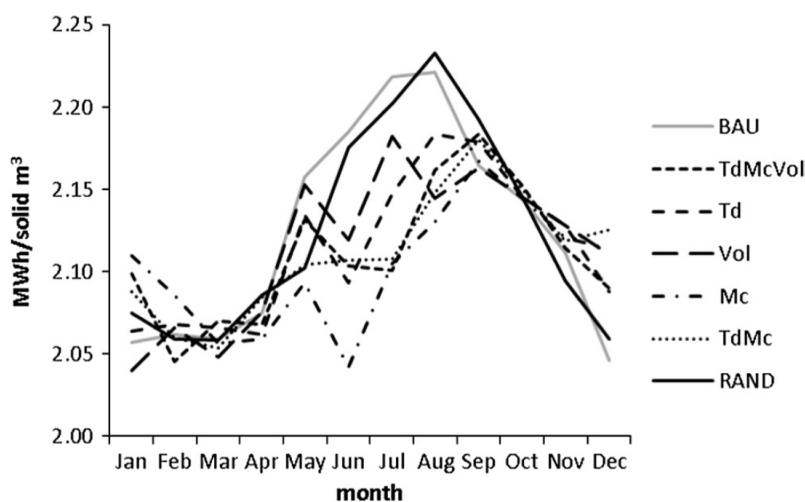
Figure 12. Monthly average energy density of the biomass delivered to the plant in different scenarios.
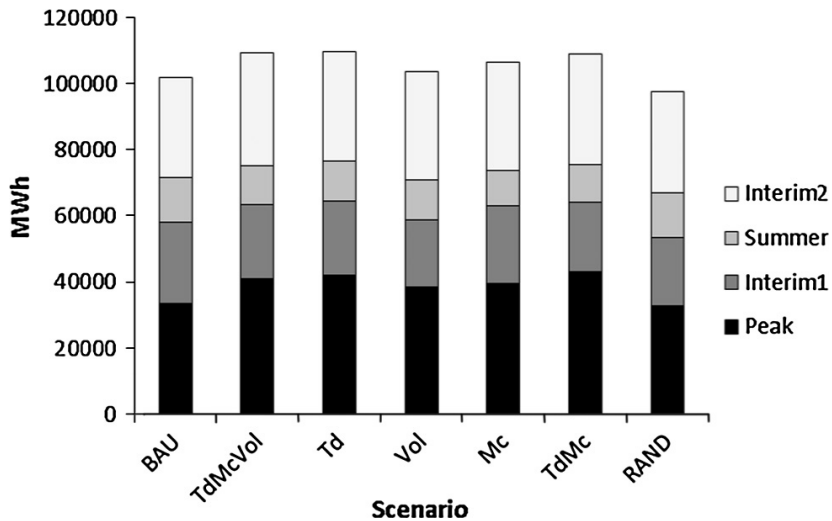
Figure 13. Deliveries to the plant per year and supply periods (Peak: January, February, December; Interim1: March to May; Summer: June to August; Interim2: September to November) for different scenarios. Abbreviations are used as described in Table 3.
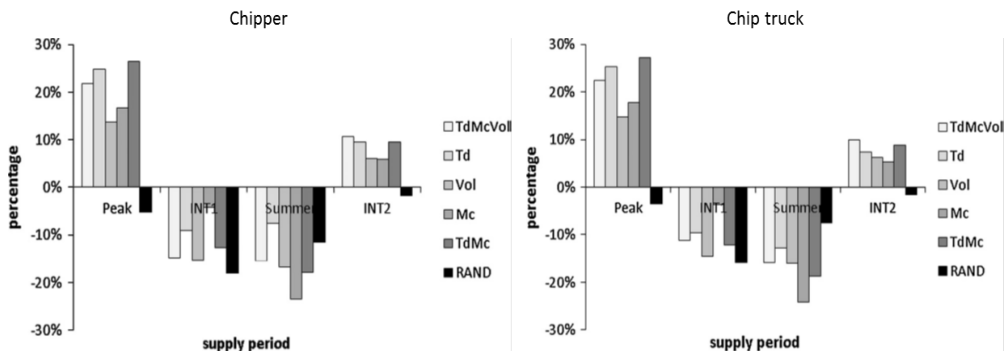
Figure 14. Productivity of the chipper and chip truck in MWh/MW H (machine work hour). The graphs shows the difference between business-as-usual and the individual precision supply scenarios in percent for the different supply periods (Peak: January, February, December; Interim1: March to May; Summer: June to August; Interim2: September to November). Abbreviations are used as described in Table 2.

In the investigated case, the PS approach led to slightly more machine work hours (MWH) compared to BAU due to the flexible shift arrangements, which was used in practice. Again, the PS scenarios improved the productivity during Peak and Interim2 period, while in Summer and Interim1 period productivity decreased due to low ranking clusters. With the precise allocation processes of PS scenarios, the productivities of the chipper and chip truck were clearly higher during Peak and Interim2 periods, whereas productivities dropped down from BAU during Summer and Interim2 (Figure 14).
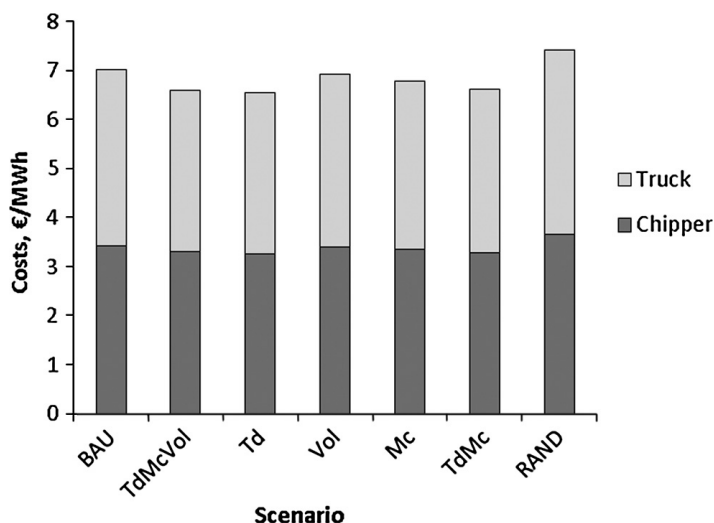
Figure 15. Supply costs per MWh. Abbreviations are used as described in Table 2.

The cost comparison demonstrated that all PS scenarios decreased the supply costs of the year compared to BAU (Figure 15). The Vol scenario lowered the costs only by 1%. However, the TdMc and the Td scenarios lowered the supply costs by 6% and 7%, respectively.

3.3 Efficient use of feed-in terminal as a part of forest chip supply (Article III)

3.3.1 The performance and supply costs of studied scenarios

While operating in one shift within the BAU-scenario, four supply operators with four chippers and 8 chip trucks in total were not enough to meet the power plant's annual demand (Figure 16). From total fuel demand, 19.3% was supplement fuel used in addition to the base supply of forest chips. The external work shift during the high season was required to meet the demand (scenario 1A2). Both terminal scenarios operated with one work shift, the forest chip supply was merely enough to satisfy the demand of the power plant; the use of supplement fuel was 6.3% and 3.4% from the total demand in terminal scenarios 1B and 1C, respectively. The share of fuel delivery via the terminal was 18.0% and 17.6% in scenarios 1B and 1C, respectively.
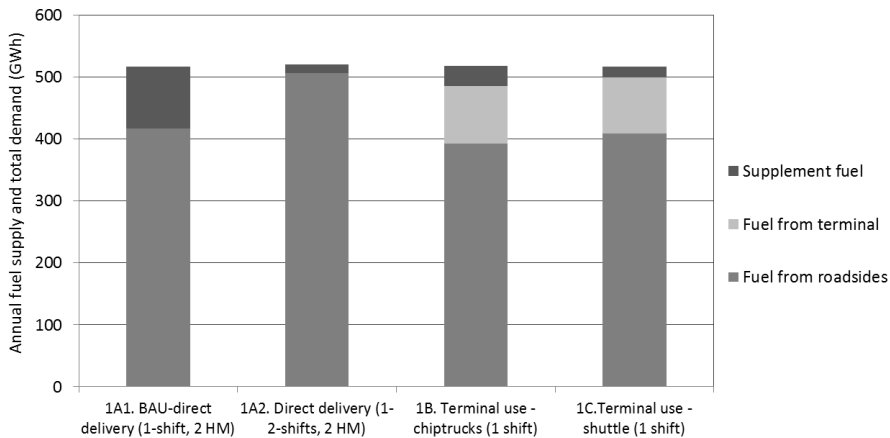
Figure 16. The annual supply of forest chips and the use of supplement fuel to meet the initial forest chip demand of the CHP plant in the four simulation scenarios. (HM = holiday month)
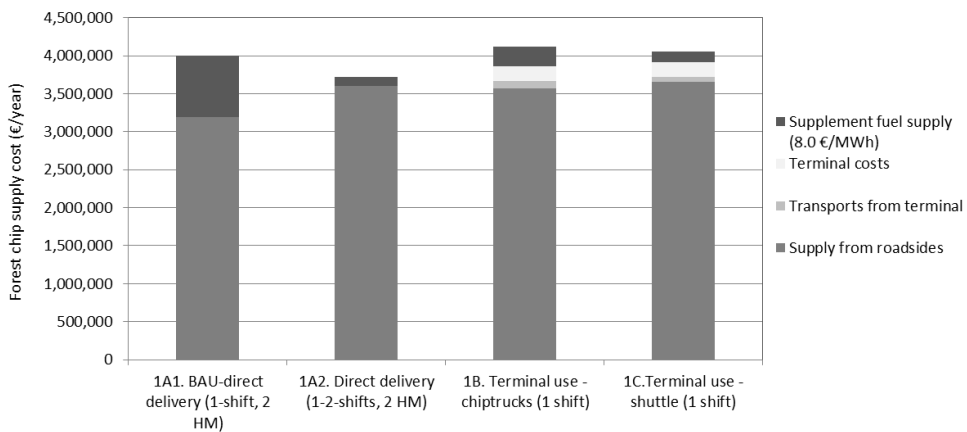
Figure 17. Annual fuel supply costs of the power plant in four simulation scenarios. Terminal costs include investment and operational costs of the terminal.

While comparing annual supply costs, the least costly scenario was 1A2, with an extra shift during the high season resulting in 7.1% lower supply costs compared to the BAU scenario (1A2) while an assumption of a EUR 8/MWh supplement fuel cost was used (Figure 17). From the terminal scenarios, the cheapest option with the lowest supply cost was 1C, with separate terminal shuttle use having a 1.4% higher annual supply cost than the BAU scenario 1A1. Respectively, terminal scenario 1B had a 3.1 % higher supply cost. The share of terminal costs of total supply costs was 4.7% and 4.8% in terminal scenarios 1B and 1C, respectively, whereas the separated costs of outbound terminal transports (terminal to power plant) were 2.3% and 1.5%, respectively.
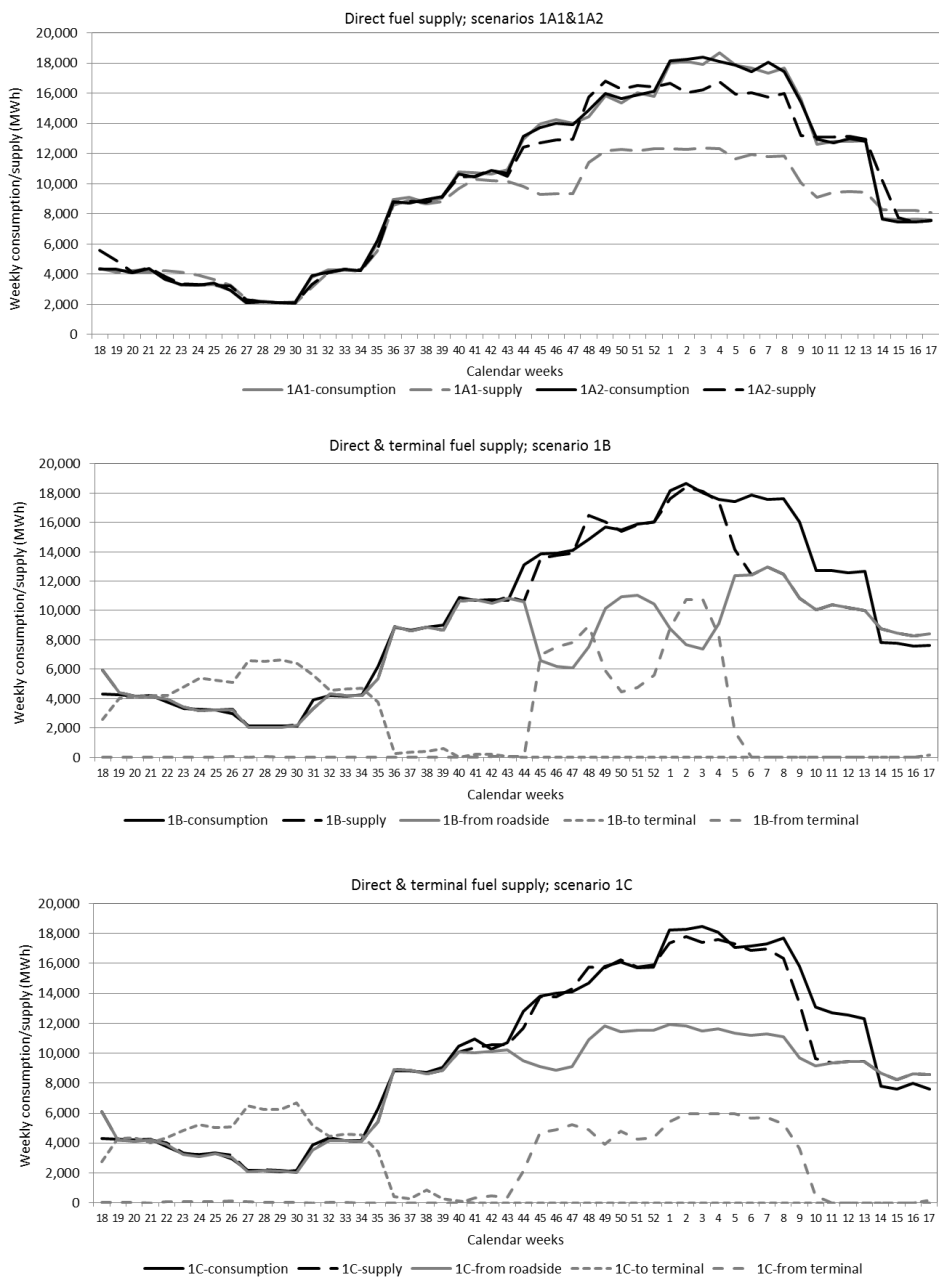
Figure 18. Weekly level statistics for the forest chip demand and transports during one year. The compared scenarios were 1A1, 1A2, 1B and 1C

3.3.2 Analysis of terminal use over the year

Only the scenario 1A2 was able to follow the power plant's fuel demand over the year, whereas the BAU scenario 1A1 could not meet the demand during the highest demand starting in January (Figure 18). In both terminal scenarios, 1B and 1C, all four fuel

suppliers were operating during the summer, being able both to fulfil the plant's fuel demand and to supply the fuel to the terminal (Figure 18). In total, the transported forest chip amount at the terminal was 92,950 MWh (45,876 solid-m³) and 90,978 MWh (45,146 solid-m³) in scenarios 1B and 1C, respectively.

3.3.3 The impact of distance, fuel quality, terminal investment and utilization of shuttle truck on supply costs

While analysing the effect of pre-defined factors of terminal-based fuel supply costs, the baseline was set to scenario 1C, where a separate shuttle truck was operating outbound terminal transports (Table 4). To keep supply costs competitive, it is crucial that the terminal is close enough to the power plant and there are other transport possibilities for the shuttle truck at other times than the chip transports from the terminal (Figure 19).

Moreover, the management of the quality of forest chips in terminal storage has a clear impact on total supply costs. The decrease of terminal investment cost by 30% resulted in a 0.9% decrease in the costs of terminal-based fuel supply.

Table 4. The terminal scenarios, in which outbound terminal transports were carried out by a shuttle truck, in comparison to scenario 1C.

Terminal scenario - option	Abbreviation	Definition
1C	Baseline	Terminal scenario with shuttle truck, 5 km distance from PP, terminal investment 1,372,500 €, other use for the shuttle 1,500 h, total shuttle use 2,433 h, DML 1 percent point higher than in RS storages, Average moist of forest chips approx. 43% in terminal
2C2	Dist. 5km->10km	Equal to 1C exept distance to PP 10 km
2C4	Dist. 5km->30km	Equal to 1C exept distance to PP 30 km
1C - lower investment cost	Invt -30%	Equal to 1C exept terminal investment cost 30% lower than in 1C
1C - higher investment cost	Invt +30%	Equal to 1C exept terminal investment cost 30% higher than in 1C
1C - Shuttle use 1,683 h	Other use 750h, 5km dist.	Equal to 1C exept other use of shuttle is decreased to 750 h
1C - Shuttle use 933 h	Other use 0h, 5km dist.	Equal to 1C exept other use of shuttle is decreased to 0 h
2C4 - Shuttle use 2,282 h	Other use 750h, 30km dist.	Equal to 1C exept distance to PP 30 km and other use of shuttle decreased to 750 h
2C4 - Shuttle use 1,532 h	Other use 0h, 30km dist.	Equal to 1C exept distance to PP 30 km and other use of shuttle decreased to 0 h
3C1	DML -1pp	Equal to 1C exept DML of forest chips 1 percent point lower
3C3	DML +1pp	Equal to 1C exept DML of forest chips 1 percent point higher
4C1	MC -3pp	Equal to 1C exept MC of forest chips 3 percent point lower
4C3	MC +6pp	Equal to 1C exept MC of forest chips 6 percent point higher
4C4	MC +6 pp & DML +1pp	Equal to 1C exept MC of forest chips 6 percent point and DML 1 percent point higher

	Dist. 5km ->10km	Dist. 5km ->30km	Invt -30%	Invt +30%	Other use 750h, 5km dist.	Other use 0h, 5km dist.	Other use 750h, 30km dist.	Other use 0h, 30km dist.	DML -1pp	DML +1pp	MC -3pp	MC +6pp	MC +6pp & DML +1pp
Cost impact in %	0,7	1,9	-0,9	0,9	0,3	1,5	2,3	3,1	-1,1	0,9	-0,4	0,5	1,7
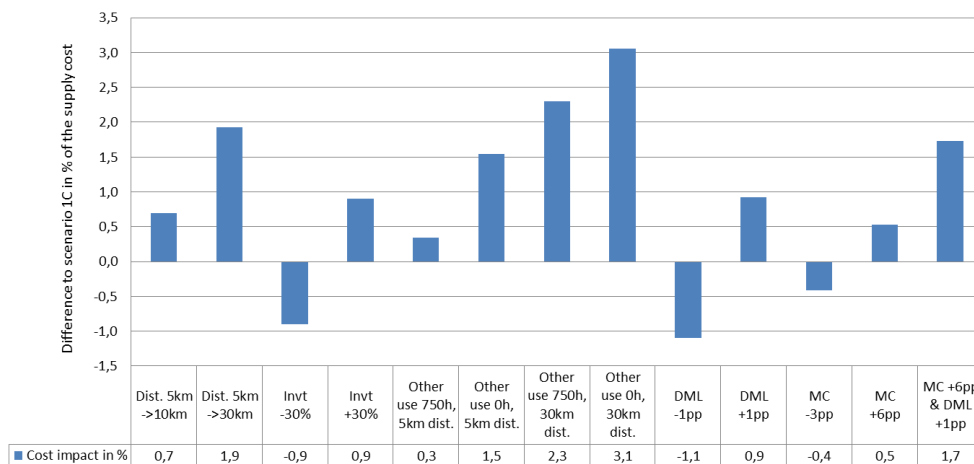
Figure 19. Differences in supply costs when comparing other terminal options to the terminal scenario 1C (see Table 4 for the definitions).

3.4 Efficient logistics for waterway transports of forest chips (Article IV)

3.4.1 Best logistics concept in waterway supply options

The most cost efficient waterway transport option was a small tugboat with 1,200 ton capacity barge and shift independency in harbour operations (Figure 20). A bigger vessel with larger transport capacity of forest chips resulted in higher costs, though with better productivity than that of the smaller one. In particular, the share of the idle time and therefore idle-time costs were relatively high compared to the smaller tugboat. Shift independency while operating in harbours was beneficial in terms of increasing productive time and decreasing supply costs; compared to harbour shift dependency, the decrease in costs was 15–17% in comparable supply options.
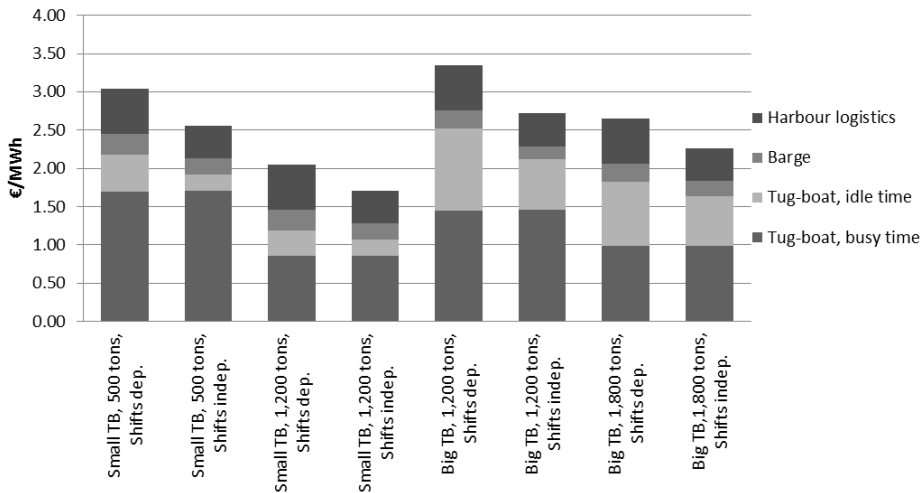
Figure 20. Waterway transport costs in simulation scenarios of a smaller and bigger tugboat with variation in barge size and harbour shift option. Costs correspond to 178.5km of waterway distance. (Shift dep. = Harbour shift dependent, Shift indep. = Harbour shift independent)
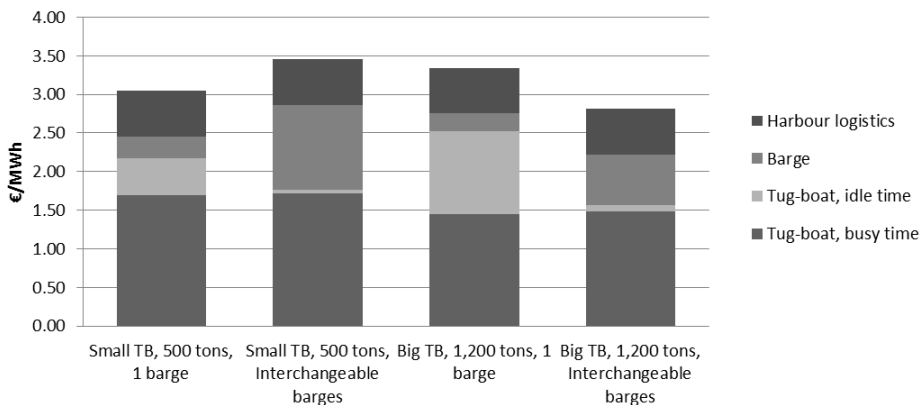
Figure 21. Waterway transport costs in simulation scenarios of a smaller and bigger tugboat with fixed and interchangeable barge options. In the presented scenarios, waterway supply of forest chips was dependent on harbours' working shifts. Costs correspond to 178.5km of waterway distance.

The interchangeable barge option was expected to be a feasible method in cases when loading and unloading was executed within harbours' working shifts. The impact of having interchangeable barges in waterway transport and the cost difference compared to fixed barge was dependent on the system of tugboat and barge (Figure 21). If a big tugboat and 1,200 tons barge system were in use, the interchangeable barge option was more cost effective than the fixed barge system (-16%). In the case of a smaller tugboat, the difference was in the opposite direction (+14%). The compared difference in waterway supply costs between fixed and interchangeable barge methods was the result of both on the transported amount of forest chips with barges and the share of idle time and its cost on waterway

transports. In interchangeable barge logistics, there is no need to wait for loading or unloading of barge. Filled or empty barges are always ready to be transported, thus decreasing idle time and the cost of vessels.

Depending on the scenario, waterway transport costs increased 50–130% when distance was increased from 100 km to 300 km (Figure 22). Small barge loads and interchangeable barge option were most sensitive for the increase of transport distance. The big tugboat with a 2,400 ton barge load resulted in the smallest impact on the increase of transport distance. Another benefit for bigger transport units was the capability to transport more forest chips during one waterway season (Figure 23). Especially in the scenario where interchangeable barge logistics were used, the annual performance was over 250,000 tons, which was 63% more than the scenario of second best annual performance with the same barge load (compared to the 1,200 ton barge with harbour shift independent).
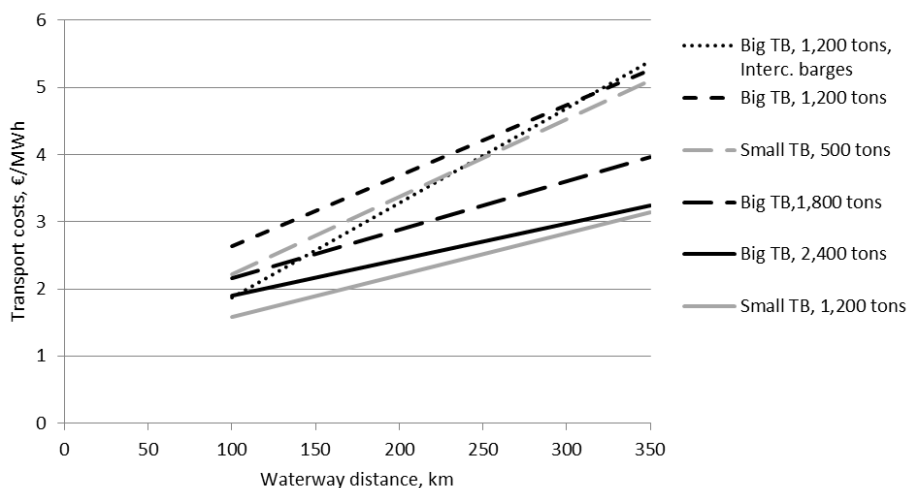
Figure 22. Impact of waterway transport distance on forest chip transport costs by waterways (costs include harbour operations; loading and unloading). All presented scenarios are harbour shift dependent in loading and unloading.
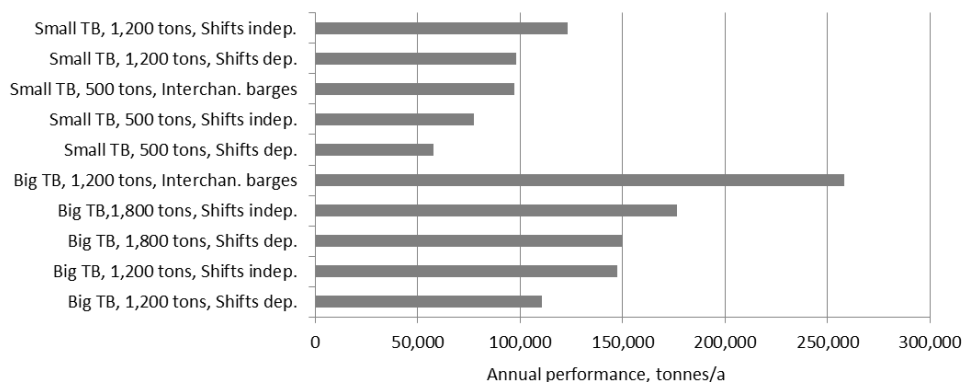
Figure 23. Annual transport performance with alternative scenarios for the small and big tugboat options. Scenarios of interchangeable barges are harbour shift dependent (Shift dep. = Harbour shift dependent, Shift indep. = Harbour shift independent).

3.4.2 Waterway supply vs. supply by roads

While comparing waterway supply and road transport supply of forest chips, road transport supply was more cost competitive up to 100–150km depending on the scenarios being compared (Figure 24). Supply by road is much more sensitive to transport distance; supply costs of forest chips increase 50% from 50km to 250km for the road transport method, whereas for the waterway transport method the cost increase was only 13% for the respective distances. In addition to road transport, the road transport supply chain cost included stumpage price (EUR 3.50/MWh) and roadside chipping (EUR 3.50/MWh), whereas waterway supply chain costs included stumpage price (EUR 3.50/MWh), roadside chipping (EUR 3.50/MWh), 30km truck transport to harbour (EUR 2.20/MWh) and piling and storing (EUR 0.30/MWh) in addition to waterway transport.
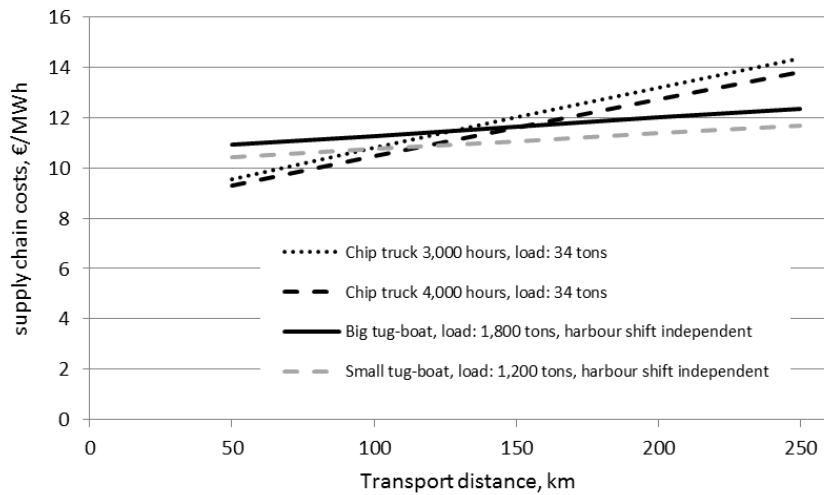
Figure 24. Cost comparison between road supply and best waterway supply chain options of forest chips.

4. DISCUSSION

4.1 Assessment of the research

Presented outcomes of the thesis provide new information on the cost factors and their impact levels on forest chip supply from roadside storage to end-use facility in the case specific approach. Moreover, the thesis suggests restructuring and updating of supply chain to improve the forest chip supply by enhancing cost-efficiency, capacity utilization of machinery and workforce, environmental efficiency and heat value management of forest chips. All study cases were based either on the real forest chip supply environments or demonstrated fuel supply by the case specific transport method. However, results can be generalized to some extent to other forest chip supply environments while having a similar structure of the supply chain as in cases studied in articles.

As suggested by the literature (e.g. Asikainen 1995, Asikainen 2001, Asikainen 2010, Karttunen et al. 2013, Belbo and Talbot 2014, Eriksson et al. 2014a, Eriksson et al. 2014b, Eliasson et al. 2017), DES was found to fit well in the modelling of selected forest chips supply chain including "hot chain" features and the specific characteristics of the supply environment with high heterogeneity of feedstock properties as an example. All articles (I–IV) incorporated machine or sub-system interactions with the tendency of increased idle time of machines and vehicles during the imbalance of system components. To use deterministic system analysis in articles II–IV would have resulted in simplifications in the system structures and would have led to overestimations in system productivity and underestimations of production costs. The study approach compiled to the study in article I required either simulation or Queuing theory.

Simulation studies have been conducted by modelling the prevailing supply system and working environment with the prevailing supply fleet technology. For example, in article I, data for model structuring was collected in 2000 and for article III in 2015. Moreover, supply costs of forest chips have been calculated using the latest cost factor values obtained at a time when studies were ongoing (II–IV). Scenario comparisons carried out by the same study parameters are still valid; however, technology development, changes in traffic legislation etc. have resulted in improved system performance in the supply of forest chips. For example, in October 2013 a new law for increasing GVW and heights of trucks was passed in Finland (Valtioneuvoston asetus… 2013). Moreover, special permits for 5 year periods granted by Trafi enable freight forwarders to operate with high capacity trucks (HCT) of up to 104 tons total mass on predetermined routes (Venäläinen & Korpilahti 2015). Therefore, especially in article IV, the comparison of long distance chip supply costs between barge transports by waterway and truck transports by road with 60 tons total mass has limited validity, with road transport being able to offer more cost-competitive results today.

Simulation models were designed to follow closely the real operations of a forest chip supply. For model building and simulation experimentation, follow up and monitoring data from the real-world and from the case environments were preferred. Most of the time, the consumption formulas of machines and operations used in simulation models were selected by the best suitability or availability related to the model purpose. However, some of the data was based on short time studies as it was in article IV. For example, productivity functions of material handling machines were compiled from such studies. Moreover, some parameters of sub-systems were acquired as estimates from the personnel operating them. However, this is a common practice in the data acquisition for the construction of

simulation models. The reliability and representativeness of the input data and models has to be taken into account in the interpretation of the final results.

System modelling in articles (I–IV) excluded phases and operations from the beginning of the supply chain of forest chips, such as the purchase, harvesting and forwarding of biomass. However, all studies were based on the forest chip supply approach, where chipping was made at the roadside. This approach segregates fuel extraction from forest site to roadside landing from the chipping and transport with a justified argument: a long storage time at the roadside is preferred and thus, hot chain linkages do not exist between harvesting and chipping. However, other supply cost factors can be added afterwards to costs presented in articles II and III to have a total supply cost. Moreover, the selected approach helped to focus each study better to the objectives. Some studies of forest chip supply conducted by DES have taken the whole supply chain into account (Asikainen 1995, Belbo and Talbot 2014, Eriksson et al. 2014b, Eliasson et al. 2017, Eriksson et al. 2017). Moreover, numerous static modelling of forest chip supply from the forest stand to end-use facility has been made (e.g. Laitila et al. 2010, Laitila & Väätäinen 2012, Laitila et al. 2017).

The required number of replications for each scenario was determined by pre-running simulation models in order to reach the desired confidence interval (CI) of decision variables. For example, in articles III and IV, in each scenario the share of CI of the supply cost was less than 1%, which confirmed that the differences between scenarios' decision variables were statistically significant. The results of each scenario simulation were mostly presented by the mean value of replications' results without presenting a standard deviation (SD) or a CI. However, presenting the CI-values of the decision variables together with the average values would have enabled the statistical interpretation of the comparisons between the scenario results. Typically, SD and CI are most often used in presenting the variation of replications and expressing the deviation wherein the forthcoming replication would appear with a given confidence level.

Except in article I, all studies included the fuel supply for one supply period, i.e. one year. To have a comprehensive work follow up of supply fleet operations over the year, work shift approach is essential to include in the model; this approach was used in articles II–IV. In practice, work shift set ups of operating personnel and opening hours of power plants, terminals and harbours have to be taken into account in planning and timing of efficient operations in the supply chain as a whole. For example in articles II and III, chipping and trucking were adjusted to work shifts of supply personnel with specific activities included to beginning and ending phases of work shifts. Recently, a few other studies related to the modelling and analyses of the supply chain of forest chips have included the work shift approach in the model (e.g. Eliasson et al. 2017, Eriksson et al. 2017).

Based on the results of studies I–IV, the alternatives to improve the holistic efficiency of the supply chain of forest chips has been discussed in more detail from the following perspectives, which were stated in the Introduction: 1) material arrival to fuel reception and timing aspects, 2) operational efficiency and monetary aspects, 3) fuel quality aspects and feedstock allocation, and 4) social and environmental aspects.

4.2 Material arrival to fuel reception and timing aspects

In big CHP plants, truck arrivals per day can rise up to 100 units during the high heating season (Väätäinen et al. 2002). An even higher number can be noticed for timber truck

arrivals to large biorefineries and pulp mills (Namidi 2015), not to mention truck arrivals at international ports and marine container terminals (Chen et al. 2013).

As noted in Article I, the scheduling of truck arrivals by truck appointment systems has been found to be very effective way to reduce queuing and waiting times in several other studies (Korpilahti 1987, Morais & Lord 2006, Huynh & Hutson 2005, Huynh & Walton 2008). However, truck scheduling is easier to generate for trucks which are operating with more fixed operation times, i.e. cycle times are more or less constant and thus more predictable. Respectively, forest chip transports from roadsides are difficult or impossible to schedule due to the large variation in load cycle times during operations. For example, truck transports from biomass terminals close to end-use facilities or large peat production areas allow better truck arrival control to end-use facilities. As a result, truck arrivals can be estimated much more precisely enabling more precise scheduling (Väätäinen et al. 2002). Scheduling becomes even more challenging while certain fuel types, such as peat and forest chips, have to arrive by turns to control the fuel quality and enable efficient combustion, as it has been the case in many CHP plants (Impola 2001, Hakkila 2004). To ensure operation efficiency and avoiding unnecessary idling of transport operators, truck scheduling should take into account starting and ending times of drivers' work shifts, shift changing times, changeover locations, compulsory rest periods and breaks and the number of weekly shifts for each truck and each driver (Goel 2012, Namidi 2015). However, during the highest fuel demand periods and morning stressed truck arrivals, scheduling of trucks is reasonable also for bigger CHP plants (Ranta et al. 2002).

Usually the size of the fleet, i.e. the number of trucks, is defined by the highest transport demand and its requirements for the fleet size. In some cases, the costs of fuel supply, including improvement costs in fuel reception, would be decreased by the shortened waiting times of trucks and increased work opportunities for truck operators. For example, Namidi (2015) found in his study that investing in a second truck dumper for the chip reception at a pulp mill would reduce truck waiting time penalties and transportation delay penalties by an average of 77% and 59%, respectively. By including the costs of a second dumper into account, the final result showed that the total transportation costs and penalties with two dumpers and 31 trucks was 31% better than the total transportation cost and penalty with one dumper and 36 trucks. In Namidi's (2015) study case, the number of trucks could be reduced by 14% from the initial stage operating in normal conditions operating with two dumpers instead of one. Therefore, introducing high capacity fuel reception with short lead-times of trucks could improve logistic efficiency not only in the plant's fuel reception but also in fuel transports (e.g. Ranta et al. 2002, Hakkila 2004, Laitila et al. 2010, Namidi 2015).

In facilities with power and heat generation, the capacity of fuel reception station can be clearly underutilized during low heating seasons. However, fuel reception facilities and equipment account only for a minor part of the total investment of the heat and power plant. According to Nojonen & Järvinen (1996), the share of fuel reception facility's total investment was estimated to be 5–15% of the total investment of heat and energy plants. Reconstructing and updating the current system of reception stations can often be more difficult and expensive to carry out compared to constructing a new one from scratch. However, as article I shows, notable improvement in fuel reception efficiency can be achieved with some moderate adjustments to the existing fuel receiving system. By directing rear-end unloading trucks to the delivery bay with the shortest queue and increasing the fuel flow at delivery bay 1 to the storage silo, the average waiting time of trucks dropped down from 20 min to 6 min during the winter season (Article I). The

approach balanced capacity utilization of delivery bays. In addition to efficient fuel reception, also fuel feeding devices and conveyors from unloading hoppers to combustion have to operate smoothly in order to ensure and secure the reliable fuel flow from fuel reception to combustion. This calls for a predetermined quality for the fuel, particularly for the forest chips (Hakkila 2004).

As in article I, in article III most of the queuing time at the end-use facility was accumulated during the first hours of the working shift of forest chip suppliers. That was partly due to the trucks, which were filled up at the very end of the previous work shift and in the beginning of the shift, during a small time window, arrived at the fuel reception of the power plant. In article III's simulation model, half of the suppliers' truck drivers started work shift one hour later than the other half to shorten the idling at the power plant. Correspondingly, Eliasson et al. (2017) noted that staggered shift scheduling of chip trucks with a one hour interval significantly decreased queuing time for the trucks on the landing compared to simultaneous shift scheduling. Adaptive shift scheduling of working personnel operating machines with different productivities in a production unit or with higher affinity for queuing tend to improve the productivity of a system and decrease idling times (e.g. Väätäinen et al. 2008, Väätäinen et al. 2010, Eliasson et al. 2017).

However, differences in work shift scheduling and restricted opening hours of sub-systems in a supply chain can cause inefficiency in the system. Article IV revealed the issue in barge transports of forest chips, where harbours' closing hours stopped the operation of vessel units with 24h/day working mode. The vessel unit stays idle until the next day if the vessel cannot be loaded or unloaded during opening hours. This quickly escalates transport costs as Spaven et al. (2006), Karttunen et al. (2008) and Enström (2016a) have also stated. In waterway transports, a separate loading/unloading option operated by vessel crew during off-shift time of harbour or interchangeable barges (Article IV) was offered as a solution for mismatched work shifts of sub-systems. Similar challenges in shift arrangements of trucks and reception times of the end-use facility can be recognized in fuel supplies to heat and energy generation especially during high heating seasons (Väätäinen et al. 2002) and in timber transports to end-use facilities (Väätäinen et al. 2016).

4.3 Operational efficiency and monetary aspects

In article II and III, the high share of chipper relocations (13–20%) and waiting of chip trucks to arrive (25–39%) resulted in a low share of chipping (35–42%) during the average working day. A high share of relocation time was due to the relocations between roadside storage locations and between parking place and roadside storage at the beginning and end of the work shift. Mainly because of relatively long distances between feedstock and CHP plant and high chipping efficiency, these were not favourable for the chipper and two chip truck system and caused a high share of waiting time for the chipper. To compare the share of comminution time on the operating time with mobile chippers, earlier studies (Spinelli & Wisser 2009, Holzleitner et al. 2013, Eliasson et al. 2012, Asikainen 1995, Eriksson et al. 2014a, Laitila et al. 2010 and Metsäalan… 2013) have presented higher rates for chipping by mobile chippers. Spinelli & Wisser (2009) found 73.8% chipping rate in the studied forest chip supply system, whereas Holzleitner et al. resulted 49% in their study in Austria. In conclusion, in the literature and articles II and III, the differences in rate levels of chipping and waiting times of mobile chippers are explained by the difference in operating environment, transport distances, performance levels of machines and the operation model

used in each of supply chain. Moreover, some of the aforementioned studies did not take the whole working cycle into account, thus neglecting the time needed for relocations.

The number of trucks serving one mobile chipper was not considered in articles II and III. In several simulation studies, the system of three trucks with one chipper has been the most cost-efficient in longer distances over 60–90 km in earlier studies (Asikainen 1995, Zamora-Cristales et al. 2013, Eriksson et al. 2014a). In practice, the average transport distance for energy wood during years of 2014–2016 has been 47 km in Finland (Tilastokeskus 2015, 2016 and 2017). Thus, most of the energy wood feedstock transported to end-use has been located within 60 km from the end-use-facilities. According to statistics, the average transport distance has increased from 40 km to 64 km from 2015 to 2016 (Tilastokeskus 2016 and 2017). In Article III, the average transport distance varied 61–64 km within scenarios. In practice, the supply area is usually large, for example 2–120 km, with feedstock located at various distances from the end-use facility, resulting more in the idling of chip trucks than the chipper at short distances and vice versa for long distances. In practice in the supply of forest chips, one chipper and two chip trucks is the most common set-up and easy to manage in Nordic conditions.

According to terminal-based studies, depending on the supplied material, supply environment, technology of the used supply fleet, the scale of supply and the cost parameters, terminal-based supply has resulted either in lower supply costs or higher than conventional direct supply. Earlier studies related to forest chip supply via terminals have been mainly focused on large scale terminals with stationary machinery (Karttunen et al. 2013, Virkkunen et al. 2016, Virkkunen & Raitila 2016). Virkkunen & Raitila (2016) compared to the direct forest chip supply to the terminal supply chain with five different options where the processing capacity of the feed-in terminal was 400 GWh per year. The cost-efficiency comparison was done for delimbed small diameter stem material either chipped at roadside storage locations or chipped at the terminal. All terminal options having electric grinders in use at terminal were more cost-competitive than direct supply chain (Virkkunen & Raitila 2016). The general conclusion was that terminal-based forest chip supply can be more cost-competitive than direct supply only if the terminal is large enough to pay off investments in the infrastructure and machines and if electricity powered chippers/grinders are used in the terminal. Furthermore, Virkkunen et al. (2016) found in their cost analysis study of a satellite terminal for forest fuels that the annually supplied wood fuel volume should be over 2.52 PJ to meet the break-event volume point of terminal machines corresponding to a minimum of 5 ha of terminal area.

A recent study into incorporating a terminal into the biomass supply for a biorefinery was executed by a mixed-integer programming model, which took into consideration biomass quality, seasonality and weather related supply restrictions (Gautam et al. 2017). The procurement cost of biomass was reduced 11–32% with terminal use compared to direct transport. The resulting cost savings of terminal scenarios were mainly due to the reduction of road maintenance costs and the improvement of fuel quality of terminal stored biomass. Contrary to article III, dry matter losses were not taken into account in calculations by Gautam et al. (2017). Laitila et al. (2017) found that the terminal-based supply of delimbed stem wood chips was slightly more expensive compared to direct supply from roadside storage locations. In the terminal scenario, inbound transports were executed as uncomminuted and chipping was carried out before transport to the end-use facility. It is worth noting that direct transport of delimbed stems and chipping at the end-use facility was EUR 1.20–3.20/MWh cheaper than other supply scenarios, when transporting stems with a 76 ton timber truck (Laitila et al. 2017).

As opposed to article III, road maintenance costs were taken into account in the Gautam et al. (2017) study, where they compared direct biomass transports to terminal aided biomass supply to the end-use facility. Gautam et al. (2017) estimated a road management cost factor for direct transports due to the fact that the supply chain is exposed to traffic on roads with trafficability problems. Particularly in heat and freeze-thaw cycles when temperature was fluctuating around zero in Celsius during winter and when demand was high, the direct supply was forced to procure biomass from the forest incurring road maintenance costs. Cost savings in total supply by reduction of road maintenance in terminal supply was over 10% compared to direct supply, wherein Gautam et al. (2017) assumed that 0.5km of the road needed to be upgraded for each cut block that required maintenance.

Longer distances from terminal to end-use facility increases costs of outbound terminal transports, whereas inbound terminal supply can become less expensive due to better location of the terminal related to the feedstock location and better balancing of a "hot chain" system. Article III took into account only one terminal, whose location with increased distance benefitted half of the chip suppliers and reduced the cost-efficiency for the other half. What if instead of one big terminal, two or even more smaller terminals would have been established in locations favourable for chip suppliers to supply forest chips to these terminals? Chip suppliers' own terminals with matched locations adjusted to their supply areas would improve the balance of the chip supply system conducted by mobile chipper and chip trucks and enhance machine utilization also during low demand for forest chips. On the other hand, machine utilization of terminal machinery in bigger terminals becomes higher than in smaller terminals thus decreasing terminal-based costs in total supply (Virkkunen et al. 2016, Virkkunen & Raitila 2016). As Ballou (2004) has stated, terminals as material storage locations can lead to lower transportation costs through the shipment of larger, more economical quantities. Today in Finland, outbound terminal transports could be carried out by trucks with higher payloads than the most used 64–68 tons chip trucks. For example, Laitila et al (2017) calculated supply costs with a 76 ton chip truck with up to 63 solid-m³ of payload operating from terminal to end-use facility. With a special permit from Trafi, a 100 ton HCT-chip truck-trailer unit is operating in Finland, thus allowing still higher transport efficiency potential in the terminal-based supply of forest chips (Metsäteho 2017).

Cost-efficient operation models for transporting forest chips and roundwood vessel-barge units via inland waterways have been studied in Saimaa and Vuoksi waterways in Finland (Asikainen 2001, Karttunen et al. 2008, Hiltunen 2010, Sorsa 2013). As in the results of article IV, the studies of Asikainen (2001), Hiltunen (2010) and Sorsa (2013) show that interchangeable barge logistics was more cost efficient than fixed barge logistics when comparing options in same barge size. For example, Sorsa (2013) concluded that interchangeable barge logistics with a separate pusher boat was most the cost-efficient option together with a self-propelled barge option. The benefit of a self-propelled barge to pusher boat–barge system was a 10–20% higher navigating speed and time saving while passing the narrow channels with short sluices. Respectively, interchangeable barge system was more productive than a fixed barge due to the availability of barges ready for transport at loading and unloading harbours. However in article IV, the most cost efficient options were vessel units with fixed barges, which operated independently regardless of on-shifts of harbours' material handling. Those options required separate "low cost" loading and unloading machinery that could be operated by the vessel's crew at any time of the day (Karttunen et al. 2008).

In article IV, each scenario had a big difference in annual performance during 8 months of operation. The difference was over four fold when comparing annual performance of the smaller tugboat-barge unit to bigger one. Therefore, for operating a full season with the option of highest production, the required amount of forest chips transported from roadsides to harbours with limited buffer size can eventually become a problem in long distance multimodal supply. As Spaven et al. (2006) have stated, increasing vessel size can bring greater economies of scale in shipping costs alone, but simultaneously it may increase other costs by peaking of road transport, storage and handling of material at each end of transit. In some cases, bigger vessels with fixed barges do not fit so well to the opening hours of ports, because of longer loading and unloading times (Spaven et al. 2006, Enström 2016a). Interchangeable barges can solve this problem and, moreover, utilize the load space of the barge as a buffer at the harbour. Moreover, interchangeable barge logistics could enable the unloading of some of the chip trucks directly to the barges, thus decreasing the need of buffer space at harbour and eliminating additional loading phases from the harbour buffer to barge (Spaven et al. 2006). One has to keep in mind that the return time for one vessel-barge unit takes often 2–4 days (Sorsa 2013) and if locations where to operate from/to are many, vessel-barge unit returns to the same harbour more seldom. Fewer transport locations and/or more vessel units increase the importance of logistics arrangements in harbours' inbound and outbound transports of forest chips as well as importance of harbour logistics itself.

4.4 Fuel quality aspects and feedstock allocation

In article III, the quality deterioration of forest biomass during storage was expected to be higher than if it was stored as in uncomminuted form. According to the literature, several factors are against storage of forest chips for longer periods. Andersson (2008) has reported that the chipping process releases soluble sugar from the wood causing a favourable environment for microbes together with heat, moisture and oxygen. Comminution by chipping produces chip particles with increased surface area increasing the speed of decay (Thörnqvist 1983). In heaps, the air movement is also more limited because of the smaller material preventing heat dissipation and causing heat accumulation, thus increasing degradation and dry matter losses (Andersson et al. 2002, Raitila et al. 2014). Moreover, heating increases a risk of spontaneous combustion (Jirjis 1995, Hakkila et al. 1998). In big heaps, the material is more compacted reducing the air flow thus resulting in poorer drying conditions, which further amplifies the abovementioned factors. Microbial activity can also make the wood fuel difficult to handle because of the high presence of allergenic spores with increased risk of health hazards (Jirjis 2005, Anheller 2009).

However, if terminal storing of forest chips are conducted, storing of chips should not be for long periods, chip material should not be too moist, chip particles should not be too small and chips should be free from green particles (Jirjis 2005, Raitila et al. 2014, Enström 2016b). Moreover, covering forest chip piles with a semi-permeable cloth or using a separate storage shelter can protect against remoistening and decreases dry matter losses compared to uncovered piles (Raitila et al. 2014, Anerud et al. 2016). On the other hand, it has been reported that covering the piles increases microbiological activity significantly in forest chip storage (Nurmi 1990, Jirjis 1995, Hofmann et al. 2017), causing dry matter losses.

Nevertheless, dry matter losses during storage are expected to turn out in both ways, both for uncomminuted and comminuted material of harvesting residues. According to

earlier studies of harvesting residue chip material, DML % per month has varied 0.75-3% (Thörnqvist 1983, Thörnqvist & Jirjis 1990, Anerud et al. 2016, Raitila & Sikanen 2016), while 0.5–3% DML has been reported for in piles of uncomminuted logging residues (Jirjis & Lehtikangas 1993, Nurmi 1999, Jirjis & Norden 2005, Pettersson & Nordfjell, 2007, Routa et al. 2015). Nonetheless, in article III the increased DML % of stored logging residue chips was taken into account to the terminal scenarios to observe the influence of DML rate on the supply costs. Despite the fact that DML per month has been somewhat similar in earlier studies as presented above for comminuted and uncomminuted material of logging residue, terminal scenarios in article III had 1–2 percentage points higher DML for terminal stored chips than for logging residues stored at roadsides. However, in the main scenario comparisons, moisture content was expected to stay the same as when it arrived to terminal.

On the contrary, Gautam et al. (2017) assumed opposite that the biomass delivered and stored in terminal would have a 4–11% lower moisture content after storing than direct supply had. With this assumption, the cost reduction was clear for terminal-based biomass supply compared to direct supply in terms of enhanced transport efficiency and better energy content of supplied material. In addition, if taking the possible pile covering costs at roadsides into account, the cost savings are also towards terminal-based supply. Pile coverage is not necessarily needed, if freshly established roadside storage locations are selected to be transported to terminal during or right after the best drying season. On the other hand, covering should be accomplished, if chipping of RS storage locations would be executed during the high heating season. However, in article III, some additional costs for terminal activities were not taken into account, such as covering of chip piles or other activities which would improve or maintain fuel quality. Without covering the heaps of forest chips, rewetting will occur according to the studies of Thörnqvist & Jirjis (1990) and Raitila et al (2014). Article III, included a sensitivity analysis of terminal scenario with 6 and 10 percent point (pp) higher moistures, in which a 6 pp increase of terminal stored chips had only a 0.5% increase in supply costs. Correspondingly, one pp increase in DML of terminal stored forest chips increased 1.1% of supply costs.

According to the results of article II, "Precision" feedstock allocation by utilizing more data from the feedstock properties improves the economy of forest chip supply and allows meeting better the demand of the end-use facility. The improvement in cost-efficiency was relatively big with even a 6–7% decrease in annual supply costs compared to the BAU scenario, while taking moisture content of fuel storage locations and transport distances into account in storage allocation. Correspondingly, the influence was more remarkable while considering only the supply periods. When preferring short distances and low moisture content of RS storage locations in feedstock allocation during the peak season, the productivity of supply system as delivered MWh was increased up to 29% compared to BAU. Respectively, the productivity was in opposite direction during low seasons (Int 1 and Summer); up to 25% less than in BAU.

Eriksson et al. (2017) made a similar conclusion of their simulation study proving the impact of moisture content and transport distance on delivering higher quality and more energy in winter than in summer. To conclude, according to article II and the study of Eriksson et al. (2017), fuel transports could be more efficient especially during the highest heating season by allocating roadside storage locations in terms of moisture and distance to plant, i.e. emphasizing low MC and short transport distance in high heating period, respectively. Furthermore, the procedure of season stressed RS storage allocation by distance enables more feasible work arrangements for the operators of supply fleet of forest

chips and moreover, follows better the fuel demand variation of energy and heat generation over the year. The presented procedure was in use also in article III. In addition, proper selection and sequencing of sites to be processed by the shortest distance improves the performance of forest biomass supply systems, as Väätäinen et al. (2008) has found. Shorter driving between sites of RS storage locations not only saves time and money in relocation of the fleet itself but ensures more time for efficient operation per work shift (Väätäinen et al. 2008).

4.5 Social and environmental aspects

Solutions to tackle seasonal variation of fuel demand in heat and energy generation have been somewhat limited in fuel supply. Traditionally, the fuel supply fleet and personnel have to adapt to variations in fuel demand. In practice, during the low demand of forest chips, part of the supply fleet is not operating at all and the fleet which is operating can have time to idle periods without fuel deliveries to the end-use facilities, as it was modelled in the study of article III. Generally, the low heating season with low machine utilization and temporary lay-offs of drivers causes problems for the business of forest chip supply entrepreneurs. Further on, this causes difficulties in driver engagement to work and recruitment of skilful drivers, which have been stated as some of the biggest problems in truck transportation of forest biomass (Nousiainen 2012, Taipalus 2013, Väätäinen et al. 2014). Supplemental operation during times of high over-capacity of fleet and personnel is highly recommended.

Balancing the seasonal fluctuation was stated as one of the most significant factors in developing the forest biomass transports (Väätäinen et al. 2014) and clearly the most significant factor in improving the efficiency of logging operations (Kaipainen 2017). As discovered in papers II and III, the potential to balance the operations during the year can be markedly improved by using alternative operation models instead of conventional direct forest chip supply model. In article II, more precise selection of roadside storages according to the distance to plant and the moisture of material could offer possibilities to even out the work time and to increase the chipper utilization during the year. On the other hand, it could decrease the demand of part time contractors operating in winter.

Alternatively, as resulted in article III, the combination of terminal based supply and more precise selection of road side storages by distance confirmed that supply operations from RS storages to plant and terminal can efficiently balance the operations year round. During the low heating seasons, most of the inbound terminal transports of forest biomass could be carried out from far distances to keep the capacity of supply fleet running, whereas during the high heating season, direct transports to end-use facility could be stressed to roadside storage locations with close distances. To fill the gap from the direct fuel supply and fuel demand, supplemental fuel is transported from terminals by big trucks with high payloads. With the following operations model which was exploited in the simulations of article III, terminal operations would also run through the year without causing higher fluctuations.

In addition, an approach of combined energy and industrial wood terminal could bring cost-efficiency and year-round working opportunities, once energy wood and industrial wood have terminal activities at different times (Venäläinen et al. 2017). Moreover, the capacity utilization of terminal area is much higher and stays more stable than using it for only one purpose (either for energy wood or industrial wood purposes).

In long distance transports, HCT options are justified not only in terms of productivity and economy, but also the environment and traffic safety (Blanquart et al. 2016). Transports by waterway, particularly inland waterways, are limited to areas where waterway routes exist. Respectively, railways are spread usually wider and offer big potential in long distance biomass transports by inlands. In the case-study of Ghazanfari (2008), while comparing CO_2-emissions in Finland between forest chip supply chains of direct transport by truck and terminal-based transports by truck, train or vessel-barge options, the least CO_2 emissions were produced by the waterway supply option with the vessel-barge unit. In comparison by CO_2/m³km-unit, vessel-barge supply had 16% and diesel-powered train 9% less than direct truck transport, whereas terminal-based supply by trucks had 15% more CO_2-emissions. Sorsa (2014) made a theoretical comparison of emissions in roundwood transports between vessel-barge, train and truck from Nurmes to Joutseno in Finland. Less CO_2 emissions had combinations of diesel-electric railway connections at 42% less than truck transport, whereas vessel-barge units had 25% less CO_2 emissions than truck transport. It is worth noting that in waterway transport, NO_x and SO_2 emissions were 2–fold and 10-fold higher than road transports by timber truck. Calculations were made with timber trucks of 60 tons total weight and vessel-barge units with old engine technology, thus with the new HCT trucks and new vessel technology CO_2 emissions would have been approximately one third smaller with both options.

4.6 Conclusions

With the results of the articles, the following main conclusions can be made to enhance the supply chain performance of forest chips from roadside storage locations to end-use facilities:

1) Rearrangements in fuel reception station's set-up and logistics of fuel trucks reception at the power plant as well as adaptive shift scheduling of trucks play an important role in the smooth and efficient transport of fuel from the feedstock to power plant. Simulation results suggested notable decrease in waiting times of fuel trucks at the power plant's fuel reception.

2) The study on forest chip supply from roadside storage locations highly encourages using storage information for smart material allocation to achieve higher energy output with lower supply costs especially during the highest fuel demand. The supply of forest fuel should focus on short distances and the driest material of storage locations during high heating season and vice versa during low seasons.

3) By introducing a feed-in terminal for forest chips supply, cost compensation for additional terminal driven costs can be gained through the higher annual use of a fuel supply fleet and more secured fuel supply to power plants by decreasing the need for supplement fuel, which can be more expensive at a time of highest fuel demand. Moreover, terminal aided forest chip supply facilitates smoother working throughout the year in chipping and transporting of forest chips, thus offering more stable working opportunities than a conventional direct supply of forest chips.

4) Inland waterway areas with existing waterway infrastructure and close connections to biomass resources and end-use facilities can offer a cost-competitive and supplemental method for long distance transports of forest chips. Reshaping the conventional fleet used for waterway transports and restructuring the logistics of waterway transports together with harbour operations can improve the cost-competitiveness of the transport method. Drawbacks are the limited waterway season of northern inland waterways such as the Saimaa waters and the need for high amount of storage and handling of material through the fuel supply chain.

4.7 Review and research notes for the future

In Finland, the forest chip consumption for heat and energy generation has slightly dropped after many years of increased consumption. To make forest chips a more competitive fuel, alternatives for improving the cost-efficiency in forest chips supply need to be researched effectively. Reasons for the latest drop and demand fluctuations in forest chips between the years have been based on continuous and short term changes in energy policies, regulations, prices of competing fuels, emission trading and lowered fuel demand for heat rather than on the availability of forest biomass. On the contrary, in Finland, technical availability of small sized stem wood and logging residues has been good and will even increase in the future due to increasing forest biomass resources. Forest industry has been investing new or boosting the production capacity of existing biorefineries and many investment plans are on the move.

According to expert opinions, today and in the near future, logging residues and small sized stem wood will be favoured for generating heat and energy from forest biomass. The Finnish Climate Change Panel released recently a report by experts on the impacts of forest utilization on climate change (Seppälä et al. 2017), where it was stated uniformly that replacing fossil fuels by forest biomass results positively on climate in the long term. Furthermore, benefits for the climate can be achieved in the short term, if forest biomass for heat and energy would focus on logging residues and small diameter stems instead of industrial sized stem wood and stump wood. Logging residues and small sized wood decompose and release CO_2 quicker than larger sized wood. Therefore, instead of leaving logging residues at the sites after final felling, they should be utilized for heat and energy purposes at a local level without causing any more CO_2 emissions than leaving them at the site to decompose. Thus, this also provides positive impacts on regional economy and employment.

One has to acknowledge that drastic changes in demand of forest chips between years cause difficulties for the business of fuel supply entrepreneurs. Expensive machinery and committed workforce requires decent utilization of machines and working opportunities throughout the year to keep the business running and profitable. As a consequence of heavy demand fluctuation of forest chips between years, increased uncertainty of entrepreneurs restrains willingness to invest in their fleets or even willingness to continue the business. Thus, it is important to search alternative business methods such as proactive business, networking and alternative operations models for profitable entrepreneurship in the supply of forest biomass to end-use facilities within a heavily fluctuating operational environment.

As highlighted earlier, the share of chipper's chipping production of the total time use is rather low in a forest chips supply system based on roadside comminution. To decrease the excessive time use for relocations, set-ups and waiting, storages for comminution should be bigger than they are currently at roadsides. Thus, dispersed terminals around the supply

area or bigger RS storages with material from several harvesting sites could offer an option to increase daily production of the supply unit of mobile chipper and chip trucks. If terminals and combined storages were located next to roads with decent trafficability, fuel deliveries to heat and power plants could be better secured and bigger chip trucks with high load capacity could be used. The following research questions for the future can be raised up: What is the impact on the supply chain performance and cost when the parameters of the roadside storages change in terms of storage size, fuel type, moisture level and location, for example? What is the influence of different sizes of trucks and productivities of mobile chippers on supply performance? How do different operations models affect the supply cost and performance?

One has to find alternative methods and solutions for forest chip deliveries especially during periods when roads are in poor condition. The initial principle of terminals is to store the timber and forest energy fractions in order to back up the supply of biomass to end-use facilities during seasons, when accessibility to roadside storage locations is limited. However, to utilize terminals efficiently as a part of forest biomass deliveries need to be studied further. When and where from biomass transports to terminals should be focused? What is the effect of road trafficability and bad road seasons on the fuel supply in scenarios of direct and terminal-supported supplies? What is the role of biomass terminals for the drying of fuel by introducing different methods for enhancing the drying such as covering the stored biomass or having larger terminal area? What are the size, location and number of terminals in different supply cases? How to organize terminal-based supply and terminal operations? What are the set-ups of transport and terminal fleet in terms of vehicle/machine sizes, transit volumes, operations models, measuring methods etc.?

In addition, terminals also offer other utilization possibilities than just buffering biomass assortments for bad road delivery seasons. Terminals can be a place for wood exchanges, node for HCT-transports, a place to accumulate low volume load assortments and a place for upgrading fuel quality. Currently, there is not enough knowledge to get adequate answers to the aforementioned concerns. The cost-efficiency of forest chip supply for heat and energy generation can be enhanced in several ways with the support of research and technology development.

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