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Improving performance and energy efficiency of biomass supply through machine alteration and organisational redesign

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Academic dissertation

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ABSTRACT

This thesis summarises the findings of four case studies focussing on the redesign of specific aspects of the forest chip supply chain, the use of alternative terminals for chip supply, the interdependencies of chipper and chip trucks and the performance of individual machines after machine alteration. The aim of the work was to analyse and improve the fuel economy and energy efficiency of the forest chip supply system by modifying the settings of CTL harvesters, investigating the performance of an innovative hybrid chipper, introducing alternative supply systems through the use of a feed-in terminal and an analysis of forest chip supply systems under selected operational and environmental conditions.

The analysis of the case studies involved individual machines and the entire forest chip supply system. Two study methods were used: work study and discrete event simulation (DES). Work study carried out to investigate the performance of individual machines and their alteration; the DES method was used for investigating the organisational redesign of the forest fuel supply system.

The study resulted in the following findings and conclusions: 1) extreme machine settings have a statistically significant impact on the fuel economy of CTL harvesting machines; 2) hybrid machine technology can improve the fuel consumption and energy efficiency of chipping operations in forest chip production; nevertheless the productivity of the analysed prototype was below that for compared traditional chippers; 3) as an alternative to the direct supply of forest chips, the effect of utilising terminal operations on the overall supply cost can be quantified; terminal use improves the annual use of the supply fleet and enhances fuel supply security to the plant thereby reducing the need for supplementary fuel and 4) applying different types of types of chipper and truck-trailer combinations, supply costs and efficiencies can be quantified and vehicles with increased carrying capacity can improve the cost competitiveness.

In the study an integrated approach taking physical, technological, enterprise and industrial levels of energy efficiency into account is proposed. Thereby state-of-the-art forest technology and current biomass supply ideally can be upgraded to achieve new, improved levels of performance and energy efficiency.

Keywords: forest biomass; biomass supply chain; work study; discrete-event simulation; chipper; chip truck

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Joensuu, May 2019
Robert Prinz

LIST OF ORIGINAL ARTICLES

This dissertation consists of a summary and the four articles listed below, which are referred to by the Roman numerals I-IV. All Articles I, II, III and IV are reprints of previously published articles with the kind permission of the publishers.

I Prinz R., Spinelli R., Magagnotti N., Routa J., Asikainen A. (2018). Modifying the settings of CTL timber harvesting machines to reduce fuel consumption and CO2 emissions. Journal of Cleaner Production 197: 208-217. https://doi.org/10.1016/j.jclepro.2018.06.210

II Prinz R., Laitila J., Eliasson L., Routa J., Järviö N., Asikainen A. (2018). Hybrid solutions as a measure to increase energy efficiency – study of a prototype of a hybrid technology chipper. International Journal of Forest Engineering, 29(3): 151-161. https://doi.org/10.1080/14942119.2018.1505350

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, GCB Bioenergy 9(11): 1657-1673. https://doi.org/10.1111/gcbb.12463

IV Prinz R., Väätäinen K., Laitila J., Sikanen L., Asikainen A. (2019). Analysis of energy efficiency of forest chip supply systems using discrete-event simulation. Applied Energy 235: 1369-1380. https://doi.org/10.1016/j.apenergy.2018.11.053

In **Study I:** Robert Prinz and Raffaele Spinelli completed the study design. The author, Raffaele Spinelli, Natascia Magagnotti and Antti Asikainen carried out the data collection. Robert Prinz, Raffaele Spinelli and Natascia Magagnotti had the responsibility for data analysis and interpretation of the results. The author took the main responsibility for writing the article with the help of all co-authors. In **Study II:** Juha Laitila, Lars Eliasson, Johanna Routa and the author completed the study design and carried out the data collection. Natasha Järviö performed the LIPASTO calculations. Juha Laitila, Lars Eliasson and the author had the responsibility for the data analysis and interpretation of the results. The author took the main responsibility for writing the article with the help of all co-authors. This article builds on -, and further expands part of the work carried out within the Infres project, report D4.6. In **Study III:** Robert Prinz, Kari Väätäinen and Lauri Sikanen completed the study design. Kari Väätäinen developed the simulation model, ran the simulations and analysed the simulation output data. The author observed the development of the simulation model and provided remarks throughout the process. The author and Kari Väätäinen wrote the first sketch of the article, and all co-authors contributed to the writing of the article. In **Study IV:** Robert Prinz took the main responsibility for planning the study, running the simulations, data analysis, interpretation of the results and writing the article. The author, Kari Väätäinen and Juha Laitila completed the study design. Kari Väätäinen made changes to the simulation model, Robert Prinz implemented changes to the simulation data output calculation part. The co-authors improved the article by commenting on the study setup, interpretation of results and the manuscript.

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GLOSSARY OF ABBREVIATIONS

CHP	combined heat and power
CO_2	carbon dioxide
CTL	cut-to-length
DBH	breast height diameter
DES	discrete-event simulation
EEI	energy efficiency indicator
E_0h	effective hour
ETS	electronic trailer steering
g	gram
GDP	gross domestic product
GHG	greenhouse gas
GPS	global positioning system
GWh	gigawatt hour
h	hour
HCT	high capacity transport
kg	kilogram
kN	kilonewton
km	kilometre
kW	kilowatt
kWh	kilowatt hour
l	litre
LCA	life cycle assessment
LP	linear programming
m	metre
mA	milliampere
mm	millimetre
m^2	square metre
m^3	cubic metre
MC	moisture content
MIP	mixed integer programming
MJ	megajoule
ms	millisecond
MWh	megawatt hour
Nm	newton metre
OBC	on-board computer
odt	oven-dry tonne
OR	operations research
p	probability value
R^2	coefficient of determination
rpm	rounds per minute
SD	standard deviation
t	tonne
Tg	teragram

1. INTRODUCTION

1.1 Background

Climate change is a serious global matter with multiple impacts and real concern for Europeans (European Commission 2018a). Global warming is an issue affecting current as well as following generations and it is caused by human activities during the time from pre-industrialisation until the present (IPCC 2018). Global warming, observed by the global mean surface temperature, is already at approximately 1.0°C above the pre-industrial level and it is likely to reach 1.5°C in the next decades given the current increasing rate of change (IPCC 2018). Anthropogenic emissions such as greenhouse gases (GHG) and aerosols are causing long-term warming effects and additional changes to the climate system (IPCC 2018). Fossil fuels are known for adding carbon to the carbon cycle thereby increasing global warming. The aim to reduce additional carbon emissions into the atmosphere requires several measures. How renewable energy solutions and low-carbon fuels, as well as efficiency improvements, contribute to such a development of reducing emissions are currently under discussion, e.g., in the Nordic region the amount of emissions has decreased despite lower prices for fossil fuels (NETP 2016). The Nordic region is currently aiming to achieve a near-zero energy system in 2050 to be supported by clean energy resources such as wind and hydropower. In this respect, wind power plays a major role with large growth expected in power generation technologies in Nordic carbon-neutral-scenarios, although bioenergy is anticipated to become the largest energy carrier in 2050 in the Nordic region (NETP 2016).

As a consequence of the global climate change and global warming, political decisions on several levels have addressed the issue and implemented measures. The Paris Agreement from 2015 was an important milestone against climate change by setting out a global action plan (European Commission 2016). The European Union has set key targets in their 2030 climate and energy framework: a reduction of GHG by at least 40% compared to 1990 levels (European Commission 2013), a share of renewable energy of at least 32% (European Commission 2018b) and an improvement in energy efficiency of at least 32.5% (European Commission 2018c). Also on the national government agendas, items such as energy efficiency or reducing greenhouse gas emissions and the use of fossil fuel to mitigate climate change can be found. In Finland, the National Energy and Climate Strategy for 2030 outlines actions to attain the Government Programme targets set in order to achieve an 80 to 95% reduction in greenhouse gas (GHG) emissions from the 1990 level by 2050 and to improve system-level energy efficiency (Ministry of Economic… 2017). Although Finland has not set a quantitative target for energy efficiency efforts under this strategy, voluntary agreements with industry and building codes with high energy performance standards are used in addition to sector-specific targets for transport (IEA 2018).

Currently there is political consensus on the increased use of biomass-based energy. This has been suggested by the Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2018). In Finland and Sweden the focus of the development of bioenergy from forest biomass has changed. The focus has shifted from energy security and reducing the dependency on fossil fuels of the 1970s towards drivers such as sustainability including climate change mitigation (Björheden 2017). Nevertheless, there are also other recommendations stating contrary arguments regarding the increased use of biomass for bioenergy (e.g. Schulze et al. 2012).

Forest biomass supply chains typically involve the sequence of operations. They involve the procurement of biomass from a source to an end-using facility where the processing or conversion takes place, which is analogous to the forest energy supply chain concept described by Röser (2012). Biomass is thereby brought from the forest site to a plant, e.g., a heating or combined heat and power (CHP) plant, with several handling steps along the way, which require a certain amount energy input. First, the felling and cutting of trees (harvesting) takes place at a forest site during the thinning or final cutting of forest stands. Next, the raw material is transported off-road (forwarding) to a nearby landing site; the material is stored until further handling commences in such roadside storages. Further material handling steps and their timing depend on the respective assortment and intended utilisation, but in the case of forest biomass production, the material is typically comminuted into forest chips. Chipping operations interact with transportation, whereby chips are usually directly blown from the chipper onto a truck-trailer unit. The trucks transport the material to an end-using facility where the conversion to heat and electricity takes place. CHP technology is considered as a powerful tool to reduce CO_2 emissions due to its high energy efficiency (Hakkila 2004).

A total of 72.4 million solid cubic metres of roundwood were removed from Finnish forests in 2017, of which 35.8 million m^3 were used for pulpwood, 27.5 million m^3 were removed as logs and 9.2 million m^3 were utilised as energy wood (Official Statistics of… 2018). In the same year, a total of 7.2 million solid cubic metres of forest chips were used for energy production (Official Statistics of… 2018). Wood fuels were the most important energy source in Finland in 2017, and heating and power plants were the main consumers of solid wood fuels (Official Statistics of… 2018). There was an increase in the combustion of industry by-products and wood residues with bark being the main by-product used, whereas the consumption of wood chips underwent a slight decrease compared to the previous year (Official Statistics of… 2018). The high consumption of solid wood fuels show the important role of heating and power plants and wood-based industries in general, however, the decline in the consumption of wood chips also indicated the importance of efficient biomass supply in order to reach the targets.

It is also crucial that the sourcing uses resource efficient supply chains. Jäppinen (2013) addressed the importance of the efficient use of resources in relation to climate-change mitigation and the reduction of GHG emissions derived from forest-biomass supply and utilisation. This is relevant especially with respect to the bioeconomy in general and the connected industry in particular. Furthermore, Anttila et al. (2018) addressed the important role of efficient logistical solutions in places of high demand, e.g., new large-scale plants which might have also a significant effect on the regional availability of forest chips. Similarly, Ko et al. (2019) mentioned the importance of efficient procurement systems as one of the main obstacles to the extension of the bioenergy industry because biomass energy sustainability is sensitive to the performance of each component in the overall process. Consequently, this also affects the research agenda, which was highlighted recently by Borz et al. (2017) who stated that studies in forest engineering should address resource efficiency in general and fuel efficiency in particular.

1.2 Forest chip supply chains and fuel quality

Wood based fuels are classified according to standards, such as EN ISO 17225-1:2014 on fuel specifications and classes of solid biofuels, and are also divided into energy from short rotation forestry and forest biomass (Röser et al. 2008). According to this classification, forest biomass can be considered primary residues, traditional firewood, secondary residues and tertiary residues. The focus of this thesis is on primary residues, which include forest residues such as logging residues from thinnings or final cuttings, small-diameter trees, as well as tree stumps. Secondary residues include wood-based industrial residues, for example sawdust, chips and shavings from the wood-industry, in addition to bark and black liquor. Tertiary residues include used wood residues, for instance, from construction.

In Finland, the raw materials used for forest chips derived from primary residues in 2017 consisted mainly of 4.0 million m^3 of material from small-sized trees, 2.3 million m^3 of logging residues, 0.5 million m^3 of tree stumps and 0.4 million m^3 of large-sized timber (Official Statistics of… 2018). These forest chips were mainly used in CHP facilities (4.6 million m^3) and heating plants (2.6 million m^3); in addition, 0.6 million m^3 of forest chips were used for heating in housing in 2017 (Official Statistics of… 2018).

Recent literature reviews have mapped the best practice examples and state-of-the-art supply chains or techniques in forest biomass supply. The main steps along the forest biomass supply chain include harvesting and forwarding, comminution and transportation (Ghaffariyan et al. 2017, Díaz-Yáñez et al. 2013, Wolfsmayr & Rauch 2014, Routa et al. 2013). Harvesting of industrial roundwood and energy wood can be done separately or as one operation (Figure 1). Decisions related to supply chains are typically divided into three main categories: strategic, tactical and operational planning. Strategic supply chain decisions in the forest fuel supply network focus on long-term decisions with a planning horizon of several years and include, for example, decisions on the overall design of the supply chain, facility locations, transportation mode or terminal locations (Rauch 2013). With a planning horizon of up to several months, tactical decisions focus on the medium-term, e.g., including the planning of transportation, material requirement, plant allocation and capacity, harvest areas and production; while operational planning focusses on short-term decisions from daily planning up to a few weeks and includes decisions on machine and site scheduling, for instance, as well as vehicle routing or transport decisions (Rauch 2013).

Figure 1. Mechanised harvesting of industrial roundwood and use of energy wood.

Díaz-Yáñez et al. (2013) have illustrated the main supply chains used in the procurement of wood chips as raw material to the plant in several European countries. They determined that the most typical chains using logging residues and industrial roundwood from final fellings, pre-commercial thinnings and industrial roundwood from thinnings, utilise harvesters for felling/cutting, forwarders for off-road transport and trucks for road transport. In Finland, the share of mechanised felling in 2017 was 99.98% using mainly cut-to-length (CTL) machines, which include harvesters and forwarders, with a number of machines in the range of 1,500 to 2,000 harvesters and forwarders (Strandström 2018a). Besides, there are also harwarders, which are a combination of these machines.

While new devices have been tested, excavators equipped with a specially designed harvesting head are generally used for roots and stump harvesting from final fellings (see Laitila et al. 2019). While the degree of mechanisation is high in the Nordic countries, particularly in Finland, manual operations are more common in other parts of Europe. Thus, other methods applied include motor-manual felling/cutting, as well as the use of small-scale equipment such as (forestry-fitted) tractors, cable-yarders and skidders (Díaz-Yáñez et al. 2013). According to the authors, comminution usually takes place at the roadside, and to some extent also at a terminal or plant. Chipping at the roadside has advantages such as improving the transport efficiency (Brunberg 2016). Chipped material is thereby directly blown from the chipper unit into a truck-trailer or container combination. This so called "hot" operation means that the processing is directly linked to the transport (Ranta 2002). The type of machine, the machine´s power, and the raw material have an effect on the productivity of comminuting machines (Bergström & Di Fulvio 2018). Additionally, different operational environments and the characteristics of the raw material have an effect on chipping productivity (Röser et al. 2012). In Finland, the share of roadside chipping out of all forest chip raw materials in 2017 was 54%, whereas the share of chipping at a terminal was 33% during 2016, while chipping at a plant accounted for a share of 12% in 2017 (Strandström 2018b). When looking at the main sources of forest chips, small diameter trees and logging residues, the importance of roadside chipping becomes even more obvious. For small-sized trees, the share of roadside chipping in 2017 was 48%, while for logging residues the share was 81% (Strandström 2018b).

For long-distance transportation, the largest share of forest chips are transported by road, while train transportation only becomes a cost-competitive alternative in Finland for long transportation distances of about 135- 165 km (Tahvanainen & Anttila 2011).

The role of terminals in the supply of forest fuel has been increasing in the Nordic countries, e.g. in Finland where an increasing importance was indicated in a study based on questionnaires by Kärhä (2011). In Sweden, Kons et al. (2014) presented the important role of terminals in Sweden where small terminals of less than two hectares handled more than 50% of the country´s total forest biomass output. In Finland, the share of chipping of small-sized trees at a terminal has grown from an average of approximately 20% during 2004-2016 to 41% in 2017, and for logging residues it reached 11% in 2017 (Strandström 2018b). This was despite the additional costs created through their establishment and operation (Virkkunen et al. 2016).

An important aspect of forest chip supply chains is the fuel quality, since it affects the efficiency of energy conversion at the end-using facilities. There are several factors affecting fuel quality depending on source of the biomass and the techniques applied for comminution, handling and storage, whereby quality is affected by properties such as the moisture content (MC), heating value, energy density, foliage content, ash content, specific emissions of CO_2 and particle size (Hakkila 2004). There has been a major focus on the control and modelling of moisture content as the most important single quality factor – with effects on the heating value, storage properties and fuel transport costs (Hakkila 2004). MC has a large effect on various stages of the supply chain and creates supply costs; especially transportation costs (Ghaffariyan et al. 2017). Conversely, the drying of wood can increase transportation productivity by up to 50% (Stampfer & Kanzian 2006). Kanzian et al. (2016) also highlighted the effect of the moisture content on supply costs and CO_2 emissions, whereby with a high MC the payload is the limiting factor in transportation.

Consequently, recent research efforts have been made towards weather-based moisture content modelling, e.g., Lindblad et al. (2018), who used weather data for estimating the moisture content of energy wood. Prediction models for estimating the moisture content of fuel wood stacks when drying outdoors during storage were validated for logging residues (Routa et al. 2016) and small diameter trees (Routa et al. 2015). In addition, dry matter losses and their related economic affects have been a focus of a recent study. Routa et al. (2018) stated that economic losses may reach 4 to 17% of the energy wood procurement costs, depending on storage time, raw material and dry matter loss rate. Acuna et al. (2012a) showed that both, the proportion and volume of biomass material delivered to a CHP plant are very sensitive to MC range limit specifications and the drying period. Laurén et al. (2018) recently presented a moisture and dry matter loss simulation and optimisation method to improve the financial performance of solid forest fuel supply, with the result that cost savings can be achieved by arranging the transportation sequence. The particle size of the chips has an effect on the performance of chippers, whereby an increased chip target length increases chipper productivity and reduces fuel consumption (Eliasson et al. 2015).

1.3 Machine development and legislative changes

Efficiency has increased through mechanisation (Berg and Karjalainen 2003). With equipment able to increase productivity and reduce costs as well as fuel consumption (Spinelli et al. 2014a), the demand for forestry equipment is increasing on a global scale (Freedonia, 2015).

Concerning the technology used in biomass supply chains, the rapid development of technology used in large-scale forest operations has been seen (Nordfjell et al. 2010). Junginger (2005) presented a method using the experience curve approach describing the development of technologies and learning mechanisms behind cost reductions. Several specific innovative technological developments or trends have been also presented in the recent literature, e.g., autonomous vehicles by Hellström et al. (2009), the integration of informatics with harvesting technology and sensing technology by Vanclay (2011), robotic devices in forestry by Parker et al. (2016), or remote controlled and autonomous machinery by Visser (2018). In their review of technological innovations, Lindroos et al. (2017) focussed on the main patterns of technological change in mechanised timber harvesting and the authors highlighted the continuous role of technological adaptation to local needs depending on complex and variable conditions. Nevertheless, the innovation potential is considered to be smaller on an operational level compared to that on the tactical or strategic level (Rauch 2013).

Because mechanised forestry equipment has increased productivity, this requires more power, which is also reflected in the fuel consumption. However, machine development has continued over the past few years also towards improvements in efficiency. The rationalisation of small-diameter energy wood supply chains to improve efficiency was studied by Petty (2014). Erber & Kühmaier (2017) analysed research trends over ten years (until 2017) in fuelwood harvesting and showed a shift towards the improvement of efficiency of the machines used. Regardless of the final product, such as logs, pulpwood or energy wood, key performance indicators in forest harvesting operations include energy savings, the reduction of greenhouse gas (GHG) emissions and machine efficiency. Forest operations account for the majority of emissions throughout the wood value chain, even though the fossil fuel energy consumption in forest bioenergy supply chains varies between 2% and 3% of the energy in the delivered forest biomass (Wihersaari 2005, Routa et al. 2011). The total emissions from forest operations on a global level are roughly estimated to range from 18 to 44 Tg of carbon dioxide per year (Marchi et al. 2018).

Within mechanised wood harvesting systems, fuel consumption is the main energy input and may account for 82% of the total (Klvac et al. 2003). Fuel consumption of CTL harvesters represents 38% of the total fuel used in the technological cycle, which is higher than that consumed during forwarding (35%) and transportation (27%) (Lijewski et al. 2017). Additionally, the strong influence of the road transport distance on the primary energy input in forest energy supply chains was highlighted through scenario analyses by Lindholm et al. (2010). The authors used the balance of energy to evaluate the energy efficiency of forest energy production systems. Furthermore, throughout the forest energy supply chains the comminution phase is another key element wherein fuel costs represent approximately a third of the total comminution costs (Laitila et al. 2015). Systems with low GHG emissions, consideration of energy effectiveness and chipping sustainability are key areas for development mentioned by Prada et al. (2015). Eriksson et al. (2013) stated that the use of efficient power sources and reduction of the power required during idling would improve the energy efficiency of comminution.

Hybrid systems are a good example of machine developments which offer an alternative to purely electric or diesel operations. Hybrid systems are systems that can use more than one power source, although typically only a single primary power source exists (Einola 2013). Immonen (2013) stated that through electric hybridisation, the energy efficiency of diesel-driven working machines can be improved, since for most of the working time diesel engines operate at poor efficiency. Hybrid systems, instead, are capable of storing excess energy generated by the diesel engine during periods of low loading for use during peak loading times (Sun et al. 2010, Einola 2013, Eriksson et al. 2013, Di Fulvio et al. 2015). Additionally, with the right combination of parameters and machine setup, the operational efficiency of the entire supply chain can increase (Röser 2012). Thus, the selection and dimensioning of the hybrid system is crucial as it has a significant impact on energy consumption (Immonen 2013). Hybrid technology was taken into account in various types of machine technology development, for example, a hybrid-electric harvester was developed (Johnsen 2017).

Motivated by a reduction of GHG emissions and to achieve cost reductions, legislative changes in dimension and weight limitations for trucks in 2013 and thereafter have been implemented in Finland. These changes have affected the transport units used in the wood fuel supply chain (Karttunen et al. 2013, Korpilahti 2015, Road Traffic Act 2013). Maximum dimensions and weight limits define the permissible payloads of trucks, and the changes in legislation allow higher gross weights and higher vehicles, from previously 4.2m to now 4.4m in new legislation (Road Traffic Act 2013), thereby increasing the load space. The legislation allows truck-trailer physical dimensions with a total vehicle length of 25.25 m, a width of 2.55 m and a height up to 4.4 m. For semitrailers, the maximum total vehicle length is 16.5m (Road Traffic Act 2013). For truck-trailer combinations above 44 tonnes, a prerequisite is an engine power for the truck of at least 5 kilowatt per tonne of the total weight of the truck-trailer combination; also the distance between the axles is specified in the legislation (Road Traffic Act 2013).

Transportation processes have the potential to become more efficient when truck configurations are adapted to operational and legal requirements and by taking MC management into account (Kühmaier & Erber 2018). Consequently, the development of machinery for timber and wood fuel transportation can be seen through a wider available range of trucks and trailers as well as their combinations, with varying load capacities and specifications (Laitila et al. 2016). A common unit in the forest industry is the 60-tonne truck-trailer combination with a three-axle truck unit hauling a four-axle trailer unit. This truck option is proven under current road conditions. In addition to the 60-tonne truck-trailer combination, the new regulations allow eight-axle 68-tonne and nine-axle 76-tonne truck-trailer units. The 68-tonne and 76-tonne truck-trailers, however, require twin tyres for at least 65% of the trailer axle's weights, without these the maximum weight limits are lower at 64 and 69 tonnes, respectively (Road Traffic Act 2013). These truck-trailers are available and are also used for timber transportation. In temporary limited and defined cases up to 104-tonne heavy units can also operate. Similarly, high capacity 74 tonne and 90 tonne (HCT) trucks for timber transportation have also been demonstrated in Sweden (Fogdestam and Löfroth 2015).

In forest fuel supply, larger truck alternatives, such as the 69-tonne truck-trailer unit or the 76-tonne truck-trailer option, are mainly used when transporting forest industry by-products such as sawdust, sawmill wood chips or bark. The truck alternatives are limited for forest woodchip transportation operations from roadside landings to end-use facilities under typical Finnish supply conditions. While larger truck alternatives have advantages in terms of their load capacities, high-capacity trucks are less flexible on small, narrow forest roads typically used during forest chip supply operations. Two main alternatives to this unit are available: semitrailers and a 69-tonne unit with an electronic trailer steering (ETS) system with a steerable axle at the rear end of the trailer. While semitrailers are a very common type of truck with a total permissible weight of 48 (five axles), or 52 tonnes (at least six axles), a 69-tonne unit with an electronic trailer steering (ETS) system offers a high load capacity, while still being capable of operating in typical forest supply conditions due to its technical specifications.

Another development trend nowadays is the ability of forest machines to collect large amounts of data during operations (Olivera & Visser 2016). This development offers new opportunities to utilise this data for performance improvements, for example, through data mining, or the development of methods and models, or for use in machine optimisation similar to that developed in the manufacturing sector (Liang et al. 2018).

1.4 Energy efficiency

In general, "energy efficiency refers to the amount of output that can be produced with a given input of energy" (EPRS 2015). The EU Energy Efficiency Directive uses the broader definition of: "'energy efficiency' means the ratio of output of performance, service, goods or energy, to input of energy" (EPRS 2015).

Patterson (1996) addressed the problematic of possible energy efficiency definitions and stated "energy efficiency refers to using less energy to produce the same amount of services or useful output".

The Commission of the European Communities (CEC) named its green paper on energy efficiency correspondingly "Energy Efficiency or Doing More With Less" (CEC 2005).

According to this document, the key barrier to increasing energy efficiency is a lack of information, e.g., on the costs and availability of new technology or energy consumption.

Energy efficiency indicators (EEIs), more generally energy performance indicators, provide links between energy use and relevant monetary or physical indicators which measure the demand for energy services (Ang 2006). Patterson (1996) noted that that energy efficiency is a generic term without unequivocal quantitative measures and stated, "Instead, one must rely on a series of indicators to quantify changes in energy efficiency." Ang (2006) furthermore notes that physical-based indicators are calculated by relating energy consumption to an activity indicator, which is given in a unit closely associated with the way energy is consumed, which varies between different end-uses.

In transportation and forest fuel supply operations, fuel consumption is typically used to measure energy consumption, expressed for example in litres per 100 kilometres or litres of diesel consumed per effective machine hour. According to Magagnotti & Spinelli (2012), "Direct energy consumption is normally measured by recording fuel consumption and then converting it to energy units through a constant that represents the energy content of the fuel." The authors also state the importance of input data from fuel consumption studies to include engine details (engine model, make, manufacturing year and displacement), fuel used during study (litres, kilograms) and the amount of output (e.g., the biomass produced) during the study, as well as relevant additional details (duration of study, emissions etc.). In contrast, fuel economy is a standard measure of the rate of motor vehicle fuel consumption expressed over the distance travelled per unit of fuel consumed for that distance, e.g., kilometres per litre. However, fuel economy is an imprecise measure of energy efficiency not taking attributes into account that may affect the value of a vehicle's services such as vehicle mass, passenger or cargo capacity, engine power etc. (Cleveland & Morris 2015).

Physical-thermodynamic indicators of energy efficiency with outputs measured in physical units are useful, however, they are limited to comparisons with the same end use service and they are therefore restrictive (Patterson 1996). For macro-level policy analysis especially, economic-thermodynamic indicators, usually based on GDP, are more useful (Patterson 1996). In this regard, Ang (2006) notes, "Defining this manner, energy efficiency reflects factors other than 'true' energy efficiency given by thermodynamic indicators." Proskuryakova & Kovalev (2015) presented an analysis of existing energy efficiency indicators (EEI) showing a discrepancy between the engineering concept of energy efficiency based on the thermodynamic definition and macroeconomic understanding of energy efficiency, the energy intensity. The authors suggest a new set of EEIs following a consistent hierarchy of parameters (Figure 2) defining various levels, starting at a physical level and reaching the macro-economic level, although the industrial and macroeconomic levels were not described in more detail (Proskuryakova & Kovalev 2015):

- Physical level – indicators on this level reflect the efficiency of physical processes such as combustion, heat transfer or throttling.
- Technological level- indicators reflect multiple physical processes where each operation is described with a physical level indicator and the process as a whole by a technological process.
- Enterprise level – this level integrates all technological indicators of an organisation and they may include several technologies.

Figure 2. End-to-end hierarchy of energy efficiency indicators according to Proskuryakova & Kovalev (2015).

In forest biomass supply, the state-of-the-art forest technology and available forest machinery effects directly the physical and technological levels, while indirectly also the enterprise level and industrial level through the existing biomass supply chains.

Marchi et al. (2018) recently provided a comprehensive overview regarding sustainability of forest operations where the authors state that fuel efficiency is a key factor for reducing the environmental impacts in logging. One method to determine energy efficiency or environmental impacts applied to the forest fuel supply is the life cycle assessment (LCA) method. LCA is a tool for a holistic assessment of environmental impacts of product or service systems and is widely recognised in various industries and it is well-documented, e.g., in ISO standards (Filimonau 2016). However, it is not yet as widely used in forestry as it is in other fields (Đuka et al. 2017). LCA looks at the entire life cycle of a product, process or activity, e.g. from extraction of raw materials to manufacturing, use, and the end of life (Đuka et al. 2017). While LCA enables the understanding of environmental impacts and quantifies environmental performance indicators, most LCA studies in the field of forestry rely on fuel consumption to measure the direct process energy consumption (Heinimann 2012). LCA studies vary in their methods for defining system boundaries, processes, functional units or allocation assumptions for areas such as production rates and the fuel consumption of machines (Klein et al. 2015). As an example, based on productivity and fuel consumption data, Prada et al. (2015) used LCA methodology to estimate CO_2 emissions of three chippers in Spain. Throughout the entire forest supply chains, LCA studies can also provide useful information on "hotspots" of emissions (de la Fuente et al. 2017). The energy requirements and environmental impacts of timber transportation were studied by Lindholm and Berg (2005) using LCA with assumed average annual data values for fuel consumption of companies. Nevertheless, the data used in the LCA processes is based on existing data, e.g., primary data from the literature. Such data then again can be based on studies, such as work studies or follow-up studies focussing on the energy consumption during operation, typically in form of fuel consumption, using either direct fuel measurements or machine data (e.g. Lijewski et al. 2017, Holzleitner et al. 2011a, b, Klvac and Skoupy 2009, Athanassiadis et al. 1996). Thus, "reliable measurements of the energy used for the supply of energy biomass are crucial to the compilation of life cycle analysis (LCA) studies, and ultimately to the compilation of policy suggestions" (Magagnotti & Spinelli 2012).

In order to substantially reduce adding carbon and emissions to the atmosphere causing global warming, energy efficiency is of high importance and has therefore politically been addressed on various levels. As a consequence, legislative changes have been implemented in Finland (Road Traffic Act 2013) which aim to improve efficiency and machine development to reduce environmental impacts. New machines have been designed particularly to reduce energy consumption and to exploit the benefits of the legislative changes (see Korpilahti 2015). Thus, the efficiency of operations throughout the forest supply chain, and the performance of machines, as well as the entire system in terms of energy consumption are key areas of interest to be investigated (see, e.g., Haavikko et al. 2019, Borz et al. 2017). The concept of energy efficiency is therefore considered suitable for the examination of forest biomass supply chains because machine alterations may improve the relationship between the amounts of product output that can be produced with a given energy input. Reliable data on the energy efficiency gained from such innovative designs can be used for added analysis (see, e.g., Magagnotti & Spinelli 2012) as well as for further machine development. New machine designs and their integration into the overall biomass supply chain might then show environmental and efficiency benefits. The re-design of organisational structures within the supply chain might be another measure to improve the overall performance and the energy efficiency of operations within the forest energy supply worth investigating. The concept may thereby also provide concrete measurable performance indicators for the further development and evaluation of forest biomass supply chains.

1.5 Work study and discrete-event simulation (DES)

In order to investigate the relationship between resource inputs, e.g., in form of energy, capital or human resources, and the output of a machine or system, the machine performance needs to be investigated. The machine performance should be considered first without interaction with other machines using suitable methods such as work studies.

The role of work studies in the field of forest engineering has been recently summarised by Koŝir et al. (2015). In their work the authors conclude that the main purpose of work studies was the improvement of operational efficiency. While the work study concept had already been developed by around 1900 by Taylor, forest work studies play an important role also today, although their focus have changed from wage setting towards system optimisation, and they have been adapted to new priorities and a wider scope (Koŝir et al. 2015). An important step of work studies in forestry was the work on basic concepts for the time measurement of work presented by Björheden (1991) which provided a basis for an internationally agreed way of comparing time study reports. Basic methodologies and theories of forest work studies (Harstela 1991, 1993) and a nomenclature of forest work studies (Björheden 1995) were then added to earlier efforts. With the aim of harmonising a work study protocol, the outcome of a network of scientists in forest engineering was presented in form of good practice guidelines by Magagnotti & Spinelli (2012), which has contributed to a common understanding within the field of forest work studies (Magagnotti et al. 2013). Furthermore, a simple study design facilitating replication was highlighted by Spinelli et al. (2013) with regards to the accuracy of elemental time studies by different researchers, regardless of the method. A typically used method is the continuous time study method (Harstela 1991). A detailed study on the possibilities of automatic and manual timing in time studies, especially on harvester operations, was presented by Nuutinen (2013), and the author also presented a new process-data model of harvester operation for automatic time studies. In addition, Brewer et al. (2018) compared two data collection methods, a manual time study and a follow-up study using computer records in harvester productivity modelling. Direct energy consumption in work studies is usually measured by the fuel consumption, which is then converted to energy units; depending on the goal, studies can be carried out at various levels of resolution (Magagnotti & Spinelli 2012).

Several studies have involved optimisation approaches applying different analytical methods as part of operations research (OR). Different mathematical methods can be found in recent literature which were applied to the topic of woody biomass supply chain optimisation. A summary review of studies using deterministic and stochastic mathematical models on value chain optimisation for bioenergy production was presented by Shabani et al. (2013). Also Koirala et al. (2018) presented a review of research including optimisation focussing on secondary transportation. Among the applied methods are for example mixed integer programming (MIP) models. Marques et al. (2018) investigated the planning of woody biomass supply for tactical decisions under variable chips energy content. Therefore the authors developed a MIP model to optimally solve biomass supply chains in hot systems in Finland. Gautam et al. (2017) presented a novel multi-period MIP model to assess the feasibility of incorporating a terminal for biomass supply chains. Their model takes biomass quality, seasonality and supply restrictions related to weather into account. A coupled approach of MIP with a network algorithm was developed and presented by Han et al. (2018) to optimise biomass feedstock logistics on a tree-shaped road network.

Other optimisation approaches include linear programming (LP); this method was for example applied by Sosa et al. (2015) to optimise biomass supply chain logistics including the moisture content and two truck configurations in two supply chain scenarios in Ireland. A coded LP technique was applied by Palander & Voutilainen (2013) for modelling fuel terminals in forest biomass supply in Finland. Ko et al. (2019) presented a mixed integer linear programming model in their biomass transportation optimisation study. Their model uses region-specific data to minimise sustainable transportation costs. A nonlinear mixed integer programming method was used by Shabani & Sowlati (2013) to optimise the supply chain of a power plant based on forest biomass. Other optimisation methodologies presented in the literature includes Simulated Annealing and a Domain Model presented by Acuna et al. (2012b) for optimising transport efficiency and costs in wood chipping operations in Australia. An integrated optimisation model was presented by Akhtari et al. (2018) for integrated strategic and tactical biomass supply chain decisions, whereas Malladi et al. (2018) developed a decomposition-based approach for optimising short-term logistics of forest biomass.

Methods of operation analysis often include simulations when a problem is too complicated to be solved by analytical methods (Harstela 1993). Simulation has been compared with other procedures of operations research (OR), but while analytic methods of OR offer algorithms for solving a problem, simulation models are unique and tailored for a specific problem with the aim to find answers to specific questions (Asikainen 1995). A general characteristic of supply chains in biomass sourcing are the complexity and highly dynamic network due to unpredictable simultaneous interactions, which makes it difficult to solve optimally (Kogler & Rauch 2018).

The high degree of machine dependency of a “hot” system has an effect on the efficiency, and a proper balance in machine capacity is essential (Eriksson 2016). A simulation model is compiled to imitate reality, thus simulation allows testing various decision-making scenarios without disturbing the real system. In some cases “simulation is the only method that can be used to experiment with new policies, ideas or organization of the work” (Asikainen 1995). Accordingly, “simulation is a powerful tool for the evaluation and analysis of new system designs, modifications to existing systems and proposed changes to control systems and operating rules” (Carson II 2005).

Discrete event simulation (DES) was developed starting in the 1960s and 1970s (Banks et al. 2010), and in Finland it was used in forestry for the first discrete-event simulation model on timber harvesting systems developed by Seppälä (1971). Asikainen (1995) used the DES method in his doctoral dissertation concerning a forest chip supply system. To date, several research papers and decision support systems have used DES in this field (e.g., Asikainen 1998, 2001, 2010, Talbot & Suadicani 2005, Belbo & Talbot 2014, Eriksson et al. 2014a, 2014b, 2017, Karttunen et al. 2013, Zamora-Cristales et al. 2013, Spinelli et al.

2014b, Windisch et al. 2013, 2015, Eliasson et al. 2017, and Gronalt & Rauch 2018). The DES approach as a main method in forest biomass supply chains was applied additionally in a few doctoral theses, most recently in Sweden by Eriksson (2016) on the efficiency of forest fuel supply chains, and in Finland by Windisch (2015) on process redesign, and Väätäinen (2018) on the development of forest chip supply chains for the redesign of supply operations and logistics. Asikainen (1995) and Väätäinen (2018) have provided detailed introduction to DES as a study method in this field including for instance simulation structures, components, evaluations and applications. Recently, a literature review on DES concerning multimodal and unimodal transportation in the wood supply chain was presented by Kogler & Rauch (2018). The authors provide comprehensive analyses of articles where DES was applied to wood transport. The authors, moreover, highlight the advantages of DES compared to other general simulation approaches such as Monte Carlo Simulation, System Dynamics or Agent-Based Simulation. Such advantages include the availability of powerful software, the model structure and an intermediate abstraction level which make DES suitable for the modelling of supply chains close to the system in reality (Kogler & Rauch 2018). A common key aspect of DES highlighted in several studies is the importance of model documentation, verification and validation processes (Balci 1994, Carson II 2005, Sargent 2007, Kogler & Rauch 2018). In summary, DES is considered a useful method in the modelling of biomass supply systems since internal interactions and random occurrences are expected within such a complex system or subsystem (Banks et al. 2010), and in particular within “hot” biomass supply chains.

1.6 Objectives and research questions

The aim of the thesis was to identify and define the magnitude of possible improvements of fuel economy and energy efficiency of the forest chip supply system by modifying the settings of CTL harvesters, introducing a hybrid chipper, in addition to introducing alternative supply systems through the use of a feed-in terminal, and an analysis of forest chip supply systems under selected operational and environmental conditions. The overall objectives covering individual machines were to identify whether the modification of machine settings has an effect on the fuel efficiency of CTL harvesting machines and to investigate if hybrid machine technology can improve the fuel consumption and energy efficiency of chipping operation in forest chip production. The objectives covering the forest chip supply system include a quantification of the effect of terminal operations on the overall supply cost as an alternative to the direct supply of forest chips. Furthermore, it was an objective to define and identify the effects to overall supply cost and efficiency of the supply system when applying different types of chipper and truck-trailer combinations.

Figure 3 presents the schematic outline of the concept of this thesis to improve energy efficiency and fuel economy throughout the forest chip supply chain. Thereby, the thesis addresses several levels of improvement and includes studies on harvesting, chipping at the roadside, and road transportation of chips directly to the end-using facility or through a feed-in-terminal.

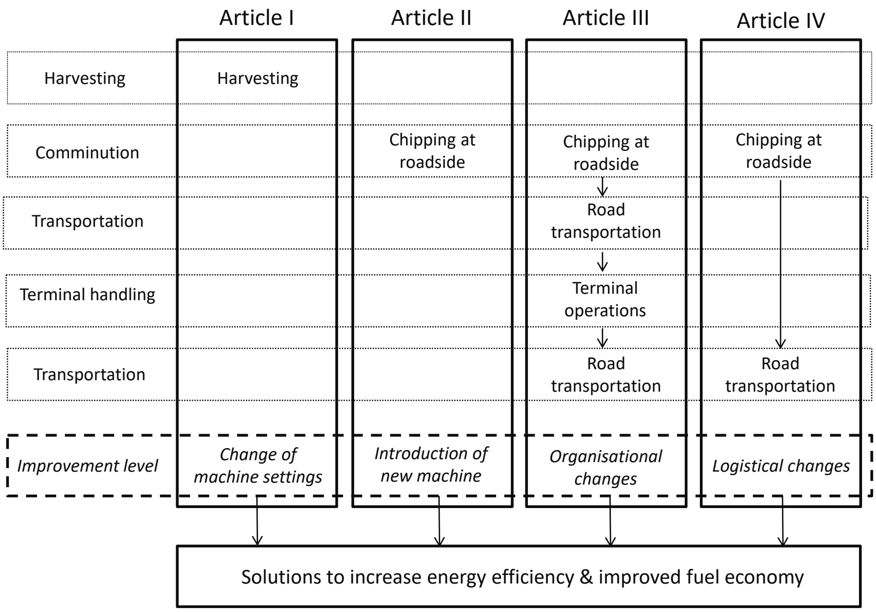


Figure 3. Schematic outline of the thesis concept to improve energy efficiency and fuel economy throughout the forest chip supply chain.

Article I focusses on harvesting as the first step in the biomass supply chain by improving the machine performance regarding fuel efficiency by altering the settings of CTL harvesters. The second article examines the energy efficiency and fuel consumption at the comminution phase with the introduction of a hybrid machine technology. Article III concentrates on the cost efficiency of the sequence of sub-systems. They range from chipping at the roadside, transportation of chips directly to the end-using facility (CHP plant) or alternatively via a terminal. The fourth article investigates the costs and efficiencies of the forest chip supply system including roadside chipping and chip transportation to the CHP plant when applying logistical changes through the use of different types of chipper and truck-trailer combinations. Overall, within the defined scope throughout the forest biomass supply chain and specific improvement level, each individual case study aims to find solutions to increase energy efficiency and to improve the fuel economy.

The objectives can be divided into following four specific research questions:

1) Can the modification of machine settings have an effect on the fuel efficiency of CTL harvesting machines?
2) Does hybrid machine technology improve the fuel consumption and energy efficiency of chipping operation in forest chip production?
3) What is the effect of terminal operations on the overall supply cost and efficiency of the supply system as an alternative to the direct supply of forest chips?
4) What is the effect on the supply costs and efficiencies when applying different types of chippers and truck-trailers?

2. MATERIAL AND METHODS

2.1 Study setting

The overall objective of the thesis was to improve fuel economy and energy efficiency of the forest chip supply system based on four individual cases. Each of the cases dealt with practical issues or concrete problems in the forest chip supply with the aim to answer the specific research questions.

The analysis of case studies involving individual machines on the one hand, and the entire forest chip supply system on the other hand, required the use of two study methods, work study and simulation. Work study was used as a study method for investigating the performance of individual machines and their alteration. The simulation method was used for investigating the redesign of organisational aspects of the forest fuel supply system when introducing a feed-in terminal, and for investigating logistical changes in the form of chipper and different-sized truck alternatives due to machine interdependencies in the fuel supply chains.

The schematic chart in Figure 4 shows the focus of the individual studies in the forest chip supply chain. In the context of the thesis, harvesting was considered a grouping of felling/cutting and off-road transportation/forwarding. Harvesting was not specifically separated from forwarding due to the fact that CTL machinery is commonly used with expected analogous machine behaviour, e.g., concerning the fuel consumption per unit product. Other steps in the supply chain included the comminution of the wood material, transportation of chips to a terminal and terminal handling in cases when a terminal was used, as well as transportation of chips to the end-using facility. The costs of the raw material, e.g., wood chips, and the related selling or purchasing actions were not considered; instead, depending on the articles, only supply and unit costs for sub-systems were considered.

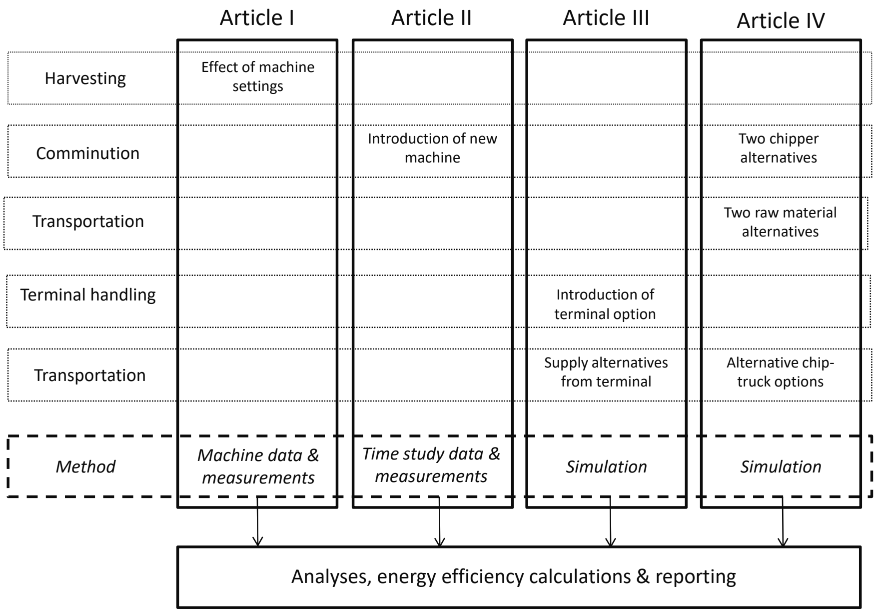


Figure 4. Schematic chart showing the focus and methods of the individual case studies in the forest chip supply chain.

Within the biomass supply system there are different levels enabling energy efficiency improvements at the various steps of the supply chain (see Figure 3). When joining them with the different energy efficiency indicator levels (see Figure 2), a framework of the thesis was obtained as shown in Figure 5. The physical level of energy efficiency was examined following machine alteration by modifying machine settings and using hybrid chipper technology. The technological level was observed by examining machine settings, an alternative hybrid technology chipper and variations in truck size options. The energy efficiency on the enterprise level was investigated by examining various means of organisational redesign by looking at terminal options and alternative supply systems. The industrial level was studied by examining the supply costs when investigating terminal usage and alternative supply systems. Thus, with the exception of the macroeconomic level, all levels were comprised in study cases. The framework of the thesis includes several performance and energy efficiency parameters within the examined levels.

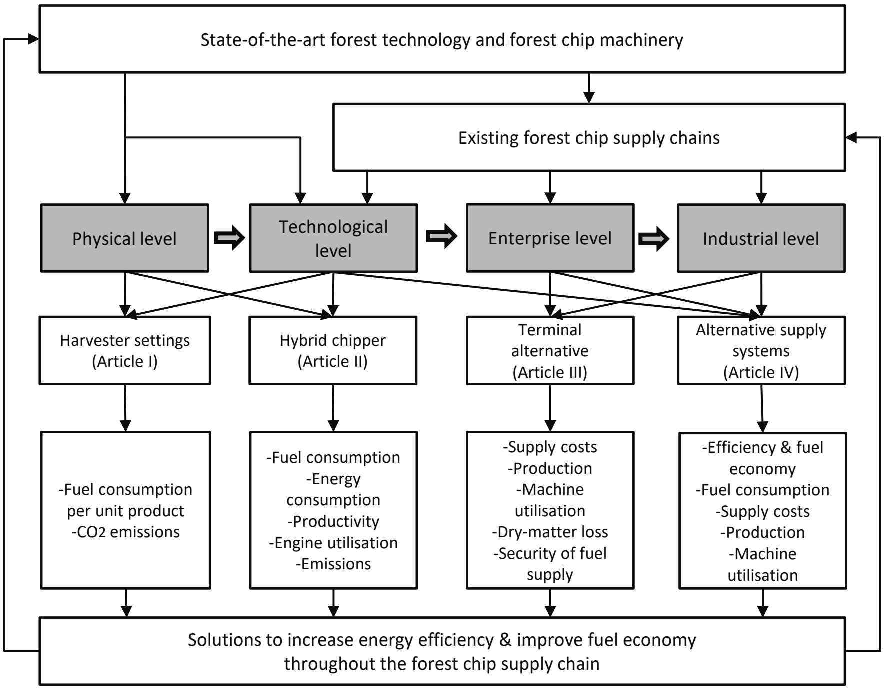


Figure 5. Framework of the thesis including performance and energy efficiency parameters applied in the thesis adopted and modified from Proskuryakova & Kovalev (2015).

Thus, the thesis summarises the findings of the presented cases focussing on the key steps of the forest chip supply chain. The thesis uses the work study method, machine data collection, and manual time study, as well discrete-event simulation (DES) to analyse and report the performance and the effects of individual changes on the overall supply system performance. Overall, all individual case studies aimed at solutions to increase energy efficiency or to improve the fuel economy. If successful, they may effect and thereby improve the state-of-the-art forest technology and forest chip machinery and influence the performance of existing forest chip supply chains.

2.2 Work studies (Articles I & II)

2.2.1 Work study methodology

The first two case studies (Articles I & II) aimed at examining the relationship between energy inputs primarily through fuel consumption and machine output in form of the machine performance. The scope of the studies were to examine the performance of single machines under real working conditions without interaction with other machinery. As a proven and suitable method for such study objectives, the work study methodology was considered. Work studies were considered useful to investigate the performance of machines in the biomass supply chain under real conditions through experiments, e.g., when alternatives are compared. The possibility to use analytical tools for answering the specific research questions under given conditions also supported the use of this methodology. Work studies include several essential steps in the process (Magagnotti & Spinelli 2012):

1. First, the problem must be defined as there are several options for the relationship between input and output as well as the influence of other variables (nuisance). These input-output relationships can involve the energy, time or mass of a product, among others.
2. Second, the goal and hypothesis should be stated. Typically there is a separation between comparative studies and modelling studies, although studies may include elements from both. While comparative studies focus on operational alternatives such as different machines, modelling studies investigate the effect of continuous variables, such as tree size.
3. Third, the experimental design to plan the study to meet the set objectives. This step includes the control of the nuisance variables through constant keeping, randomisation or inclusion. This step also includes how the collected data should be analysed. The experimental characteristics are either observational where variables affecting the output cannot be controlled, or experimental where the variables are controlled. Comparative studies normally use a factorial design (a certain number of repetitions for treatment and block combinations), while modelling studies focus on actively selecting nuisance variables of interest within a certain range.
4. Fourth, in this step the study layout and objects are designed.
5. Fifth, the time study method and tools are selected.
6. It is recommended to choose and check the statistical methods at this point.
7. A checklist of field work helps to prepare the work in the field.
8. The selection of a suitable study site for the study is important; the preparation of the site also belongs to this step.
9. In this step the study is carried out. This might include a recommended pre-study, which then again might affect the further refinement of the study layout and objects and subsequent steps until the actual study is carried out.
10. Once the data has been collected, the next step contains the data processing.
11. In this step the statistical analysis is performed. The statistical analysis and the techniques used are usually closely linked to the study type.
12. Finally, the reporting of the study must be done.

Work studies focussing on energy use need to reliably measure the energy input; depending on the goal of the study, the measurement resolution of fuel consumption studies can vary between a) continuous, b) operation or shift level, c) daily or weekly, as well as d) monthly, quarterly or yearly levels (Magagnotti & Spinelli 2012). Specific energy use is equal to the energy input per product output, whereby the product output is measured using various units such as the solid volume, bulk volume, fresh weight, dry weight and their respective measurement techniques (Magagnotti & Spinelli 2012). In the applied cases, the work studies included the utilisation of machine data and time study data. While time studies can be carried out using different techniques and various technical measurement devices, a commonly used method is observation using a stop-watch or devices with similar timing principles. Additionally, video recording can be used for time studies; the recorded data can then be analysed for time elements, e.g., using software developed at the Natural Resources Institute Finland (Niemistö et al. 2012, Nuutinen et al. 2016). Video was recorded as a back-up substitute of operations in both the studied cases in parallel to the machine data collection and time study measurements, although it was not used for further analysis.

The first case study utilised machine data for investigating the effect of altering the machine settings on the performance of CTL harvesting machines under real working conditions. The study primarily looked at resource input in form of fuel consumption per unit product. The main performance parameters were collected by the machine's own on-board-computer (OBC). In addition to the continuous high-accuracy instant data collected by the harvesters, fuel consumption was manually measured when re-fuelling the machines (at a shift level). This data was then utilised by applying a correction factor to the machine's OBC data on fuel consumption. The product output in form of solid volume was measured and provided by the harvester's measurement system.

The second case study looked at an innovative machine by examining a prototype of a hybrid technology chipper. With the aim of investigating the performance of the machine (at an element level), time studies were conducted applying the continuous timing method (Harstela 1991, 1993). In this comparative study, the performance of the prototype chipper was then related to two conventional chippers under similar circumstances. The productivity of all the studied chippers were based on the time study using the effective working time (E_0h) and weight measurements of loads using scales at the end-using facilities. Fuel consumption was measured on a shift level and connected to the production figures. The time study was conducted manually using hand-held computers without disturbing the regular work routine of the machine operators. The time study considered the chipping operation from loading the raw material onto the chipper's feeding table with its crane up to the chipping phase where the chips are directly blown out of the chipping unit. Chip samples were taken for further quality analyses. The energy efficiency and fuel economy calculations were performed based on the machine's nominal engine power and the fuel consumption, as well as the productivity data gained through the experiments.

2.2.2 The effect of machine settings on fuel consumption (Article I)

The case study examined the possibility of reducing fuel consumption of CTL harvesting machines by applying various technical settings to the machine. The simple adjustments of the machine settings through the machine's own software package included a set of parameters for each scenario case.

The case scenarios studied under real working conditions included three main settings, the business-as-usual (BAU) setting, the ECO setting (aiming at a reduction of fuel consumption), and the POWER mode (aiming at maximum production). Each of the three modes was tested in three different CTL machine types (Table 1) under comparable stand environment and silvicultural prescriptions.

Machine data was used for collecting relevant performance parameters added by the manual measurement of fuel consumption to calculate a correction factor for the data collected for each machine and setting. The machine data included the collection of key parameters including the fuel consumption, stem number, harvest volume in solid cubic metres and engine load factor.

Table 1. General characteristics of the harvesters.

Harvester	Beaver	Scorpion	Ergo
Make and model	Ponsse Beaver	Ponsse ScorpionKing	Ponsse Ergo
Wheels	6	8	6
Power [kW]	150	210	210
Engine model	Mercedes-Benz /MTU OM 934 LA EU Stage IV	Mercedes-Benz OM936 EU Stage IV	Mercedes-Benz OM936LA EU Stage IV
Harvester head model	H5	H6	H7
Crane type	C44+	C50	C5
Typical weight [kg]	17,500	22,500	20,000
Engine's maximum torque [Nm]	800	1,150	1,150
Tractive force [kN]	130	180	160

The machines' own data collection system were used for collecting the fuel consumption to an accuracy of 0.05 litres per hour. Therefore, the instant fuel consumption at 20 millisecond intervals was used, which represents the current fuel consumption in litres per hour at the respective time interval (defined as the time between the first and the last instant fuel consumption readings). Then, the instant fuel consumption was integrated over its duration. Manual fuel measurements at the end of each trial allowed a correction factor to be estimated that was then applied to the records from each repetition. CO_2 emissions were calculated based on the fuel consumption (EPA 2016).

A statistical analysis was performed on the dataset in order to check the significance of the differences between the settings and machines. A significance level of $\alpha < 0.05$ was applied in the analyses. Data was tested for normality and homoscedasticity before transformation, regression, ANOVA and non-parametric tests (Mann-Whitney) were completed.

The tested case scenarios include the machine setting adjustments of each harvesting machine under CTL operation with the following three main scenarios (Table 2):

- BAU represents the business as usual setting under which the operator would normally work, and which is adjusted carefully by the operators, typically optimised for their skills and preferences to obtain highest productivity for the given machine and conditions.
- ECO represents the economy mode setting where various fuel saving features were implemented aiming to achieve the lowest fuel consumption in litres per harvested cubic metre of wood.
- POWER represents a production mode setting where various features to increase productivity were implemented aiming at the highest productivity.

Table 2. Specifications for each of the three setting modes for each of the CTL harvester models.

	Beaver			Scorpion			Ergo		
Setting	BAU	ECO	POWER	BAU	ECO	POWER	BAU	ECO	POWER
Engine									
Engine RPM [r min^{-1}]	1,700	1,550	1,750	1,600	1,450	1,750	1,650	1,550	1,750
Harvester head pump flow									
Fast feeding [l min^{-1}]	215	220	250	300	265	320	366	300	387
Sawing [l min^{-1}]	242	210	231	245	245	245	225	225	225
Harvester head pump pressure									
Fast feeding [bar]	280	250	280	280	250	280	280	250	280
Slow feeding [bar]	280	250	280	280	250	280	280	250	280
Sawing [bar]	250	235	250	250	235	250	280	250	280
Base level [bar]	160	130	160	160	130	160	160	130	160
Tilt up [bar]	160	130	160	160	130	160	160	130	160
Engine control									
Increase of engine speed [r min^{-1}]	100	60	100	125	0	100	125	50	100
Increase of engine speed [ms]	500	300	500	500	0	500	500	280	500
Drop of engine speed when power limitation starts [r min^{-1}]	100	80	125	70	not used	125	100	not used	125
Power limitation function, decrease of pump control current [mA]	50	50	50	80	not used	60	80	not used	60

Each of the three machines carried out a total of five replications for each of the three machine settings modes, each mode lasting approximately one hour: in total 45 repetitions.

2.2.3 Performance of innovative hybrid technology chipper (Article II)

The objectives of this case study were to examine the performance of the Kesla C860 H hybrid technology chipper and relate the results to two conventional diesel-powered chippers. Productivity, fuel consumption and the quality of the wood chips were measured and analysed. Manual time studies were carried out in two locations in Finland, and the chipped material included conifer pulpwood and logging residues.

The case study was conducted under real operating conditions with chipping of the material at the roadside landing or terminal directly into a truck-trailer or truck container. Energy consumption, emissions levels and engine utilisation were calculated based on the collected data.

Time studies were conducted applying the continuous timing method (Harstela 1991, 1993; Magagnotti et al. 2013) dividing the working time into eight work elements (Table 3). The productivity of studied chippers were based on the time study using the effective working time (E_0h) and weight measurements of loads using scales in form of weigh bridges at the end-using facilities.

Table 3. Description of work elements.

Work element	Description of work element
Boom out	Boom movement from the chipper to the piled material
Grip	Gripping of material
Boom in	Boom movement from the pile to the feeding table
Feeding	Placing the material into the feed orifice and release of the grapple load
Adjustment	Possible adjustments of the material on the feeding table
Pure chipping	Chipping while the timber loader is idle
Moving and preparation	Repositioning of the chipper to the next pile and preparing the chipper for chipping work
Delays	Time not related to chipping work, but for which the interruption was recorded

At the roadside landing, the hybrid chipper performance was compared to the results from a conventional high-powered drum chipper intended for similar working sites. Both chippers were chipping logging residues originating from a Norway spruce-dominated mixed coniferous stand operating on the same work site. At the second terminal location, conifer pulpwood, predominantly Lodgepole pine, chipped with the hybrid chipper was compared to Scots pine pulpwood from a first thinning chipped with two conventional chippers, a high-powered truck-mounted drum chipper and a medium-powered tractor-powered chipper (Table 4).

Table 4. Characteristics of the studied chippers and chipping equipment.

Chipper	Hybrid	Conventional, High power	Conventional, Medium power
Chipper model	Kesla C 860 H	Kesla C 1060 A	Kesla C 1060 T
Type	truck-mounted	truck-mounted	tractor-trailer
Base machine	Volvo FM 440	Volvo FH 750	Valtra S280
Engine power [kW]	160	559	209
Power transmission	electric drivetrain	intermediate transmission	power take-off
Crane type	Kesla 2112T	Kesla 1200T	Kesla 800T
Mass chipper [kg]	8,200	10,200	14,800
Intake opening, width and height [mm]	800 x 600	1,000 x 600	1,000 x 600
Knives	8	10	10
Drum diameter [mm]	860	860	860
Drum speed [rpm]	550-600	550-600	550-600
Mesh sieve size [mm]	100 x 100	100 x 100	80 x 80

The fuel consumption was measured on shift level by refilling the tank at the same location before and after the trials. Fuel quality aspects were studied based on chip samples taken from each load for further analyses in the laboratory according to EN standards applicable to solid biofuels. Statistical analysis was conducted for the particle size distribution of the wood chips.

In order to achieve an indicative estimation of the environmental impact, emission factors were calculated based on the fuel consumption data for the studied chippers applying the LIPASTO-calculation system (VTT 2017). The energy consumption was calculated using the average power of the chippers and the effective hourly output.

The engine utilisation was estimated in order to take the estimated utilised engine power in contrast to the nominal engine power into account. The engine utilisation was applied in calculating the productivity of the hybrid chipper in oven-dry tonnes (odt) per effective hour (E_0h) per the estimated utilised engine power (odt E_0h^{-1} kW^{-1}) for chipping logging residues and conifer pulpwood with the hybrid chipper when compared to the conventional chipper alternatives.

The engine utilisation was estimated using the following equation (Eq. 1):

$$Engine\ utilisation = \frac{Fuel\ consumption \times Energy\ content \times Conversion\ efficiency}{Engine\ power \times Time} \quad (1)$$

Where
Fuel consumption = the fuel consumption in litre per odt
Energy content = the energy content of diesel fuel per litre
Conversion efficiency = the ratio between the useful output of the machine engine and the energy input; typically 38 to 42% for modern diesel engines
Engine power = the maximum engine power output in kW
Time = the time per chipped odt in hours.
An energy content of 9.8 kWh per litre diesel fuel and conversion efficiencies of 40% for all chippers were assumed in the calculations.

The case study included the chippers' performance results when chipping logging residues and conifer pulpwood using the hybrid chipper, a high-powered truck-mounted and a medium-powered conventional tractor-powered chipper.

Case study analyses included measurements or calculations of productivity, fuel consumption, time consumption of work elements, energy consumption, engine utilisation and the emission levels for each of the studied chipper alternatives. The study also investigated fuel quality aspects in form of the particle size of chips from logging residues and conifer pulpwood.

2.3 DES studies (Articles III & IV)

2.3.1 DES study methodology

The latter case studies (Articles III & IV) examined the relationship between energy inputs and the system output in form of the supply system performance. Compared to the single machines studied in previous case studies, the scope of the case studies in Articles III and IV included the performance of an entire supply system. The system performance cases build on the existing fuel supply to a typical CHP plant and include potential new fuel supply chain alternatives involving terminal operations, the use of innovative chipper and vehicle types with their respective practical issues and concrete problems. The cases especially take the machine interaction between chipper units and transportation into account. The selected study method for these objectives was the discrete-event system simulation (DES) methodology. DES, in general, means the modelling of systems where a state variable changes only at a discrete set of points in time (Banks et al. 2010). DES was selected as the method for this research work due to the benefits of DES in biomass supply modelling compared to other OR methods (see Section 1.5). DES also allows various scenarios to run, and its advantages also include the possibility to simulate informational, organisational and environmental changes and investigate their effects on the model's behaviour. It also provides options to experiment with new designs before implementation (Banks et al. 2010). Due to the existence of interactions between machines within the biomass supply system and the occurrence of random impacts, dynamic simulation models provide consistent results in studying complex supply chains whereas static models may underestimate the impacts of such interactions, for example, the impact of waiting times (Asikainen 2010).

The desk-based simulation studies were performed using the WITNESS® discrete-event simulation software. Common steps in a simulation study are described below (Banks et al. 2010):

1. Problem formulation (understandable problem statement)
2. Project plan and setting objectives (questions to be answered by simulation)
3. Model conceptualisation (construction of a model)
4. Data collection (collection of the needed input data)
5. Model translation (programming of the model or use of purpose-built simulation software)
6. Verification (proper performance of the model)
7. Validation (calibration of the model, compared with actual system behaviour)
8. Experimental design (alternatives to be simulated)
9. Production runs and analysis (estimation of measures of performance for the system design)
10. Additional production runs (additional runs if required after analysis)
11. Documentation and reporting (program and progress documentation)
12. Implementation (involvement of model user)

Since the system performance cases reflected the real environment and were built on an existing fuel supply example, the system boundaries were defined, and simplifications were made. In this respect, data and input parameters were preliminary obtained from existing datasets or literature. Model verification was done following the logic of the model through a step-wise approach. Validation was carried out by relating the simulation results to findings from the literature in the field from similar simulation studies or practice, although comparable studies are available only to a limited extent. The experimental design followed the objectives of the individual case studies. In order to reach the expected confidence interval level of key variables, a repetition of runs was required due to the involvement of stochasticity and machine interdependencies under varying conditions, consequently, each scenario run was repeated seven times.

2.3.2 Simulation cases (Articles III & IV)

The first simulation case study (Article III) examined the cost effect of introducing a feed-in terminal to the forest chip supply for a combined-heat-and-power (CHP) plant compared to the conventional direct fuel supply from roadside storages to the end-using facility. The simulation model included four supply chains, each including a chipper and two chip trucks which were supplying logging residue chips directly to the plant in the business-as-usual direct-supply case (see Section 2.3.4 for simulation scenarios). A terminal (including the required terminal operation and related extra costs) was added to the supply. In one case, the suppliers' chip trucks were used for terminal transportation, while in another case a separate shuttle truck was added for terminal transports. In addition, the effect of moisture content, dry matter loss and the terminal location in terms of the distance to the plant were studied.

The objective of the second simulation case study (Article IV) was to investigate how vehicle types with an increased chip load capacity and the hybrid chipper would affect the cost and energy efficiency of the forest chip supply system. Legislative changes in Finland have increased the permitted dimensions and weights for heavy transport vehicles, which are essential for the efficiency of wood chip transportation. Suitable alternatives for chip transportation under typical Finnish conditions from the roadside to the end-using facility included in this study were a 52-tonne semitrailer truck, a 60-tonne truck-trailer unit and a larger 69-tonne truck-trailer unit with an electronic trailer steering (ETS) system. Two chipper alternatives were examined, a hybrid chipper and a high-power truck-mounted conventional chipper with data input from the results presented in Article II.

2.3.3 Simulation materials

The case study in Article III corresponded to the real situation of the local CHP plant in the city of Joensuu and roadside locations of spruce-dominated logging residues from final felling in the region in North Karelia in Eastern Finland. Theoretical distributions of roadside storage parameters and moisture data were used and the fuel supply was distance oriented, emphasising shorter distances at times of higher fuel demand at the plant.

The fuel demand of this plant was used based on the typical monthly demand, and based on this, an additional daily demand variation was added using a theoretical distribution. The plant's total demand was 517 GWh. A buffer storage was set for the plant's fuel reception with a limit of 6,000 MWh.

Chipping was done using a conventional truck-mounted drum chipper with a productivity of 50 solid m^3 per effective hour (E_0h). For the transportation of forest chips conventional truck-trailer units with a maximum of 64 tonnes, a frame volume of 131.6 loose m^3 and a load capacity of 50 solid m^3 were used. A larger truck was used for cases using a shuttle truck with a total weight of 76 tonnes, a frame volume of 157.9 loose m^3 and a load capacity of 60 solid m^3. For the feed-in terminal an area requirement factor of 1.2 solid-m^3 per m^2 was applied (Impola & Tiihonen 2011, Virkkunen et al. 2015) and a wheeled loader was used for various terminal operations. Additional details on the machine interaction parameters, machine costs, fleet and terminal operation factors are introduced in Article III.

For the case in Article IV, the simulation model presented in Article III with the same operational logic was applied and expanded through the use of small diameter trees as raw materials in addition to logging residues and also by adding new truck and chipper alternatives to the system's operational environment. For this case study, the terminal option was not included and only direct supply from roadside storages to the plant were used. Similarly to the method used by Windisch et al. (2015), depending on the moisture content and dry matter weight of the forest chips, the respective load capacities of the trucks were either limited by the mass of their payload or the maximum volume.

The performance input data of the chip trucks and chippers were defined based mainly on the literature, or, in case of the hybrid chipper and the high-power truck-mounted conventional chipper, they were based on the results presented in Article II.

2.3.4 Simulation scenarios

The case study of Article III included scenario comparisons of direct fuel supply from roadside storages to the plant with terminal operation scenarios. Two alternative business-as-usual (BAU) scenarios with varying shift settings were simulated for the direct fuel supply (scenarios 1A1 and 1A2). Two terminal scenarios were added; the first using the existing supplier's chip trucks for terminal transports (1B), the second applying a shuttle truck for transports from the terminal to the plant (1C).

Another scenario examined the location of the terminal in terms of the distance between terminal and plant. In these scenario runs, the distance increased from 5 km, 10 km, 20 km to 30 km using either the supplier's trucks (2B1, 2B2, 2B3, 2B4) or a separate shuttle truck for each distance (2C1, 2C2, 2C3, 2C4).

Scenario runs were completed with the examination of dry matter loss as well as the moisture change when storing the chipped material at a terminal based on both, literature and practical assumptions.

The case study in Article IV included five main simulation scenarios, whereby the business-as-usual (BAU) scenario was the base-line using a one shift operation and a 60-tonne truck-trailer unit and a traditional, conventional chipper when chipping logging residues and an average transportation distance of approximately 60 km from the roadside to the plant.

The second main scenario compared truck alternatives between the 60-tonne truck-trailer unit, a 52-tonne semitrailer and a 69-tonne truck-trailer unit with an electronic trailer steering system (ETS) when chipping logging residues with the traditional chipper. The third scenario focussed on investigating chipper alternatives using the traditional chipper and the hybrid chipper in its current development stage for each truck alternative. In addition, one scenario examined the hypothetical case of an improved and further developed version of the hybrid chipper whereby the productivity was assumed to be same as for a traditional chipper while having the same lower fuel consumption of the current hybrid chipper.

The fourth scenario investigated the effect of the transportation distance on the supply system. Average transportation distances of approximately 20 km to 140 km (in 20 km steps) were simulated for each truck alternative. The fifth main scenario focussed on the effects of changing the raw material whereby small diameter trees were added as an alternative to logging residues.

3. RESULTS

3.1 The effect of machine settings on fuel consumption (Article I)

3.1.1 Differences between studied settings

The study and the resulting data showed clear differences between machines and machine settings (Figure 6). The main focus of the case study was on the assessment of the fuel consumption per unit product for different settings and the results showed a range of 1.02 to 1.48 l m^{-3} on average across all machines. Nevertheless, different machines behaved differently under various settings (Figure 6). The Beaver and ScorpionKing machines showed a clear difference for the POWER setting, whereas Ergo showed a relative indifference to the settings.

The stem size varied between 0.14 and 0.23 m^3 without a statistical difference in the mean stem size between settings indicating equal conditions. The statistical analysis showed the strongest and most significant effect on fuel consumption per unit product (LOG transformed) for the stem size (ANOVA analysis: $p < 0.0001$), but also a significant effect for the machine setting (ANOVA analysis: $p = 0.0424$).

CO_2 emissions varied between 2.8 and 4.0 kg m^{-3}. The productivity results for different settings differed between the studied machines (Table 5).

Figure 6. Box plot graph of the fuel consumption per unit product (l m^{-3}) for the three studied machines under the three machine settings.

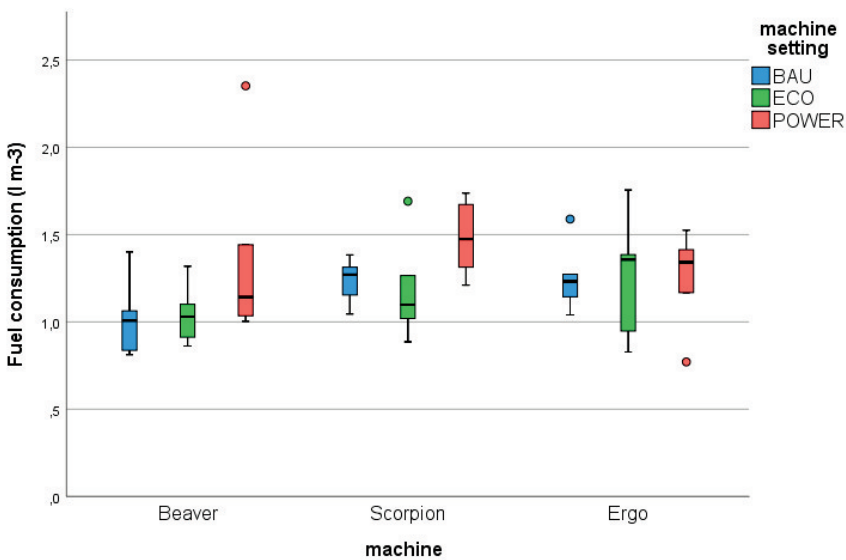


Table 5. Tree size, fuel consumption, CO_2 emissions and relative hourly productivity (BAU set as 1.0) levels according to the machine and setting.

machine	setting	tree size [m^3]	Fuel consumption [$l\ m^{-3}$]	CO_2 emissions [$kg\ m^{-3}$]	Relative productivity
		Mean (min/max)	Mean (min/max)	Mean (min/max)	Mean (min/max)
Beaver	BAU	0.177 (0.110/0.284)	1.024 (0.812/1.401)	2.751 (2.181/3.764)	1.000 (1.000/1.000)
Beaver	ECO	0.167 (0.116/0.219)	1.045 (0.862/1.318)	2.806 (2.314/3.541)	0.876 (0.863/1.001)
Beaver	POWER	0.150 (0.075/0.200)	1.395 (1.003/2.352)	3.747 (2.695/6.319)	0.831 (0.602/0.868)
Scorpion	BAU	0.158 (0.130/0.201)	1.233 (1.045/1.383)	3.313 (2.807/3.717)	1.000 (1.000/1.000)
Scorpion	ECO	0.154 (0.089/0.217)	1.192 (0.886/1.691)	3.203 (2.381/4.543)	1.015 (0.714/1.087)
Scorpion	POWER	0.140 (0.097/0.182)	1.482 (1.210/1.738)	3.980 (3.252/4.668)	0.958 (0.876/1.009)
Ergo	BAU	0.206 (0.140/0.298)	1.255 (1.040/1.589)	3.373 (2.793/4.269)	1.000 (1.000/1.000)
Ergo	ECO	0.200 (0.114/0.321)	1.254 (0.827/1.755)	3.370 (2.222/4.716)	0.962 (0.725/1.232)
Ergo	POWER	0.229 (0.143/0.458)	1.244 (0.771/1.525)	3.341 (2.070/4.097)	1.127 (1.109/1.471)
total (n=45)		0.176 (0.075/0.458)	1.236 (0.771/2.352)	3.320 (2.070/6.319)	

Notes: m^3= cubic metres solid volume; min=minimum value; max= maximum value.

3.1.2 Focus on the two extreme settings

The results of the mean values for key performance parameters indicated only a few differences between the BAU and ECO settings. Consequently, in the next step, the analysis focussed on the two extreme ECO and POWER settings to investigate the differences due to these drastically altered approaches. In addition, limiting the analysis to two choices solved the problem of identifying differences and enabled the use of non-parametric statistics. Additionally, the Ergo machine behaved differently and in the opposite direction than the other machines and was thus removed from further analyses. Results of the ANOVA analysis show significant differences for the extreme settings for the two remaining machines (Beaver and ScorpioKing) and the stem size (Table 6). In addition to the performed ANOVA analysis, without the Ergo and BAU data, non-parametric statistics were performed using the Mann-Whitney test on the non-transformed fuel consumption data. The results showed that the fuel consumption differences between the ECO and POWER settings for the Beaver and Scorpion data were statistically significant ($p = 0.04$).

Table 6. Results of the ANOVA analysis for the LOG transformed fuel consumption per unit product ($l\ m^{-3}$) without the Ergo machine and BAU setting input data.

Effect	DF	SS	η^2	F-Value	P-Value
Setting	1	0.026	0.13	12.709	0.0026
Machine	1	0.003	0.01	1.565	0.2289
Stem size	1	0.146	0.71	72.886	<0.0001
Residual	16	0.032	0.15		

Where: DF = degrees of freedom; SS = the sum of squares; η^2 = the effect size, expressed as the ratio between the SS for the specific effect and the total SS.

Table 7. Results of the regression analysis for the fuel consumption per unit product (l m^{-3}). The analysis excludes the Ergo machine and BAU setting input data.

Fuel consumption = a + b S + c ECO

R^2 adj = 0.765; n = 20; F = 31.994; p <0.0001				
	Coeff	SE	T	P
a	3.384	0.148	16.127	<0.0001
b	-6.523	0.943	-6.918	<0.0001
c	-0.220	0.081	-2.711	0.015

Where: The fuel consumption = l m^{-3}; S = the stem size in m^3; n = the number of valid observations; SE = the standard error; ECO = the indicator variable for the ECO setting: if ECO = 1, if POWER = 0.

The data for the two extreme setting treatments showed a clear stratification of the fuel consumption figures, whereas this was not the case for productivity. A regression analysis was conducted (Table 7) for the fuel consumption, productivity and the effect of machine setting through a dummy variable (ECO setting). The stem size had a significant effect as well as the machine setting, and overall the regression equation was significant and explained a large part of the total data variability (R^2 adj = 0.765). Thus, the fuel consumption per unit product decreased with an increasing stem size and was lower for the ECO setting compared to the POWER setting.

3.2 Performance of the innovative hybrid technology chipper (Article II)

3.2.1 Fuel and energy consumption of chippers

The study revealed an average fuel consumption of 2.9 litres per oven dry metric tonne (l odt^{-1}) for the hybrid chipper when chipping logging residues, while for conifer pulpwood the fuel consumption was 3.1 l odt^{-1} (Table 8). This result is 1.0 litre per chipped odt lower compared to the high-powered conventional chipper for chipping logging residues, and 0.2 l odt^{-1} lower for pulpwood. Compared to the medium-powered conventional chipper the hybrid was 0.4 l odt^{-1} lower.

Table 8. Fuel consumption (l odt^{-1}), energy consumption (kWh odt^{-1}) and fuel consumption in litres per odt per kW engine power (l odt^{-1} kW^{-1}) of the studied wood chippers.

	Fuel and energy consumption of wood chippers					
	Logging residues			Pulpwood		
	l odt^{-1}	kW odt^{-1}	l odt^{-1} kW^{-1}	l odt^{-1}	kW odt^{-1}	l odt^{-1} kW^{-1}
Hybrid chipper	2.9	12.2	0.020	3.1	14.2	0.023
High powered conventional chipper	3.9	26.8	0.012	3.3	17.9	0.008
Medium powered conventional chipper				3.5	14.8	0.018

The calculation of the energy consumption showed that the hybrid chipper was the most energy efficient for chipping both raw materials (logging residues and conifer pulpwood) (Table 8). With its high nominal engine power, the high-powered conventional chipper achieved the lowest values of fuel consumption in litres per odt per kW of engine power.

3.2.2 Productivity and work elements of chippers

The time study revealed an average chipping productivity of 13.1 oven-dry tonnes per effective hour (± 1.2 odt E_0h^{-1}) for the hybrid chipper when chipping logging residues. For conifer pulpwood the hybrid chipper achieved an average productivity of 11.3 odt E_0h^{-1} (± 0.7 odt E_0h^{-1}).

Conventional chippers achieved higher chipping productivities per effective hour for both raw material assortments (Figure 7). For logging residues, the high-powered conventional truck-mounted chipper achieved a productivity of 20.8 odt E_0h^{-1}, and when chipping conifer pulpwood the same chipper reached an average productivity of 31.2 ± 3.8 odt E_0h^{-1}. The medium-powered tractor-powered conventional chipper had a productivity of 14.0 ± 0.8 odt E_0h^{-1} when chipping conifer pulpwood.

The calculation of engine utilisation resulted in higher engine utilisation for the hybrid chipper compared to the high-powered conventional chipper for both raw materials. The hybrid chipper resulted in an engine utilisation of 0.93 when chipping logging residues and 0.86 for conifer pulpwood. For logging residues, the high-powered conventional chipper had an engine utilisation of 0.57. For conifer pulpwood the rate was 0.72 with the high-powered conventional chipper and 0.93 with the medium-powered conventional chipper. When taking the estimated utilised engine power into account, the productivity per estimated utilised kW engine power of the hybrid chipper (in odt E_0h^{-1} kW^{-1}) is higher compared to conventional chipper alternatives (Figure 8).

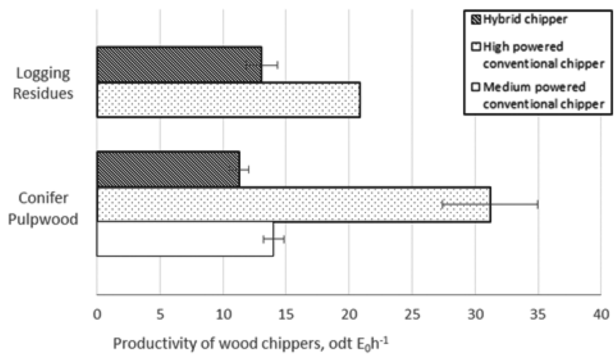


Figure 7. Productivity of the compared wood chippers (in odt per effective hour, E_0h) for logging residues and conifer pulpwood chipping with the hybrid chipper (diagonally hatched columns), high powered conventional chipper (dotted columns) and medium powered conventional chipper (unfilled columns). The graph shows 95% confidence intervals with error bars shown with the columns.

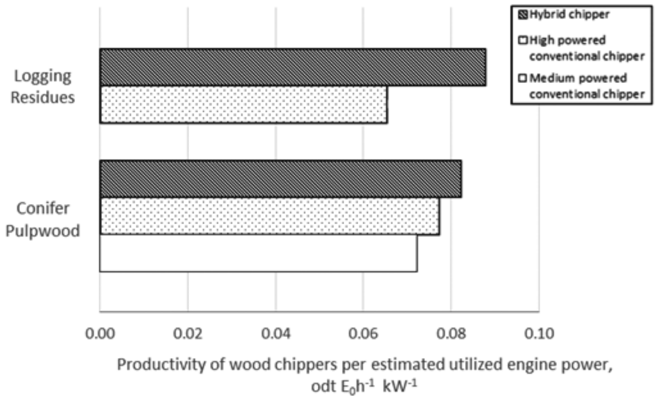


Figure 8. Productivity of compared wood chippers (in odt per effective hour (E_0h) per estimated utilised engine power, kW) for logging residues and conifer pulpwood chipping with the hybrid chipper (diagonally hatched columns), high powered conventional chipper (dotted columns) and medium powered conventional chipper (unfilled columns).

The analysis of the time consumption of the work elements for the hybrid chipper revealed that the "chipping" work element required the largest proportion of the overall time for logging residues (53%) and conifer pulpwood (81%) out of the total effective work time of 276 s per odt for logging residues and 320 s per odt for pulpwood. The medium-powered conventional chipper achieved the same proportion of chipping (81%) when chipping conifer pulpwood, indicating that the timber loader provided material continuously to the chipper unit without long idling times. When chipping logging residues, the proportion of feeding was higher for both, the hybrid (13%) and especially for the conventional high-powered chipper (27%).

3.2.3 Particle size of chips and chipping emissions

The study also examined the particle size of the chips from logging residues and conifer pulpwood. The analyses of the wood chips chipped with the hybrid chipper resulted in particle size class P31 (Alakangas and Impola 2014). The chip size distribution was significantly affected by both, the chipper and the chipper material. The hybrid chipper produced fewer chips in the 3.15 to 8 mm class compared to the high-powered conventional chipper, and, in general, chipping logging residues produced more fines and fine particle chips compared to conifer pulpwood chipping.

As a consequence of the fuel and energy consumption, the hybrid chipper resulted in the least emissions for both chipped raw materials. The hybrid chipper had CO_2 emissions of 7714 g odt^{-1} when chipping logging residues compared to the high-powered conventional chipper with CO_2 emissions of 10,374 g odt^{-1}. When chipping conifer pulpwood, the hybrid chipper had CO_2 emissions of 8246 g odt^{-1}, whereas the conventional machines resulted in higher CO_2 emissions of 8778 g odt^{-1} for the high-powered chipper and 9310 g odt^{-1} for the medium-powered chipper.

3.3 Introduction of a feed-in terminal for fuel supply (Article III)

3.3.1 Forest chip supply: direct vs. terminal supply

When comparing the main scenarios with direct deliveries or deliveries through a feed-in terminal, the case study revealed that the most supplemental fuel, as an addition to the supplied forest chips to meet the demand of the plants, was needed when operating in the BAU scenario with one shift and direct delivery to the plant. Operating in two shifts during high-season or operating using a feed-in terminal fulfilled the major part of the plant's fuel demand.

The results of the study show that the supply cost per MWh unit was lowest for the direct supply scenario operating with an additional shift during the high-season, resulting in forest chip supply costs from the chipping site to the end-use facility of 7.12 € MWh^{-1} (Figure 9). The BAU scenario with direct supply in one shift resulted in supply costs of 7.65 € MWh^{-1}. The use of a feed-in-terminal in addition to direct fuel deliveries added extra costs for the terminal operation to the supply costs. The use of a shuttle truck for transports from the terminal to the plant resulted in slightly lower supply costs (7.84 € MWh^{-1}) compared to the use of a terminal when transporting fuel with chip trucks (7.95 € MWh^{-1}).

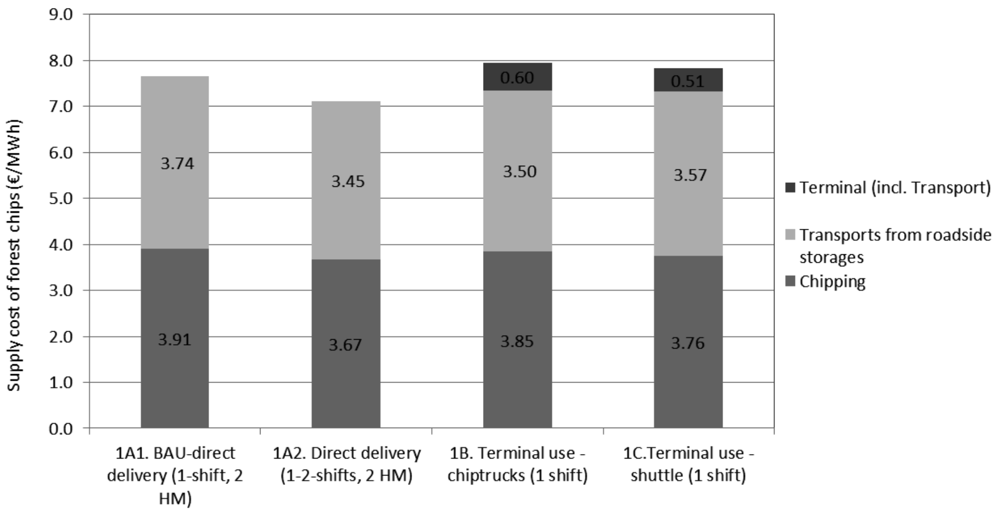


Figure 9. Supply costs of forest chips in the four selected main simulation scenarios. (HM = holiday month)

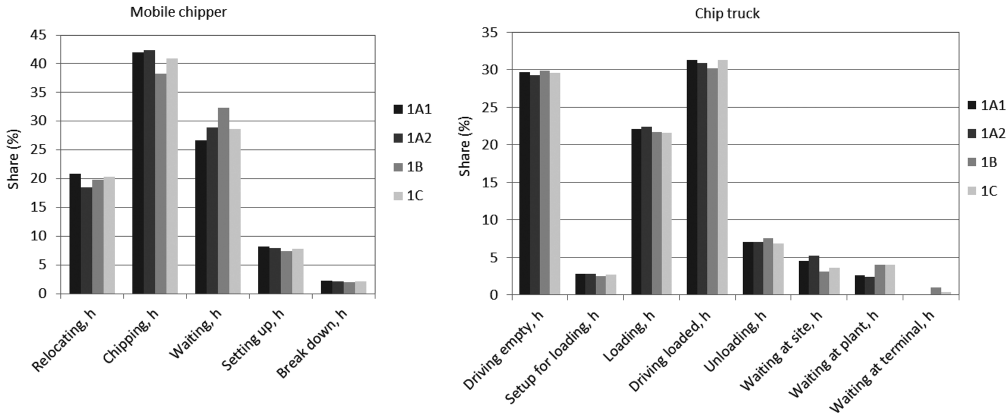


Figure 10. Distribution of work elements for the mobile chipper (left) and chip truck (right) in the main scenarios 1A1, 1A2, 1B and 1C.

3.3.2 Work elements of chipper and chip trucks

The analysis of the time consumption of the work elements for the mobile chipper revealed that the “chipping” work element accounted for the largest proportion for all simulated scenarios (Figure 10). This proportion was lowest in scenario 1B when using a terminal and when chip transportation was done by chip trucks, which increased the waiting time for the chipper. The BAU scenario (1A1) had the lowest amount of waiting time compared to other scenarios whereas the time for relocating the machine was slightly higher than in other scenarios.

The work elements of the chip truck showed little variation between the different scenarios (Figure 10). “Driving loaded” was the work element with the highest proportions of 30% or marginally above. The work element “driving empty” reached proportions of close to 30% for all scenarios followed by the element “loading” with 20 to 25 %. The results show a difference between direct supply and the use of a terminal in the proportions of “waiting at site” element where the shares are higher for the direct supply scenarios and vice versa for the time element “waiting at plant” where the terminal scenarios had higher shares.

3.3.3 Effect of the terminal location on chip supply cost

The study investigated the effect of the terminal location – in terms of the distance between the terminal and the heat and power plant – on the supply cost of forest chips. The results show that the total supply costs rise with the increasing distance of the terminal from the plant (Figure 11).

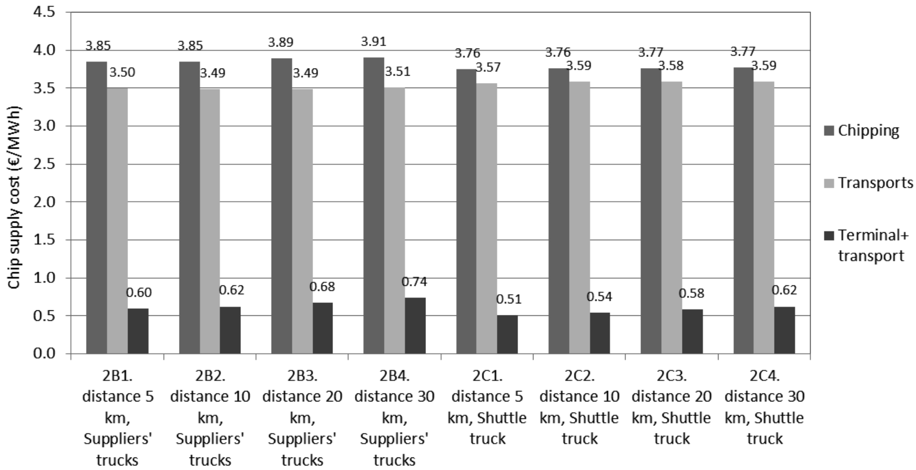


Figure 11. The supply cost structure of forest chips based on the distance between the terminal and the heat and power plant varying from 5, 10, 20 to 30 km. The transports represent direct transports to the plant and to the terminal using the suppliers' own chip trucks or a separate shuttle truck.

In case the supplier's trucks were used for terminal transports, the total chip supply costs increased from 7.95 € MWh^{-1} for a distance of 5 km between the terminal and the plant, 7.96 € MWh^{-1} for 10 km, 8.06 € MWh^{-1} for 20 km, and up to 8.16 € MWh^{-1} for a distance of 30 km. The supply costs were marginally lower in all cases where a separate shuttle truck was used for terminal transports from the terminal to the plant, nevertheless the total chip supply costs increased from 7.84 € MWh^{-1} for a distance of 5 km between the terminal and the plant, 7.89 € MWh^{-1} for 10 km, 7.93 € MWh^{-1} for 20 km to 7.98 € MWh^{-1} for a distance of 30 km.

3.4 Analysis of energy efficiency of supply systems (Article IV)

3.4.1 Efficiency and fuel consumption of chippers and trucks

The study investigated truck transport efficiency, energy density, transportation productivity, truck fuel economy and the chipper fuel economy for the main scenarios taking into account two chipper options, two raw materials and three truck alternatives. The result reveal that all the mentioned performance and efficiency indicators were positive for the larger 69-tonne ETS truck, improving efficiency by 4 to 17%, compared to the business-as-usual (BAU) scenario (Figure 12). Efficiency measure improvements were seen for the larger 69-tonne ETS truck compared to the 60-tonne truck-trailer unit when handling both raw materials, logging residues and small diameter trees. For the 52-tonne semitrailer option, only the truck fuel economy when using logging residues improved compared to the BAU scenario. When using the hybrid chipper in scenario 3A2, the chipping fuel economy improved by 13% on the one hand, whereas, on the other hand, transportation productivity decreased by 16% compared to the BAU scenario. The use of small diameter trees with a 60-tonne truck-trailer in scenario 5A2 improved the transportation productivity, but otherwise affected the efficiencies negatively.

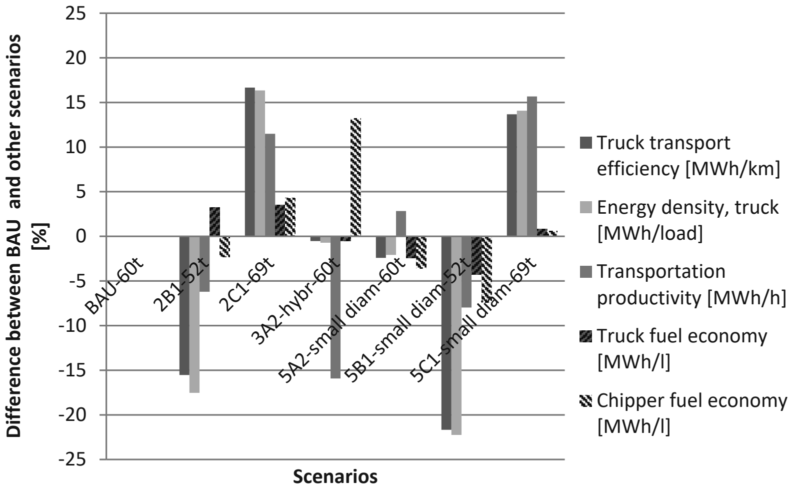


Figure 12. Truck transport efficiency (MWh km^{-1}), energy density of the trucks (MWh $load^{-1}$), transportation productivity (MWh h^{-1}), truck fuel economy (MWh l^{-1}), and the chipper fuel economy (MWh l^{-1}) for selected scenarios. The figure shows the difference between the business-as-usual and other supply scenarios as percentage values.

The study showed that diesel fuel consumption per unit product (l MWh^{-1}) for both, chipper and truck fuel consumption varied little between the compared main scenarios. Fuel consumption was lowest for the hybrid chipper (Figure 13). However, this figure only considers the fuel consumption and does not take the transportation productivity into account as shown in Figure 12.

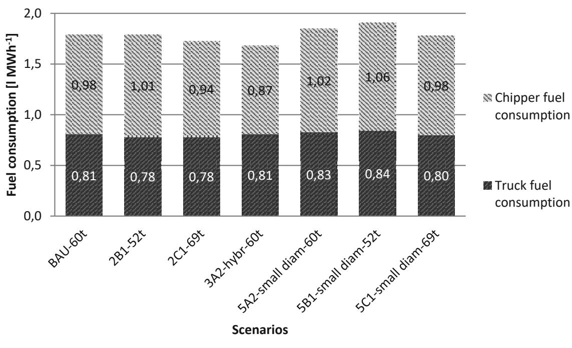


Figure 13. Diesel fuel consumption (l MWh^{-1}) for trucks and chippers for selected scenarios.

3.4.2 The effect of the transportation distance on supply costs

The results of the study showed increasing supply costs for the three truck transportation alternatives as a function of growing transportation distances. Supply costs are separated into transportation costs, chipping costs and the total supply costs as a sum of these (Figure 14). The differences between the truck alternatives were marginal over short transportation distances but increased with the distance. Chipping costs increased with the distance due to increasing shares of waiting time for the chippers. Independent of simulated transportation distances, the 69-tonne ETS truck-trailer resulted in the lowest chipping and total supply costs for forest chip transportation originating from logging residues.

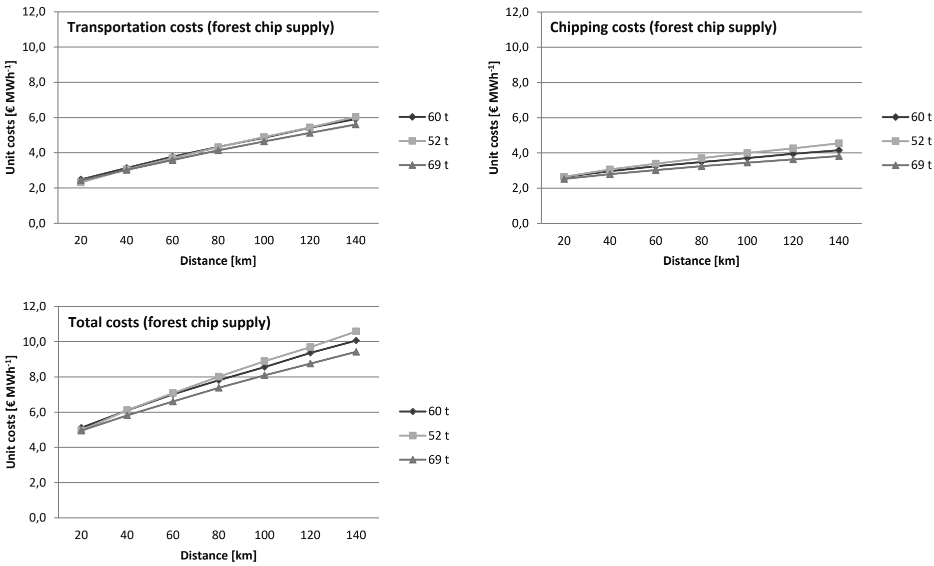


Figure 14. Transportation costs (upper left), chipping costs (upper right) and total costs (lower) for the forest fuel supply of logging residues, € MWh^{-1}, as a function of the transportation distance (in km).

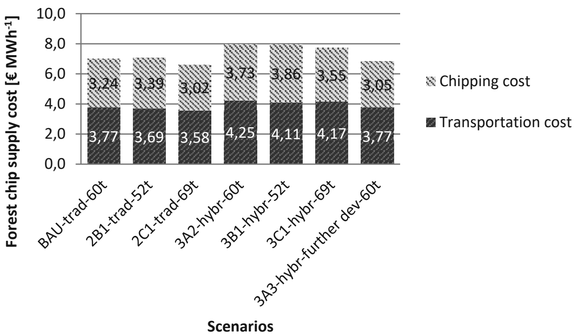


Figure 15. Forest chip supply costs of logging residues (€ MWh^{-1}) for simulated chipper scenarios at a transportation distance of approximately 60 km.

3.4.3 The effect of chipper choice on the supply costs

The study investigated the effect of the choice of chipper, between a traditional chipper or hybrid chipper in its current development stage, on the unit costs of the forest chip supply. The results showed that the traditional chipper was the economically feasible choice regardless of truck alternative used (Figure 15). The result revealed that the 69-tonne ETS truck-trailer unit had the lowest supply costs when using a traditional chipper. In this case the total supply costs were 6.6 € MWh^{-1}. In a case with further development of the hybrid chipper, whereby the same productivity as in the traditional chipper at a lower fuel consumption was assumed, a decrease of 3% in the overall forest chip supply costs compared to the BAU scenario was shown.

3.4.4 The effect of the raw material on supply costs

The raw material used for forest chip supply in this study consisted of logging residues or small diameter trees and this had an effect on the forest chip supply costs, whereby the 69-tonne ETS truck-trailer unit showed the lowest and the 52-tonne semitrailer unit the highest overall supply costs (Figure 16). For both the larger truck-trailer units the small diameter tree assortment was beneficial, in terms of supply costs, compared to the transportation of logging residue chips. In contrary, the 52-tonne semitrailer unit showed higher overall supply costs for the small diameter tree assortment compared to logging residues.

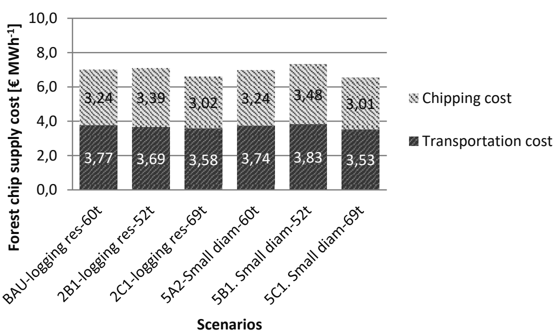
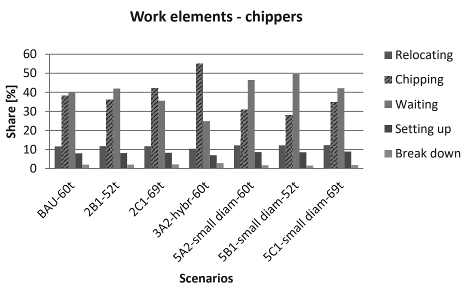


Figure 16. Forest chip supply costs (€ MWh^{-1}) for simulated raw material scenarios at a transportation distance of approximately 60 km.

3.4.5 Work elements for the chipper and chip trucks

The analysis of the time consumption of work elements for the chippers in different scenarios revealed that the "waiting" work element had the largest proportion for all other simulated scenarios except the scenarios including the 69-tonne ETS truck-trailer when chipping logging residues and when using the hybrid chipper. In both these cases "chipping" accounted for the largest proportion of the time elements (Figure 17). The waiting time for the chippers was higher and consequently chipping time was lower when chipping small diameter trees compared to the chipping of logging residues. Relocating the machines took a proportion of 10 to 12% of the working time, while setting up the chipper accounted for 7 to 9% of the time and breakdowns accounted for less than 3% of the working time.

The analysis of the time consumption of the work elements for the chip trucks in different scenarios revealed that the "driving loaded" work element accounted for the largest proportion for all simulated scenarios except the scenario using the hybrid chipper where "loading" accounted for the largest proportion of the time elements (Figure 17). "Driving loaded" accounted for between 26 and 36% of the overall working time, while the "driving empty" work element reached proportions of 24 to 32% for all scenarios followed by the element "loading" with 14 to 29%. The results show a marginal difference between the transportation of different raw materials: the driving shares are higher and loading times are lower for the transportation of chips from small diameter trees compared to logging residue chips.



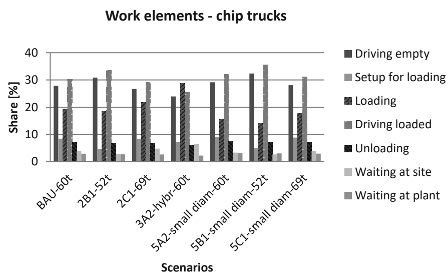


Figure 17. Distribution of the time elements of the chippers (left) and chip trucks (right) for selected scenarios.

4. DISCUSSION

This study looked at efficiency and performance measures at various levels. The focus was mainly, but not exclusively, on fuel efficiency and the related energy efficiency. One aim in this respect was also to identify the effects influenced by studied efficiency measures, including:

- Change within the machine through modifications to various settings
- Change of machine with hybrid technology
- Change of supply chain by adding a terminal
- Change of supply system and the effect on fuel supply costs

Each study looked at ways to quantify the different effects, using distinct fuel efficiency measures. According to Magagnotti and Spinelli (2012), "Work measurement studies can be classified according to their scope, goals and characteristics, with different study types normally requiring different experimental designs and statistical techniques." The thesis has applied two main methods in the studies (Articles I-IV): first, work study was the main method applied in Articles I and II, second, a desktop-based simulation study method was used in Articles III and IV. The work studies included both automatic data collected by machines and manual time study measurements. The range of the presented methods was considered suitable and was applied in order to benefit from the advantages of each method compared to alternative methods in each specific case and operational environment. Consequently, the approach allowed the effects of certain changes to the applied machinery or entire supply chain to be studied which would otherwise not be possible, especially given a rational timeframe. This is the case in particular for studying the effects of newly developed or applied machinery or machine parameters and prototypes.

Energy efficiency was considered differently, adapted to the context of the thesis, than the particular way described by existing sets of indicators (see Proskuryakova & Kovalev 2015); however, it was not the intention of this study to develop new energy efficiency indicators. The physical level was included and covered in Articles I and II. Article I on the harvester settings was affected by direct modifications of technical machine settings and included performance indicators such as the fuel consumption per unit product and linked CO_2 emissions. The hybrid chipper study (Article II) was also implemented on a physical level through the conversion of mechanical energy produced by the diesel engine into electric energy used in the motors driving the chipper's operational parts. The performance aspects included the fuel consumption, energy consumption, productivity, engine utilisation and emissions. The technological level was covered by Articles I, II and IV in which the fuel consumption especially was the common performance parameter.

In Article I, the data was based on machine records with additional measurements of fuel consumption. These measurements were then taken into account by calculating a correction factor. The advantages of both the manual and automatic recording of data in time studies on harvesters was discussed by Nuutinen (2013), in which the limitations of manual time studies in providing detailed and diverse information in order to continue the development of harvesters or harvester functions were discussed. Also Arlinger and Möller (2014) compared manual and automatic time studies for two harvesters, which resulted in similar results with only minor differences. Brewer et al. (2018) compared productivity models derived from two methods of data collection using manual time study and machine data recording using StanForD stem records. The authors revealed significant differences in

DBH and volume measurements whereas no significant difference in the productivity models was found. The authors highlight the advantages of automatically collected data from stem files as a more efficiency method of productivity modelling mentioned by Olivera et al. (2016), Nuutinen (2013) or Strandgard et al. (2013). In addition to the convenience of automatically recorded data, Olivera et al. (2016) mentions the economic benefits due the absence of direct additional costs of data collection. Strandgard and Mitchell (2015) used the Global Positioning System (GPS) and a sensor for an automated time study of three forwarders and compared them with traditional time and motion studies. While the study showed that the automatic time study accurately determined cycle times, the labelling of the time elements revealed some errors which might need further controlling to the system. The limitations of machine data are also discussed by Brewer et al. (2018), e.g., when element level details or other observational details are required. In the case of the study presented in Article I, the choice of method can be justified by the focus on the detailed level of fuel consumption for defined settings applied to several machines. Thus a large dataset was collected automatically by the harvesters; a detailed element level was not required in this case. As a result, detailed information from the studied CTL harvesting machines is presented in Article I and showed that extreme machine settings had a statistically significant impact on fuel economy. This is generally similar to a recently published study on reduced fuel use of excavator-based machines using a machine control system (Spinelli and Moura 2019). Nevertheless, the results show some indication that the currently used business-as-usual setting may already integrate characteristics of the ECO mode regarding fuel economy in regular operations.

While modern harvesting machinery collects data using their on-board computers (OBC), data collection of machines without such systems needs to rely on external observation methods such as time and motion studies. Traditional time or motion study methods have been applied to the forest biomass supply in a large number of studies, although the effect of the skills of the observers in minimising errors has been discussed (Spinelli et al. 2013, Nuutinen et al. 2008). Additionally, other observer effects which might interfere with normal work, such as the Hawthorne effect, which describes the tendency of the performance of individuals to change when being observed, must be considered (Magagnotti and Spinelli 2012, Eriksson and Lindroos 2014). In Article II, data was collected applying the continuous time study method (Harstela 1991, 1993; Magagnotti et al. 2013) when observing the studied chipper alternatives including the hybrid chipper prototype. This method was chosen and found suitable for the studied machines due to the limited observational units and short period of observations, as well as a lack of follow-up data and automated data collection systems; the observation by an experienced researcher allowed the time consumption on an element level to be investigated. As a result, the relative time consumption for pure chipping is an indicator of the capacity utilisation of the chipping unit, and observations indicated that both the hybrid chipper and the medium-powered conventional chippers showed lower capacity utilisation. Nevertheless, the study revealed that the hybrid chipper was the most energy efficient machine in terms of litres of diesel or kWh per odt of chipped material compared to conventional chippers; although in general, the fuel consumption reported in Article II were similar compared to previous studies (Spinelli et al. 2011, Laitila and Routa 2015, Eliasson et al. 2015, Holzleitner et al. 2013).

On the enterprise level, Article III on the terminal alternative and Article IV on the alternative supply systems can be mentioned. Relevant indicators included the supply costs, production, machine utilisation, dry matter loss and the security of fuel supply at this level.

On the enterprise level, Article IV enlarged the performance indicators by including efficiency and fuel economy in addition to the otherwise overlapping indicators presented in Article III. In the context of this thesis, different efficiency measures were used and applied to the context of the forest chip supply, truck transport efficiency, energy density, truck fuel economy and chipper fuel economy. The transport efficiency was expressed in MWh of transported chips per kilometre driven, and the energy density was expressed in MWh per load. The fuel economy values for trucks and chippers in this context were expressed as MWh of handled material per litre of diesel fuel consumed. The industrial level was partly covered by Articles III and IV, although the economic indicators were limited to supply costs of supplying wood chips to a CHP plant typically involving several enterprises, including fuel supply sub-contractors comprising numerous machines, eventually a terminal operating enterprise and the enterprise operating the plant itself. The macroeconomic level in energy efficiency indicator sets (see Proskuryakova & Kovalev 2015) was considered to be outside the scope of the thesis.

The effect of adding a feed-in-terminal to the forest chip supply chain was shown in Article III, in which the use of a feed-in-terminal in addition to direct fuel deliveries added extra costs to the supply costs because of the operation of the terminal. However, a benefit was shown in the improved balance of seasonal fluctuation of the fuel supply fleet and its use of machinery.

Discrete-event simulation was used in Articles III and IV. This method allowed the testing of findings from a technological level originating from a time study (Article II) on the entire supply system on the enterprise level (Article IV). This was in line with Asikainen (1995) who stated that “the effect of an improvement in one stage can be seen at the system level”. The aim in Articles III and IV was to apply a DES model which imitates reality and behaves close to reality, similarly to Windisch et al. (2015). A comparison between time study and the DES approach by She et al. (2018) revealed only minor differences for machine cycle times and productivity, but found that machine utilisation rates were somewhat different. However, the authors favoured DES when analysing complex systems with machine process interactions (She et al. 2018). Furthermore, the DES method allowed effect of selected changes on the supply condition of forest chips to the end-using facility to be investigated without having the need for actual practical implementation of a terminal or innovative machinery on a larger scale, which would be risk and investment intensive, as well as time consuming. However, this method stresses the importance of the validation process by relating results to findings from literature and practice. Similarly, by using DES, Asikainen (1995) stated the possibility to test a new chipper development under conditions in which they will or could operate. According to the author, interactions between machines should be minimised, and chipper and long-distance transport are systems with advantages for the DES method. In addition, simulation helps to identify bottlenecks (Asikainen 1995), e.g., if a number of trucks would be sufficient or not to fulfil the plant’s demand.

The findings of Article III show that cost compensation for additional terminal investment and operation costs can be gained through a higher annual use of a fuel supply fleet. This might be of interest to entrepreneurs in the transportation sector who see a challenge in the future regarding labour costs due to a possible lack of skilled drivers (Malinen et al. 2014). Additionally, the use of a terminal can better secure fuel supplies to power plants by reducing the need for (expensive) supplementary fuel. A lack of wood fuel terminals was found to be one of the challenges for the supply security of wood fuel (Karhunen et al. 2015). The findings moreover showed that machine utilisation of mobile chippers was low compared to earlier studies (Asikainen 1995, Spinelli & Visser 2009, Eliasson et al. 2012), whereas the results in general were rather comparable to the findings of Windisch et al. (2015). In addition, the study revealed that although the overall chip supply costs increased, the supply costs were marginally lower in all cases when a separate shuttle truck with a higher load space was used for terminal transports from the terminal to the plant. Nevertheless, Gautam et al. (2017) showed that the incorporation of a terminal in a biofuel supply chain network can provide a lower MC for forest biomass and reduce the procurement cost.

Interestingly, the performance of the hybrid chipper prototype when observed on the machine level showed high energy efficiency compared to conventional chippers (Article II). However, when looking at this on the system level, this advantage was diminished by the poor productivity of the truck waiting for the chipper to load the truck's load. Thus, the effect of the very positive fuel economy of the chipper was reduced by the low transportation productivity. In contrast, the use of the 52-tonne semitrailer showed marginally positive truck fuel economy. However, at the same time there was negative truck transport efficiency, energy density of the trucks, transportation productivity and chipper fuel economy compared to the basic (BAU) scenario. Under the given simulation conditions the study revealed that vehicles with a higher carrying capacity improved the overall supply cost competitiveness compared to lower capacity trucks. Lower costs were achieved when using the highly productive traditional chipper. Due to the lower bulk weight densities of the transported material, forest chips from small-diameter trees were found to be more beneficial for the larger truck alternatives; smaller semitrailers increased their competitiveness for both short distances and for higher moisture content or higher bulk-weight densities of transported material. New, alternative machine types, such as the 69-tonne truck-trailer with an electronic trailer steering system, improve the fuel economy and efficiency. Thus, the work presented fills a gap mentioned by Koirala et al. (2018) who mentioned the need for additional research on increasing the efficiency of transportation systems, in particular trucking, and the transportation costs. The authors furthermore consider discrete-event simulation models for biomass supply logistics to be a suitable and economically viable tool to estimate transportation costs and performance. The findings of Article IV with positive efficiency impacts when utilising larger transport vehicles are in line with results presented in previous studies. Large and heavy vehicles (LHVs) and their utilisation in Finland have shown to have a positive impact on both energy and environmental efficiency (Palander 2016, 2017, Palander and Kärhä 2017, Palander et al. 2018). Correspondingly, Busenius et al. (2015) showed the reduction of CO_2 emissions when using increasing payloads in log transportation.

Lautala et al. (2015) conclude in their study that "energy consumption, GHG emissions, and overall environmental impacts should be evaluated in unison with logistics costs, as they vary greatly according to transport and logistical decisions made." The authors recommend focussing future research on establishing a common framework allowing the comparison of potential implementations or their impact, improved integration of the supply chain and related analysis, the use of new technologies in transportation logistics and a robust biomass trading market. The authors also conclude that the analysis and monitoring of potential and actual implementations is difficult with a lack of a common framework and a set of environmental, economic, and social sustainability metrics and indicators to compare locations, technologies and practices (Lautala et al. 2015). Additionally, Ko et al. (2018) concluded that studies have concentrated on improving the system efficiency of truck transportation, but that there is a lack of sustainable transportation cost model taking economic, environmental and social factors into account.

Therefore, a new approach to improve energy efficiency and fuel economy in the forest chip supply is proposed in this thesis (Figure 18). This integrated approach takes proposed levels of energy efficiency into account whereby suitable performance and efficiency indicators are selected which are fitting to the study content. In addition, suitable, proven and adjusted research methods such as continuous time study and discrete-event simulation as well as their data sources are an essential part of this approach in which one method or data source can complement another for a more holistic analysis. The overall aim is to gain a better understanding and ideally improve the energy efficiency and fuel economy of the state-of-the-art forest technology and forest biomass supply chains. Furthermore the sustainability of the biofuel industry depends on its capability to develop an economically competitive supply chain (Lautala et al. 2015), although the choice of the biomass source is an essential aspect.

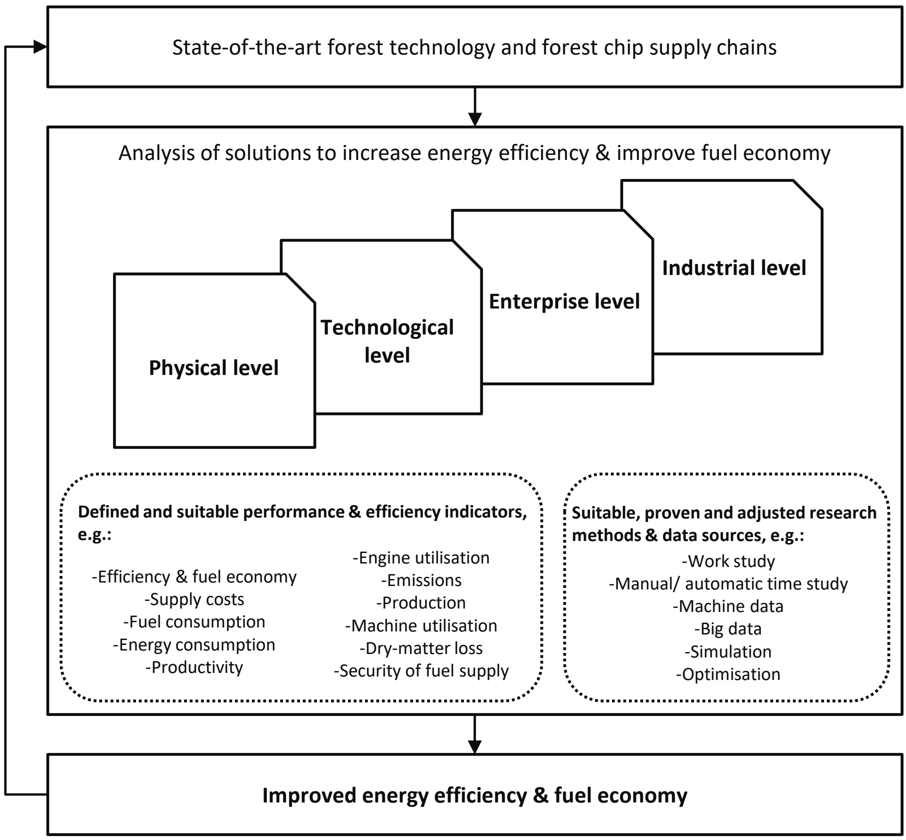


Figure 18. Proposed approach to improve energy efficiency and fuel economy in forest chip supply.

In reflection of Patterson (1996), by consuming less energy (in this case in form of diesel fuel for machines operating in the forest biomass supply) to produce the same amount of useful output (in this case in terms of the handled cubic meters or MWh of biomass), the economic, environmental and social outcome for all the stakeholders involved will be better than it would be without such an effort. The costs per unit can be lower, fewer emissions can be emitted and positive employment effects can be seen. Economic (e.g., supply costs) and environmental effects (e.g., emissions) were shown in this thesis.

Taking the results of this thesis into account and considering sustainability aspects crucial in forest operations, the CEC's energy efficiency catchphrase could be re-formulated to the following phrase: "Doing Better With Less".

The state-of-the-art of forest technology and current biomass supply can be affected and upgraded to a new, improved performance and energy efficiency.

Based on the results of the four articles, the research questions can be answered and concluded as follows:

1) Extreme machine settings have a statistically significant impact on fuel economy of CTL harvesting machines and should be considered in CTL harvesting operation, e.g. in machine design. However, the results show also some indication that the currently used business-as-usual setting may already integrate characteristics of the ECO mode regarding fuel economy in regular operations.
2) Hybrid machine technology can improve the fuel consumption and energy efficiency of chipping operations in forest chip production and has an effect on CO_2 emissions, although the productivity of the analysed prototype was below that of the compared traditional chippers.
3) Using a feed in terminal as an alternative to the direct supply of forest chips has a negative effect on the overall supply cost, and can be quantified. However, terminal use improves the annual use of the supply fleet and enhances the fuel supply security to the plant, thereby reducing the need for supplementary fuel.
4) The effect of applying different type chipper and truck-trailer combinations on the supply costs and efficiencies can be quantified. Thereby vehicles with increased carrying capacity, such as the 69-tonne truck-trailer with an electronic trailer steering system, improve the fuel economy and the cost competitiveness.

5. FUTURE RESEARCH NOTES

The topics studied and presented in this thesis could not cover all the aspects of energy efficiency and performance parameters of the investigated machines under various operational environments. Therefore a research gap remains for future research in the field, which could be addressed in possible forthcoming studies and experiments.

Based on the research conducted so far, future research could look deeper into the factors causing differences in the performance parameters with selected machine settings. It was shown that extreme machine settings have a statistically significant impact on the fuel economy of CTL harvesting machines. An upcoming study could look into a single machine whereby single machine parameters are modified one at a time. Thereby the parameters most influencing the performance could be identified, and consequently also modified according to operational needs. In addition, other machines could be tested with different machine settings for fuel consumption and energy efficient performance, for example, forwarders in CTL harvesting or excavators, which could also be similar to the excavator-based harvesting system and machine control system presented recently by Spinelli and Moura (2019). Moreover, machine setting tests could also be conducted under other silvicultural prescriptions or stand characteristics. The presented study was conducted in thinning operations, while a future study should correspondingly include clear felling in order to see the effects of higher average diameters and larger stem volumes. In this case, machines might reach some limitations when operating in clear felling in ECO mode, which were not identified in thinnings operations. In general, future research should also look into standardised automated data collection methodologies and procedures for analysing collected data ensuring the reliability and professionality of research in the field of forest technology and logistics. Big data is an increasingly important topic with a large potential for investigating performance improvements on various levels.

The use of an innovative hybrid chipper and new vehicles, which in practice are currently only in the prototype phase or not yet in common use in the forest chip supply chain, will need further investigation and follow-up studies from the research side following further developments for a more accurate determination of their long-term productivity, fuel consumption, and operating costs.

Another topic for upcoming research could be the terminals and their utilisation. As there is an increasing amount of material flowing through the terminals, a future study could investigate the effects of the terminal size and the distance of the terminal to the plant. The presented work has shown that a terminal location closer to the plant is favourable, but in this case, the size of the terminal was not limited and therefore it was fairly large. It could be studied whether smaller, but larger numbers of terminals along the main supply roads or distributed throughout the supplying area would be beneficial. Especially when considering climate related changes and their effect on the bad-road season in spring, it will have to be shown whether such distributed terminal options might be favoured. In times when soft roads cannot be accessed at all, terminals located next to asphalted roads might provide a measure to ensure the year-round supply of raw material to end-using facilities. The discrete-event simulation methodology could allow new developments related to regulatory or legislative changes concerning the loading capacity of transportation vehicles, chipping equipment and their interactions to be studied as well as new logistical solutions. The importance of the verification and validation process in studies using discrete-event simulations was identified as a common shortcoming, among others, recently by Kogler & Rauch (2018). Therefore, it would be beneficial for future research to also include long-term follow up studies to validate simulated cases and their cost calculations. This, however, would require that the investigated alternative(s) or solution(s) applied in the simulation studies are introduced into common practice allowing for follow-up studies to be conducted in a real working environment.

REFERENCES

Acuna M., Anttila P., Sikanen L., Prinz R., Asikainen A. (2012a). Predicting controlling moisture content top optimise forest biomass logistics. Croatian Journal of Forest Engineering 33:2. 225-238.

Acuna M., Mirowski L., Ghaffariyan M.R., Brown M. (2012b). Optimising transport efficiency and costs in Australian wood chipping operations. Biomass and Bioenergy 46: 291-300. https://doi.org/10.1016/j.biombioe.2012.08.014.

Akhtari S., Sowlati T., Griess V.C. (2018). Integrated strategic and tactical optimization of forest-based biomass supply chains to consider medium-term supply and demand variations. Applied Energy 213: 626-638. https://doi.org/10.1016/j.apenergy.2017.10.017.

Ang B.W. (2006). Monitoring changes in economy-wide energy efficiency: From energy-GDP ratio to composite efficiency index. Energy Policy 34: 574-582. https://doi.org/10.1016/j.enpol.2005.11.011.

Anttila P., Nivala V., Salminen O., Hurskainen M., Kärki J., Lindroos T.J., Asikainen A. (2018). Regional balance of forest chip supply and demand in Finland in 2030. Silva Fennica vol. 52 no. 2 article id 9902. https://doi.org/10.14214/sf.9902.

Arlinger J., Möller J.J. (2014). Time studies based on automatic data collection. In: Proceedings of the 47th International Symposium on Forestry Mechanisation: "Forest engineering: propelling the forest value chain", September 23-26, 2014 in Gerardmer, France. 8 p.

Asikainen A. (1995). Discrete-event simulation of mechanized wood harvesting systems. D. Sc. (Agr. and For.) thesis. Research Notes 38, University of Joensuu, Faculty of Forestry. 86 p.

Asikainen A. (1998). Chipping terminal logistics. Scandinavian Journal of Forest Research 13(3): 386-391. https://doi.org/10.1080/02827589809382998.

Asikainen A. (2001). Simulation of Logging and Barge Transport of Wood from Forests on Islands. International Journal of Forest Engineering 12(2): 43-50. https://doi.org/10.1080/14942119.2001.10702445.

Asikainen A. (2010). Simulation of stump crushing and truck transport of chips. Scandinavian Journal of Forest Research 25: 245-250. https://doi.org/10.1080/02827581.2010.488656.

Athanassiadis D., Lidestav G., Wästerlund I., (1999). Fuel, hydraulic oil and lubricant consumption in Swedish mechanized harvesting operations, 1996. International Journal of Forest Engineering 10(1): 59-66.

Balci O. (1994). Validation, verification, and testing techniques throughout the life cycle of a simulation study. Annals of Operations Research 53: 121-173. https://doi.org/10.1007/BF02136828.

Banks J., Carson II J.S., Nelson B.L., Nicol D.M. (2010). Discrete-Event System Simulation. Fifth Edition. Pearson Education, Inc. 640 p.

Belbo H., Talbot B. (2014). System analysis of the supply chains for whole tree chips. Forests 5: 2084-2105. https://doi.org/10.3390/f5092084.

Berg S., Karjalainen T. (2003). Comparison of greenhouse gas emission from forest operations in Finland and Sweden. Forestry 76(3): 271-284. https://doi.org/10.1093/forestry/76.3.271.

Bergström D., Di Fulvio F. (2018). Review of efficiencies in comminuting forest fuels. International Journal of Forest Engineering 30(1): 45-55. https://doi.org/10.1080/14942119.2019.1550314.
Björheden R. (1991). Basic Time Concepts For International Comparisons of Time Study Reports. Journal of Forest Engineering 2: 33-39. https://doi.org/10.1080/08435243.1991.10702626.
Björheden R. (2017). Development of Bioenergy from Forest Biomass – a Case Study of Sweden and Finland. Croatian Journal of Forest Engineering 38:2. 259-268.
Björheden R., Apel K., Shiba M., Thompson M. (1995). IUFRO forest work study nomenclature. Swedish University of Agricultural Science. Department of Operational Efficiency. Garpenberg. 16 p.
Borz S.A., Acuna M., Heinimann H.R., Palander T., Spinelli R. (2017). Innovating the competitive edge: from research to impact in the forest value chain: half-century of FORMEC. Annals of Forest Research 60(2): 199-201. https://doi.org/10.15287/afr.2017.914.
Brewer J., Talbot B., Belbo H., Ackerman P., Ackerman S. (2018). A comparison of two methods of data collection for modelling productivity of harvesters: manual time study and follow-up study using on-board-computer stem records. Annals of Forest Research 61(1): 1-16. https://doi.org/10.15287/afr.2018.962.
Brunberg T. (2016). Forest fuel - trends over 5 years. In: Palmér C.-H., Eliasson L., Iwarsson Wide M. (eds). Forest energy for a sustainable future. Composite report from the R&D programme efficient forest fuel supply systems 2011-2015. Uppsala (Sweden). Skogforsk. p. 36–37.
Busenius M., Engler B., Smaltschinski T., Opferkuch M. (2015). Consequences of increasing payloads on carbon emissions – an example from the Bavaria State Forest Enterprise (BaySF). Forestry Letters 108: 7-14.
Carson II J.S. (2005). Introduction to modeling and simulation. In: Proceedings of the 2005 Winter Simulation Conference. Kuhl M.E., Steiger N.M., Armstrong F.B. and Joines J.A. (eds.). p. 16-23. https://doi.org/10.1109/WSC.2005.1574235.
CEC (2005). Green Paper on Energy Efficiency or Doing More With Less. COM(2005) 265 final. Commission of the European Communities. Brussels 2005. 51 p.
Cleveland C.J., Morris C. Dictionary of Energy (Second Edition) (2015). Fuel Economy. 700 p. https://doi.org/10.1016/C2009-0-64490-1.
de la Fuente T., Athanassiadis D., González-García S., Nordfjell T. (2017). Cradle-to-gate life cycle assessment of forest supply chains: Comparison of Canadian and Swedish case studies. Journal of Cleaner Production 143: 866-881. https://doi.org/10.1016/j.jclepro.2016.12.034.
Díaz-Yáñez O., Mola-Yudego B., Anttila P., Röser D., Asikainen A. (2013). Forest chips for energy in Europe: Current procurement methods and potentials. Renewable and Sustainable Energy Reviews 21: 562-571. https://doi.org/10.1016/j.rser.2012.12.016.
Di Fulvio F., Eriksson G., Bergström D. (2015). Effects of wood properties and chipping length on the operational efficiency of a 30 kW electric disc chipper. Croatian Journal of Forest Engineering 36(1): 85–100.
Đuka A., Vusić D.,Horvat D.,Šušnjar M.,Pandur Z.,Papa I. (2017). LCA Studies in Forestry – Stagnation or Progress? Croatian Journal of Forest Engineering 38(2): 311–326.
Einola K. (2013). Prestudy on power management of a cut-to-length forest harvester with a hydraulic hybrid system. The 13th Scandinavian International Conference on Fluid

Power, SICFP2013, June 3–5 2013, Linköping, Sweden, p. 71–83. https://doi.org/10.3384/ecp1392a8.
Eliasson L., Eriksson A., Mohtashami S. (2017). Analysis of factors affecting productivity and costs for a high-performance chip supply system. Applied Energy 185: 497-505. https://doi.org/10.1016/j.apenergy.2016.10.136.
Eliasson L., von Hofsten H., Johannesson T., Spinelli R., Thierfelder T. (2015). Effects of Sieve Size on Chipper Productivity, Fuel Consumption and Chip Size Distribution for Open Drum Chippers. Croatian Journal of Forest Engineering 36:1: 11-17.
Eliasson L., Granlund P., von Hofsten H., Björheden R. (2012). Studie av en lastbilsmonterad kross – CBI 5800 study of a truck-mounted CBI 5800 grinder. Arbetsrapport Från Skogforsk nr 775. 16 p. [Swedish with English abstract].
EPA (2016). Direct Emissions from Mobile Combustion Sources. Greenhouse Gas Inventory Guidance. United States Environmental Protection Agency. Washington DC. 23 p.
EPRS (2015). Understanding energy efficiency. Briefing October 2015. European Parliamentary Research Service. 10 p.
Erber G., Kühmaier M. (2017). Research Trends in European Forest Fuel Supply Chains: a Review of the Last Ten Years (2007-2017) – Part One: Harvesting and Storage. Croatian Journal of Forest Engineering 38:2. 269-278.
Eriksson A. (2016). Improving the efficiency of forest fuel supply chains. Acta Universitatis Agriculturae Sueciae 2016:101. 73 p.
Eriksson A., Eliasson L., Sikanen L., Hansson P.-A., Jirjis R. (2017). Evaluation of delivery strategies for forest fuels applying a model for weather-driven analysis of forest fuel systems (WAFFS). Applied Energy 188: 420-430. https://doi.org/10.1016/j.apenergy.2016.12.018.
Eriksson A., Eliasson L., Jirjis R. (2014a). Simulation-Based evaluation of supply chains for stump fuel. International Journal of Forest Engineering 25(1): 23-36. https://doi.org/10.1080/14942119.2014.892293.
Eriksson A., Eliasson L., Hansson P.-A., Jirjis R. (2014b). Effects of Supply Chain Strategy on Stump Fuel Cost: A Simulation Approach. International Journal of Forest Research Vol. 2014 Article ID 984395. 11 p. https://doi.org/10.1155/2014/984395.
Eriksson G., Bergström D., Nordfjell T. (2013). The state of the art in woody biomass comminution and sorting in Northern Europe. International Journal of Forest Engineering 24(3): 194–215. https://doi.org/10.1080/14942119.2013.852391.
Eriksson M., Lindroos O. (2014). Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. International Journal of Forest Engineering 25(3): 179-200. https://doi.org/10.1080/14942119.2014.974309.
European Commision (2013). A 2030 framework for climate and energy policies. Green Paper. COM(2013) 169 final.. Brussels 2013. 16 p.
European Commision (2018a). A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank. COM(2018) 773 final.. Brussels 2018. 25 p.
European Commision (2018b). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). Brussels 2018. 128 p.

European Commision (2018c). Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. Brussels 2018. 21 p.

Filimonau V. (2016). Life Cycle Assessment (LCA) and Life Cycle Analysis in Tourism. A Critical Review of Applications and Implications. 136 p. https://doi.org/10.1007/978-3-319-26224-6.

Fogdestam N., Löfroth C. (2015). ETTdemo 2011–2013: Slutrapport, demonstration av ETT- och ST-fordon [ETT-demo, demonstration of ETT- and ST-vehicles]. Arbetsrapport Från Skogforsk nr. 872–2015. 50 p. [In Swedish with English summary].

Freedonia (2015). World Forestry Equipment. Industry Study 3270. June 2015. 371 p.

Gautam S., LeBel L., Carle M.-A. (2017). Supply chain model to assess the feasibility of incorporating a terminal between forests and biorefineries. Applied Energy 198: 377-384. https://doi.org/10.1016/j.apenergy.2017.01.021.

Ghaffariyan M.R., Brown M., Acuna M., Sessions J., Gallagher T., Kühmaier M., Spinelli R., Visser R., Devlin G., Eliasson L., Laitila J., Laina R., Iwarsson Wide M., Egnell G. (2017). An international review of the most productive and cost effective forest biomass recovery technologies and supply chains. Renewable and Sustainable Energy Reviews 74: 145–158. https://doi.org/10.1016/j.rser.2017.02.014.

Gronalt M., Rauch P. (2018). Analyzing railroad terminal performance in the timber industry supply chain – a simulation study, International Journal of Forest Engineering 29:3. 162-170. https://doi.org/10.1080/14942119.2018.1488913.

Haavikko H., Kärhä K., Hourula M., Palander T. (2019). Attitudes of Small and Medium-Sized Enterprises towards Energy Efficiency in Wood Procurement: A Case Study of Stora Enso in Finland. Croatian Journal of Forest Engineering 40(1): 107–123.

Hakkila P. (2004). Developing technology for large-scale production of forest chips. Wood Energy Technology Programme 1999-2003. Technology Programme Report 6/2004. Final Report. 99 p.

Han H., Chung W., Wells L., Anderson N. (2018). Optimizing Biomass Feedstock Logistics for Forest Residue Processing and Transportation on a Tree-Shaped Road Network. Forests 2018, 9, 121. 19 p. https://doi.org/10.3390/f9030121.

Harstela P. (1991). Work studies in forestry. University Joensuu Silva Carelica. 18:41.

Harstela P. (1993). Forest work science and technology, Part I. Silva Carelia. 25:113.

Heinimann H.R. (2012). Life Cycle Assessment (LCA) in Forestry – State and Perspectives. Croatian Journal of Forest Engineering 33(2): 357-372.

Hellström T., Lärkeryd P., Nordfjell T., Ringdahl O. (2009). Autonomous Forest Vehicles: Historic, envisioned, and state-of-the-art. International Journal of Forest Engineering 20:1. 31-38. https://doi.org/10.1080/14942119.2009.10702573.

Holzleitner F., Kanzian C., Stampfer K. (2011a). Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager. European Journal of Forest Research 130: 293–301. https://doi.org/10.1007/s10342-010-0431-y.

Holzleitner F., Stampfer K., Visser R. (2011b). Utilization Rates and Cost Factors in Timber Harvesting Based on Long-term Machine Data. Croatian Journal of Forest Engineering 32(2): 501–508.

Holzleitner F., Kanzian C., Höller N. (2013). Monitoring the chipping and transportation of wood fuels with a fleet management system. Silva Fennica. 47(1) article id 899. 11 p. https://doi.org/10.14214/sf.899.

IEA (2018). Energy policies of IEA countries. Executive summary. Finland. 2018 Review. International Energy Agency. 9 p.

Immonen P. (2013). Energy efficiency of a diesel-electric mobile working machine. Acta Universitatis Lappeenrantaensis 518. 133 p.

Impola R., Tiihonen I. (2011). Terminaalikäsikirja (Terminal guidebook). VTT-R-08634-11. Jyväskylä. VTT Technical research centre of Finland. 38 p. [in Finnish].

IPCC (2018). Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 p. http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf. [accessed 04 February 2019].

Jäppinen E. (2013). The effects of location, feedstock availability, and supply-chain logistics on the greenhouse gas emissions of forest-biomass energy utilization in Finland. Acta Universitatis Lappeenrantaensis 527. 61 p.

Johnsen T. (2017). Logset 12H GTE Hybrid-electric Harvester. https://www.forestry.com/editorial/logset-12h-gte-electric-hybrid-harvester/. [Accessed 12 February 2018].

Junginger H.M. (2005). Learning in Renewable Energy Technology Development. Utrecht University. Dissertation. 215 p.

Kanzian C., Kühmaier M., Erber G. (2016). Effects of Moisture Content on Supply Costs and CO_2 Emissions for an Optimized Energy Wood Supply Network. Croatian Journal of Forest Engineering 37:1. 51-60.

Kärhä K. (2011). Industrial supply chains and production machinery of forest chips in Finland. Biomass and Bioenergy 35: 3404–3413. https://doi.org/10.1016/j.biombioe.2010.11.016.

Karhunen A., Laihanen M., Ranta T. (2015). Supply security for domestic fuels at Finnish combined heat and power plants. Biomass and Bioenergy 77: 45-52. https://doi.org/10.1016/j.biombioe.2015.03.019.

Karttunen K., Lättilä L., Korpinen O.-J., Ranta T. (2013). Cost-efficiency of intermodal container supply chain for forest chips. Silva Fennica 47(4) article id 1047. 24 p. https://doi.org/10.14214/sf.1047.

Klein D., Wolf C., Schulz C., Weber-Blaschke G. (2015). 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production. International Journal of Life Cycle Assessment 20(4): 556-575. https://doi.org/10.1007/s11367-015-0847-1.

Klvac R., Skoupy A. (2009). Characteristic fuel consumption and exhaust emissions in fully mechanized logging operations. Journal of Forest Research 14(6): 328-334. https://doi.org/10.1007/s10310-009-0143-7.

Klvac R., Ward S., Owende P.M.O., Lyons J. (2003). Energy Audit of wood harvesting systems. Scandinavian Journal of Forest Research 18(2): 176-183. https://doi.org/10.1080/02827580310003759.

Ko S., Lautala P., Fan J., Shonnard D.R. (2019). Economic, social, and environmental cost optimization of biomass transportation: a regional model for transportation analysis in plant location process. Biofuels, Bioproducts and Biorefining. https://doi.org/10.1002/bbb.1967

Ko S., Lautala P., Handler R.M. (2018). Securing the feedstock procurement for bioenergy products: a literature review on the biomass transportation and logistics. Journal of Cleaner Production 200: 205-218. https://doi.org/10.1016/j.jclepro.2018.07.241.

Kogler C., Rauch P. (2018). Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review. Silva Fennica vol. 52 no 4 article id 9984. 29 p. https://doi.org/10.14214/sf.9984.

Koirala A., Kizha A.R., De Hoop C., Roth B.E., Han H.-S., Hiesl P., Abbas D., Gautam S., Baral S., Bick S., Sahoo K. (2018). Annotated Bibliography of the Global Literature on the Secondary Transportation of Raw and Comminuted Forest Products (2000-2015). Forests 9(7), 415. 28 p. https://doi.org/10.3390/f9070415.

Kons K., Bergström D., Eriksson U., Athanassiadis D., Nordfjell T. (2014). Characteristics of Swedish forest biomass terminals for energy. International Journal of Forest Engineering 25: 238–246. https://doi.org/10.1080/14942119.2014.980494.

Korpilahti A. (2015). Bigger vehicles to improve forest energy transport. Metsätehon tuloskalvosarja 3/2015. 33 p.

Koŝir B., Magagnotti N., Spinelli R. (2015). The role of work studies in forest engineering: status and perspectives. International Journal of Forest Engineering 26(3): 160-170.

Kühmaier M., Erber G. (2018). Research trends in European forest fuel supply chains: a review of the last ten years (2007–2016) – part two: comminution, transport & logistics. Croatian Journal of Forest Engineering 39(1): 139–152.

Laitila J., Routa J. (2015). Performance of a small and a medium sized professional chippers and the impact of storage time on Scots pine (*Pinus sylvestris*) stem wood chips characteristics. Silva Fennica 49(5) article id 1382. 19 p. https://doi.org/10.14214/sf.1382.

Laitila J., Ranta T., Asikainen A., Jäppinen E., Korpinen O.-J. (2015). The cost competitiveness of conifer stumps in the procurement of forest chips for fuel in Southern and Northern Finland. Silva Fennica 49(2) article id 1280. 23 p. https://doi.org/10.14214/sf.1280.

Laitila J., Asikainen A., Ranta T. (2016). Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. Biomass and Bioenergy 90: 252–261. https://doi.org/10.1016/j.biombioe.2016.04.011.

Laitila J., Poikela A., Ovaskainen H., Väätäinen K. (2019). Novel extracting methods for conifer stumps. International Journal of Forest Engineering. https://doi.org/10.1080/14942119.2019.1564614.

Laurén A., Asikainen A., Kinnunen J-P., Palviainen M., Sikanen L. (2018). Improving the financial performance of solid forest fuel supply using a simple moisture and dry matter loss simulation and optimization. Biomass and Bioenergy 116: 72-79. https://doi.org/10.1016/j.biombioe.2018.05.014.

Lautala P.T., Hilliard M.R., Webb E., Busch I., Hess J.R., Roni M.S., Hilbert J., Handler R.M., Bittencourt R., Valente A., Laitinen T. (2015). Opportunities and Challenges in the Design and Analysis of Biomass Supply Chains. Environmental Management 56: 1397-1415. https://doi.org/10.1007/s00267-015-0565-2.

Liang Y.C., Lu X., Li W.D., Wang S. (2018). Cyber Physical System and Big Data enabled energy efficient machining optimisation. Journal of Cleaner Production 187: 46-62. https://doi.org/10.1016/j.jclepro.2018.03.149.

Lijewski P., Merkisz J., Fuc P., Ziolkowski A., Rymaniak L., Kusiak W. (2017). Fuel consumption and exhaust emissions in the process of mechanized timber extraction and transport. European Journal of Forest Research 136: 153-160. https://doi.org/10.1007/s10342-016-1015-2.

Lindblad J., Routa J., Ruotsalainen J., Kolström M., Isokangas A., Sikanen L. (2018). Weather based moisture content modelling of harvesting residues in the stand. Silva Fennica vol. 52 no. 2 article id 7830. https://doi.org/10.14214/sf.7830.

Lindholm E.-L., Berg S. (2005). Energy requirement and environmental impact in timber transport. Scandinavian Journal of Forest Research 20:2. 184–191. https://doi.org/10.1080/02827580510008329.

Lindholm E.-L., Berg S., Hansson P.-A. (2010). Energy efficiency and the environmental impact of harvesting stumps and logging residues. European Journal of Forest Research 129: 1223–1235. https://doi.org/10.1007/s10342-010-0412-1.

Lindroos O., La Hera P., Häggtröm C. (2017). Drivers of Advances in Mechanized Timber Harvesting – a Selective Review of Technological Innovation. Croatian Journal of Forest Engineering 38:2. 243-258.

Magagnotti N., Spinelli R. (eds.) (2012). COST Action FP-0902 - Good practice guidelines for biomass production studies. 50 p.

Magagnotti N., Kanzian C., Schulmeyer F., Spinelli R. (2013). A new guide for work studies in forestry. International Journal of Forest Engineering 24(3): 249-253. https://doi.org/10.1080/14942119.2013.856613.

Malinen J., Nousiainen V., Palojärvi K., Palander T. (2014). Prospects and Challenges of Timber Trucking in a Changing Operational Environment in Finland. Croatian Journal of Forest Engineering 35(1): 91-100.

Malladi K.T., Quirion-Blais O., Sowlati T. (2018). Development of a decision support tool for optimizing the short-term logistics of forest-based biomass. Applied Energy 216: 662-677. https://doi.org/10.1016/j.apenergy.2018.02.027.

Marchi E., Chung W., Visser R., Abbas D., Nordfjell T., Mederski P.S., McEwan A., Brink M., Laschi A. (2018). Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. Science of the Total Environment 634: 1385-1397. https://doi.org/10.1016/j.scitotenv.2018.04.084.

Marques A., Rasinmäki J., Soares R., Amorim P. (2018). Planning woody biomass supply in hot systems under variable chips energy content. Biomass and Bioenergy 108: 265-277. https://doi.org/10.1016/j.biombioe.2017.11.016.

Ministry of Economic Affairs and Employment (2017). Government report on the national energy and climate strategy for 2030. Publications of the Ministry of Economic Affairs and Employment 12/2017. 121 p.

Niemistö P., Korpunen H., Laurén A., Salomäki M., Uusitalo J. (2012). Impacts and productivity of harvesting when retaining young understorey spruces in final cutting of downy birch (*Betula pubescens*). Silva Fennica 46(1): 81-97. https://doi.org/10.14214/sf.67.

Nordfjell T., Björheden R., Thor M., Wästerlund I. (2010). Changes in technical performance, mechanical availability and prices of machines used in forest operations in Sweden from 1985 to 2010. Scandinavian Journal of Forest Research 25(4): 382–389. https://doi.org/10.1080/02827581.2010.498385.

NETP 2016. Nordic Energy Technology Perspectives (2016). Cities, flexibility and pathways to carbon-neutrality. International Energy Agency (IEA), Nordic Energy Research 2016. 269 p.

Nuutinen Y. (2013). Possibilities to use automatic and manual timing in time studies on harvester operations. Dissertationes Forestales 156. 68 p. https://doi.org/10.14214/df.156.

Nuutinen Y., Petty A., Bergström D, Rytkönen M., Fulvio F., Tiihonen I., Lauren A., Dahlin B. (2016). Quality and productivity in comminution of small-diameter tree bundles. International Journal of Forest Engineering 27(3): 179-187. https://doi.org/10.1080/14942119.2016.1223926.

Nuutinen Y., Väätäinen K., Heinonen J., Asikainen A., Röser D. (2008). The accuracy of manually recorded time study data for harvester operation shown via simulator screen. Silva Fennica 42(1): 63-72. https://doi.org/10.14214/sf.264.

Official Statistics of Finland (OSF) (2018). Wood in energy generation 2017 [web publication]. Helsinki. Natural Resources Institute Finland. http://stat.luke.fi/en/wood-energy-generation-2017_en. [accessed 7 June 2018].

Olivera A., Visser R. (2016). Using the harvester on-board computer capability to move towards precision forestry. NZ Journal of Forestry 60:4. 3-7.

Olivera A., Visser R., Acuna M., Morgenroth J. (2016). Automatic GNSS-enabled harvester data collection as a tool to evaluate factors affecting harvester productivity in a Eucalyptus spp. harvesting operation in Uruguay. International Journal of Forest Engineering 27(1): 15-28. https://doi.org/10.1080/14942119.2015.1099775.

Palander T. (2017). The environmental emission efficiency of larger and heavier vehicles – a case study of road transportation in Finnish forest industry. Journal of Cleaner Production 155: 57–62. https://doi.org/10.1016/j.jclepro.2016.09.095.

Palander T. (2016). Environmental benefits from improving transportation efficiency in wood procurement systems. Transportation Research Part D: Transport and Environment 44: 211–218. https://doi.org/10.1016/j.trd.2016.03.004.

Palander T, Kärhä K. (2017). Potential Traffic Levels after Increasing the Maximum Vehicle Weight in Environmentally Efficient Transportation System: The Case of Finland. Journal of Sustainable Development of Energy, Water and Environment Systems 5(3): 417–429. https://doi.org/10.13044/j.sdewes.d5.0154.

Palander T, Haavikko H, Kärhä K. (2018). Towards sustainable wood procurement in forest industry – the energy efficiency of larger and heavier vehicles in Finland. Renewable and Sustainable Energy Reviews 96: 100–118. https://doi.org/10.1016/j.rser.2018.07.043.

Palander T., Voutilainen J. (2013). Modelling fuel terminals for supplying a combined heat and power (CHP) plant with forest biomass in Finland. Biosystems Engineering 114: 135–145. https://doi.org/10.1016/j.biosystemseng.2012.11.005.

Parker R., Bayne K., Clinton P.W. (2016). Robotics in forestry. NZ Journal of Forestry 60:4. 8-14.

Patterson M.G. (1996). What is energy efficiency? Concepts, indicators and methodological issues. Energy Policy 24:5. 377-390. https://doi.org/10.1016/0301-4215(96)00017-1.

Petty A. (2014). Opportunities for cost mitigation and efficiency improvements through rationalization of small-diameter energy wood supply chains. Dissertationes Forestales 175. 47 p. https://doi.org/10.14214/df.175.

Prada M., Martínez-Alonso C., Sánchez-García S., Canga E. (2015). Analysis of three forest chippers: productivity, costs and GHG emissions in Northern Spain. Journal of Cleaner Production 101: 238-244. https://doi.org/10.1016/j.jclepro.2015.03.066.

Proskuryakova L., Kovalev A. (2015). Measuring energy efficiency: Is energy intensity a good evidence base? Applied Energy 138: 450-459. https://doi.org/10.1016/j.apenergy.2014.10.060.

Ranta T. (2002). Logging residues from regeneration fellings for biofuel production- a GIS-based availability and supply cost analysis. Acta Universitatis Lappeenrantaensis 128. Dissertation Lappeenranta University of Technology. 180 p.

Rauch P. (2013). Improving the primary forest fuel supply chain. Bulletin of the Transilvania University of Brasov 6:1.1-8.

Road Traffic Act (2013). Valtioneuvoston asetus 407/2013 Ajoneuvojen Käytöstä Tiellä [The Finnish Government Regulation for Road Vehicles]. http://www.finlex.fi/fi/laki/alkup/2013/20130407#Pidm1799696/; 2013. [accessed 3 August 2017].

Röser D. (2012). Operational efficiency of forest energy supply chains in different operational environments. Dissertationes Forestales 146. 83 p. https://doi.org/10.14214/df.146.

Röser D., Asikainen A., Raulund-Rasmussen K., Stupak I. (eds.). (2008). Sustainable use of forest biomass for energy. A Synthesis with Focus on the Baltic and Nordic Region. Springer, Dordrecht. 259 p. https://doi.org/10.1007/978-1-4020-5054-1.

Röser D., Mola-Yudego B., Prinz R., Emer B., Sikanen L. (2012). Chipping operations and efficiency in different operational environments. Silva Fennica 46(2): 275–286. https://doi.org/10.14214/sf.60.

Routa J., Kolström M., Sikanen L. (2018). Dry matter losses and their economic significance in forest energy procurement. International Journal of Forest Engineering 29:1. 53-62. https://doi.org/10.1080/14942119.2018.1421332.

Routa J., Kolström M., Ruotsalainen J., Sikanen L. (2016). Validation of prediction models for estimating the moisture content of logging residues during storage. Biomass and Bioenergy 94: 85-93. https://doi.org/10.1016/j.biombioe.2016.08.019.

Routa J., Kolström M., Ruotsalainen J., Sikanen L. (2015). Validation of Prediction Models for Estimating the Moisture Content of Small Diameter Stem Wood. Croatian Journal of Forest Engineering 36:2. 283-291.

Routa J., Asikainen A., Björheden R., Laitila J., Röser D. (2013). Forest energy procurement – state of the art in Finland and Sweden. WIREs Energy and Environment 2(6): 602–613. https://doi.org/10.1002/wene.24.

Routa J., Kellomäki S., Kilpeläinen A., Peltola H., Strandman H. (2011). Effects of forest management on the CO2 emissions of wood energy in integrated production of timber and energy biomass. GCB Bioenergy 3: 483–497. https://doi.org/10.1111/j.1757-1707.2011.01106.x.

Sargent R.G. (2007). Verification and validation of simulation models. In: Proceedings of the 2007 Winter Simulation Conference, Henderson S.G., Biller B., Hsieh M.-H., Shortle J., Tew J.D. and Barton R.R. (eds.). p. 124-137. https://doi.org/10.1109/WSC.2007.4419595.

Schulze E.-D., Körner C., Law B.E., Haberl H., Luyssaert S. (2012). Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. GCB Bioenergy 4(6): 611-616. https://doi.org/10.1111/j.1757-1707.2012.01169.x.

Seppälä R. (1971). Simulation of timber-harvesting systems. Folia Forestalia 125. 36 p.

Shabani N., Sowlati T. (2013). A mixed integer non-linear programming model for tactical value chain optimization of a wood biomass power plant. Applied Energy 104: 353-361. https://doi.org/10.1016/j.apenergy.2012.11.013.

Shabani N., Akhtari S., Sowlati T. (2013). Value chain optimization of forest biomass for bioenergy production: A review. Renewable and Sustainable Energy Reviews 23: 299-311. https://doi.org/10.1016/j.rser.2013.03.005.

She J., Chung W., Kim D. (2018). Discrete-Event Simulation of Ground-Based Timber Harvesting Operations. Forests 9, 683. 20 p. https://doi.org/10.3390/f9110683.

Sosa A., Acuna M., McDonnell K., Devlin G. (2015). Controlling moisture content and truck configurations to model and optimise biomass supply chain logistics in Ireland. Applied Energy 137: 338-351. https://doi.org/10.1016/j.apenergy.2014.10.018.

Spinelli R., Moura A.C.de A. (2019). Decreasing the Fuel Consumption and CO_2 Emissions of Excavator-Based Harvesters with a Machine Control System. Forests 10, 43. https://doi.org/10.3390/f10010043.

Spinelli R., Lombardini C., Magagnotti N. (2014a). The effect of mechanization level and harvesting system on the thinning cost of Mediterranean softwood plantations. Silva Fennica 48(1) article id 1003. 15 p. https://doi.org/10.14214/sf.1003.

Spinelli R., Di Gironimo G., Esposito G., Magagnotti N. (2014b). Alternative supply chains for logging residues under access constraints. Scandinavian Journal of Forest Research 29(3): 266-274. https://doi.org/10.1080/02827581.2014.896939.

Spinelli R., Laina-Relano R., Magagnotti N., Tolosana E. (2013). Determining Observer and Method Effects on the Accuracy of Elemental Time Studies in Forest Operations. Baltic Forestry 19(2): 301-306.

Spinelli R., Magagnotti N., Paletto G., Preti C. (2011). Determining the impact of some wood characteristics on the performance of a mobile chipper. Silva Fennica 45(1): 85–95. https://doi.org/10.14214/sf.33.

Spinelli R., Visser R. (2009). Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy 33: 429–433. https://doi.org/10.1016/j.biombioe.2008.08.003.

Stampfer K., Kanzian C. (2006). Current state and development possibilities of wood chip supply chains in Austria. Croatian Journal of Forest Engineering 27:2. 135-145.

Strandgard M., Mitchell R. (2015). Automated Time Study of Forwarders using GPS and a vibration sensor. Croatian Journal of Forest Engineering 36(2): 175-184.

Strandgard M., Walsh D., Acuna M. (2013). Estimating harvester productivity in *Pinus radiata* plantations using StanForD stem files. Scandinavian Journal of Forest Research 28(1): 73-80. https://doi.org/10.1080/02827581.2012.706633.

Strandström M. (2018a). Timber Harvesting and Long-distance Transportation of Roundwood 2017. Metsätehon tuloskalvosarja 8b/2018. Metsäteho Oy. 31 p.

Strandström M. (2018b). Metsähakkeen tuotantoketjut Suomessa vuonna 2017. Metsätehon tuloskalvosarja 11/2018. Metsäteho Oy. 20 p. [In Finnish].

Sun H., Yang L., Jing J. (2010). Hydraulic/electric synergy system (HESS) design for heavy hybrid vehicles. Energy 35(12): 5328–5335. https://doi.org/10.1016/j.energy.2010.07.027.

Tahvanainen T., Anttila P. (2011). Supply chain cost analysis of long-distance transportation of energy wood in Finland. Biomass and Bioenergy 35: 3360- 3375. https://doi.org/10.1016/j.biombioe.2010.11.014.

Talbot B., Suadicani K. (2005). Analysis of Two Simulated In-field Chipping and Extraction Systems in Spruce Thinnings. Biosystems Engineering 91(3): 283-292. https://doi.org/10.1016/j.biosystemseng.2005.04.014.

Väätäinen K. (2018). Developing forest chips supply chains by redesigning supply operations and logistics. Dissertationes Forestales 250. 75 p. https://doi.org/10.14214/df.250.

Vanclay J.K. (2011). Future harvest: shat might forest harvesting entail 25 years hence? Scandinavian Journal of Forest Research 26: 183-186. https://doi.org/10.1080/02827581.2010.545828.

Virkkunen M., Kari M., Hankalin V., Nummelin J. (2015). Solid biomass fuel terminal concepts and a cost analysis of a satellite terminal concept. VTT. 69 p.

Virkkunen M., Raitila J., Korpinen O.-J. (2016). Cost analysis of a satellite terminal for forest fuel supply in Finland. Scandinavian Journal of Forest Research 31: 175–182. https://doi.org/10.1080/02827581.2015.1082617.

Visser R. (2018). Next Generation Timber Harvesting Systems: Opportunities for remote controlled and autonomous machinery. Forest & Wood Products Australia Limited. Project No: PRC437-1718. 34 p.

VTT (2017). TYKO 2015 results. http://lipasto.vtt.fi/en/tyko/tyko2015results.xlsx. [accessed 24 February 2017].

Wihersaari M. (2005). Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 28: 435–443. https://doi.org/10.1016/j.biombioe.2004.11.007.

Windisch J. (2015). Process redesign in development of forest biomass supply for energy. Dissertationes Forestales 189. 55 p. https://doi.org/10.14214/df.189.

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.

Windisch J., Röser D., Mola-Yudego B., Sikanen L., Asikainen A. (2013). Business process mapping and discrete-event simulation of two forest biomass supply chains. Biomass and Bioenergy 56: 370-381. https://doi.org/10.1016/j.biombioe.2013.05.022.

Wolfsmayr U.J., Rauch P. (2014). The primary forest fuel supply chain: A literature review. Biomass and Bioenergy 60: 203-221. https://doi.org/10.1016/j.biombioe.2013.10.025.

Zamora-Cristales R., Boston K., Sessions J., Murphy G. (2013). Stochastic simulation and optimization of mobile chipping economics in processing and transport of forest biomass from residues. Silva Fennica vol. 47 no 5 article id 937. https://doi.org/10.14214/sf.937.