Research Trends in European Forest Fuel Supply Chains: A Review of the Last Ten Years (2007–2016) – Part Two: Comminution, Transport & Logistics

Martin Kühmaier, Gernot Erber

Abstract

Within the fuel wood supply chain, comminution and transport have been identified as processes with the highest costs, energy consumption and emissions. The coordination of comminution and transport aimed at avoiding operational delays is also complex. Nevertheless, the use of forest biomass helps to reduce the effects of climate change and produces an additional income, especially in rural areas. About 20 years ago, at the beginning of the industrial forest fuel utilisation, the focus of the research was on developing and analysing adequate supply chains and machines. Nowadays, as state-of-the-art systems have been established, the focus is on improving the efficiency of the processes and the quality of the products. This paper provides a review of research trends of the last ten years focusing on comminution and transport of forest biomass in Europe.

Comminution should become more efficient by analysing the effects of wood characteristics on chipper performance and product quality, by tailoring chipper configuration according to those findings and by introducing mechanical devices for improving the quality of chips. Transport processes have the potential to become more efficient if the configuration of trucks is adapted according to operational and legal requirements, and when considering moisture content management. Finally, economic and environmental assessment of supply chains was made by several studies. Future research is expected to focus on customizing the product quality according to user's requirements and on optimising the coordination of chipper and truck by simulation and automatization tools.

Keywords: forest biomass, chipping, environmental assessment, wood energy

1. Introduction

The generation of energy from biomass plays an important role in current international strategies to mitigate climate change and to enhance energy security. The European Union (EU) has committed to produce 27% of its energy from renewable sources by 2030 (COM/2014/015). Forest biomass is a key renewable energy source to help countries meet their long-term renewable energy targets. However, a large proportion of the available wood biomass is not utilised due to difficult operating conditions, low efficiency and high supply chain costs (Ghaffariyan et al. 2017). Therefore, the key objectives of the research are to improve the efficiency and reduce the supply chain cost.

Several overviews of state-of-the-art technologies and efficient biomass harvesting have been compiled recently. Stampfer and Kanzian (2006) focused on the current and development possibilities of comminution and transport in Austria, outlining the challenges and opportunities in mountainous regions. Routa et al. (2013) investigated the driving forces behind the current technical solutions of forest energy procurement systems in Finland and Sweden and presented some perspectives on possible future developments.

Díaz-Yáñez et al. (2013) compiled a general overview of current procurement methods of forest chips in Europe. Ghaffariyan et al. (2017) provided a state-of-the art overview of best practice examples of forest biomass harvesting technologies and supply chains used in North America, Europe and the Southern Hemisphere. Eriksson et al. (2013) were providing an overview of state-of-the-art in woody biomass comminution and sorting in Northern Europe. Wolfsmayr and Rauch (2014) compiled a review of the primary forest fuel supply chain, focusing on transportation of primary forest fuel to heat and/or power plants. Gold and Seuring (2011) presented a review of articles published from 2000 to 2009, covering the interface of bio-energy production and logistics and supply chain management issues. De Meyer at al. (2014) gave an overview of the optimisation methods and models focussing on decisions regarding the design and management of the upstream segment of the biomass-for-bioenergy supply chain. Eskandarpour et al. (2015) did the same but focusing on sustainability. However, no paper covers comprehensively all relevant research trends in the field of forest fuel supply chains.

Therefore, this paper, as part two of a series of two, aims to cover the last two steps in the forest fuel supply chain, namely comminution and transport. Part one, dealing with harvesting and storage, was analysed by Erber and Kühmaier (2017). Papers published between the years 2007–2016 will be classified according to key supply processes and research trends. Finally, the need for future research will be identified to push forward both industrial and academic development.

2. Material and methods

To access and collect the papers relevant for this review, an extensive literature search was conducted. »Scopus«, »Web of Science« and »Google Scholar« are the most used search engines. A combination of the following key words was applied so that at least one word from each of the search terms in boxes (logical OR operator) and at least one term from each box should appear (logical AND operator) either in the title or the abstract of the paper: »comminution«, »chipping«, »transport«, »fuelwood«, »energy wood« and »supply chain«. Except for some highly relevant papers from other continents, only studies performed or demonstrated in Europe were included in the analysis. This brute-force search resulted in a gross list of about 105 papers, of which 7 were not relevant for the focus of this paper, leaving 98 papers for the review.

The remaining papers were summarised and classified into comminution and transport processes and 12 research trends, each section containing novel knowledge gained during the last decade. Many papers fitted to more than one supply process or research trend and were, therefore, counted multiple times (Table 1). It showed that comminution was an extensively studied supply process during the last 10 years (Fig. 1).

3. Results

3.1 Comminution

Biomass supply is very challenging in European mountain forests because of steep terrain, limited space, narrow roads and extreme weather conditions. Despite the challenging operating conditions, chipping contractors in Italy are able to achieve a high machine use and product output. Chipping contractors adopt different operational strategies to achieve their production targets (Spinelli and Magagnotti 2014a).

3.1.1 Allocation of the comminution process within the supply chain

The efficiency of the comminution process within the fuel supply chain varies greatly depending on the production site. Of the various supply chain designs considered, chipping at the landing seems to be often the most suitable option (Röser et al. 2011). Roadside

Table 1 Supply processes and research trends. As many publications included more than one research trend, publications can be counted several times and the sum of the numbers in the right column does not represent the total number of papers

Topic	Research trends	Publications
Comminution	Allocation of the comminution process within the supply chain	6
	Effects of wood characteristics on chipper performance	14
	Effects of wood characteristics on product quality	11
	Evaluating the effects of chipper design	14
	Evaluating the effects of knife configuration	14
	Evaluating the effects of screens and sieves	8
	Operator effects and impacts on human health	9
Transport	Selecting suitable transportation modes	6
	Improving the efficiency of fuel wood transportation	13
	Coordination of supply processes	3
	Economic assessment of supply chains	15
	Environmental assessment of supply chains	11
	Multi tree handling in fuel wood harvesting	18

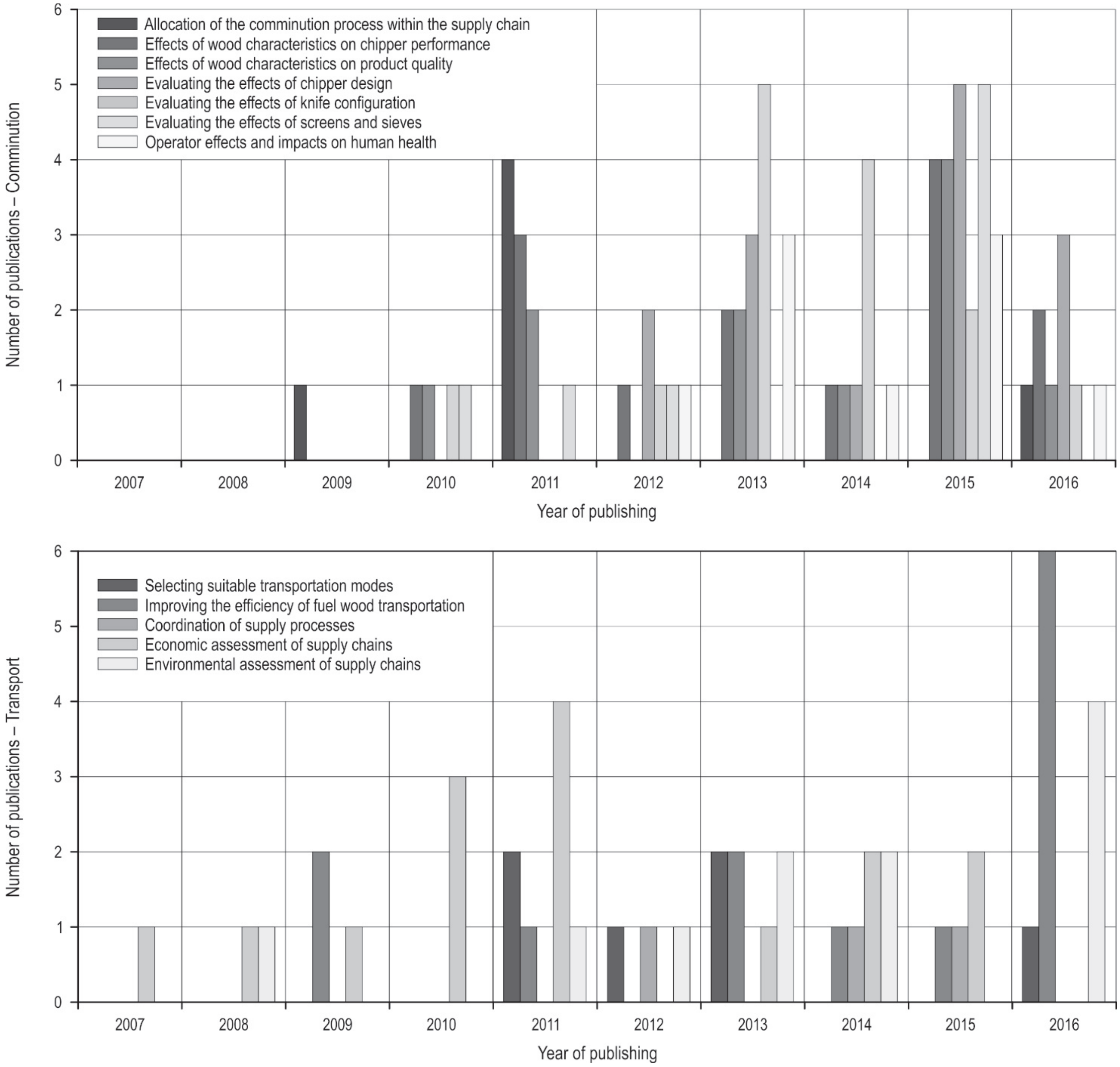

Fig. 1 Number of publications by topic and year. As many publications included more than one research trend, publications can be counted several times for different research trends and supply processes

chipping is very common in Europe and usually more productive than terrain chipping, and it allowes reducing harvesting costs (Kärhä 2011, Marchi et al. 2011). At the roadside, space is limited because operations are executed on narrow roads and small landings. Since wood is often directly chipped into transport vehicles, waiting and delay times will occur. The organization of the supply chain, especially scheduling vehicles, changing transport units and transferring the chipper to the next pile is a crucial point (Spinelli and Visser 2009).

At the terminal or at the plant, however, there is more space for changing transport units and for chipping without coordinating transport vehicles. Therefore, higher productivities can be achieved (Ranta and Rinne 2006). Depending on the assortments to be comminuted, the efficiency at the terminal could be increased by up to 43% compared to chipping at the forest landing. This also leads to a reduction in chipping costs between 0.11 and 1.02 €/m^3 loose (Kühmaier et al. 2016). In an Irish case study, whole tree terrain chipping was the lowest cost method of woodchip production in conifer first thinning but no brash was left on the extraction racks for machines to operate on (Kent et al. 2011). The majority of all stump wood chips consumed were comminuted at the plant, and with only around one fifth comminuted at terminals (Kärhä 2011, Röser et al. 2011).

3.1.2 Effects of wood characteristics on chipper performance

The characteristics of the raw material have an effect on chipper productivity (e.g. Mizaras et al. 2011, Kováč et al. 2011, Röser et al. 2012, Mola-Yudego et al. 2015). Pochi et al. (2015) and Assirelli et al. (2013) analysed the chipping performance of logs and tops. Chipping stems required more power and torque than chipping residues. Fuel consumption was not affected by tree part, storage or their combination. According to a study of Nuutinen et al. (2015), the productivity of forest residues grinding was the highest. The productivity of whole tree grinding was second highest and the lowest productivity was observed in stump grinding. Nuutinen et al. (2016) have shown that, when comminuting bundles, the productivity was 1.5–3.2 times higher than for unbundled forest residues. Spinelli et al. (2011b) determined that species and moisture content have a secondary effect on chipper productivity and fuel consumption, which are primarily controlled by piece size. Eisenlauer and Teipel (2016) have shown that the energy demand during chipping increases with a higher moisture content and lower particle sizes of the final products.

At the physical level, cutting along rather than across the fibre direction generally requires less force, and cleavage close to the surface requires less force because the pressure on the knife from the surrounding wood is lower. Abdallah et al. (2014) developed a chipping test bench to measure cutting forces during the wood chipping process, which implied the use of oversized chipper motors. Energy consumption can also be reduced by exploiting movement in the direction of the knife edge (Eriksson et al. 2013).

3.1.3 Effects of wood characteristics on product quality

The quality of wood chips is dependent on the raw material processed (e.g. Patterson et al. 2011, Kuptz and Hartmann 2015, Nuutinen et al. 2016). Nati et al. (2010) have shown that tree species (poplar or pine) and tree part (residues or logs) have a significant impact on chip size distribution. The requirements for high fuel quality are best met when wood chips are produced from round wood because they contain a smaller proportion of oversize particles and a higher proportion of accepts. In contrast, wood chips from forest residues can be considered more suitable for medium or larger CHP and heating plants as they do not require high quality chips (Kuptz and Hartmann 2015). The effect of feedstock type has generally a strong effect on energy efficiency and product quality (Spinelli and Magagnotti 2013, Spinelli et al. 2015, Kons et al. 2015).

For the same large mesh screen, poplar chips tend to be larger than pine chips and to contain a higher proportion of oversize particles. On the contrary, pine chips tend to be smaller and to contain a higher proportion of fines. The average size of beech chips is significantly larger than that of poplar chips, possibly due to the higher strength of beech wood (Spinelli and Magagnotti 2013). Krajnc and Dolšak (2014) found that softwood biomass has rougher structures and hardwood biomass finer structures, which is more suitable for larger systems. When residues were chipped, a larger share of smaller chip fractions, a lower ash content, and a slightly higher moisture content were found (Vangansbeke et al. 2015). Spinelli et al. (2011b) came to the conclusion that moisture content has a significant effect on the particle size distribution.

3.1.4 Evaluating the effects of chipper configuration

Productivity and energy use are more likely to be determined by machine types (Nuutinen et al. 2016, Yoshida et al. 2016), machine configuration and machine-level factors (Kuptz and Hartmann 2015), such as the speed of rotation, feeding rate, available power, and conversion efficiency. Using more efficient power sources and reducing the power required during interruptions may be at least as important as improving the performance of the physical comminution process (Eriksson et al. 2013).

3.1.4.1 Chipper design

Long-term productivity varies with machine type on which the chipper is mounted: tractor-powered units are less productive than larger independent-engine chippers (Spinelli and Magagnotti 2014a, Laitila and Routa 2015). The productivity of drum chippers is higher than that of disc chippers (Spinelli and Magagnotti 2013, Facello et al. 2013b). Spinelli et al. (2015) tested two alternative drum chipper designs on different feedstock types and under different knife wear conditions. The closed drum full-length knife design was more efficient than the open drum staggered-knife design, when negotiating branches, especially when knives were dull. Under these conditions, productivity was higher, fuel use lower and product quality better for the closed drum design.

The grapple load of the crane had a large effect on the overall productivity of the operations (Röser et al.

2012). A smaller crane will have positive secondary effects on the operation since it should reduce the fuel consumption and the equipment stress (Laitila and Routa 2015). Picchi and Eliasson (2015) evaluated a container handling chipper truck (CCT) to study the utilisation and to determine if the choice of grapple on the CCT or the preceding forwarder influenced chipping productivity. A standard residue grapple was the better choice for the CCT, while residues forwarded with an asymmetrical grapple increased chipping efficiency.

Latest chipper models feature new in-feed and evacuation systems that can be adjusted on the fly to match variable work conditions. A study by Spinelli et al. (2016a) verified the effects of the two systems on productivity, diesel fuel consumption and chip quality. The feedstock type has a dominant effect on all the studied parameters, whereas in-feed mode has no effect on any of them. In contrast, blower setting has a significant effect and offers a strong potential for increased wood fuel processing efficiency. In particular, decreasing blower speed, when full ejection power is not necessary, allows reducing diesel fuel consumption while increasing chip integrity.

Spinelli et al. (2012b) analysed a chipper prototype fitted with innovative tubular blades, mounted on a flywheel, designed to produce high quality chips when processing delimbed logs. The machine was as efficient as most conventional disc or drum chippers in the same size class, but offered a much better chip quality. Chips were free from any particles longer than 45 mm, and with a very limited content of fine particles. A tractor-powered drum chipper was designed to reduce the gap between industrial chippers and small-scale chippers (Spinelli and Magagnotti 2013). Using hybrid systems may yield higher energy efficiency compared to direct diesel-powered comminution systems. In order to design hybrid chippers, a series of data on load variations is required, in order to estimate the amount of energy that needs to be stored, and the peak power required. Di Fulvio et al. (2015) have studied the effects of wood properties on the specific power and energy demand and time consumption of a 30 kW electric chipper.

3.1.4.2 Knife configuration

Depending on feedstock type, the knife configuration is 50% more productive than the hammer configuration and requires 24% less energy. Fuel consumption is 52% higher for the hammer configuration (Spinelli et al. 2012a). Hammer mills are not suitable for the comminution of raw material with high water content. On the other hand, the comminution of wood with low moisture content with hammer mills produces chips with smaller particles sizes, using the same processing energy as knive mills (Eisenlauer and Teipel 2016). Knife angle, moving speed and drum spinning speed have an influence on the average grain size, the dust share and the form constancy (Krajnc and Dolšak 2014). In case of use of a larger knife-edge angle, a reduction of energy consumption can be achieved due to the increased compressive loading parallel to the wood fibres. Isaksson et al. (2013) defined a chip damage parameter D of spruce, which is relevant for cracking parallel to the fibres. D is defined and its dependence on chip length and edge angle of the chipping knife is analysed numerically by means of finite element analyses.

Wearing chipper knives causes a significant reduction of chipping productivity and a remarkable increase of fuel consumption (e.g. Nati et al. 2010, Facello et al. 2013a, Spinelli and Magagnotti 2014a, Spinelli et al. 2014a, Kuptz and Hartmann 2015). Dry sharpening with a grinder mitigated this effect, but it could not replace proper wet sharpening. Increasing the frequency of wet sharpening sessions determined a moderate increase of knife depreciation cost, but it could drastically enhance machine performance and reduce biomass processing cost (Spinelli et al. 2014a). Increasing knife sharpness requires more downtime, and therefore an optimum time interval between knife replacements has to be found (Eriksson et al. 2013). Costs of severe damage caused to conventional knife set-ups, following accidental introduction of metal contaminants inside the chipper, can amount to over 30,000 €. Disposable micro-knives may avoid such severe damage and offer savings of about 30% of the knife-related cost of a conventional knife set, or about 18 Euro cents per tonne (Spinelli and Magagnotti 2014b).

Cut length setting and piece breaker option are relevant drivers of chip size, and they are manipulated with the main purpose of managing particle size distribution. A study of Facello et al. (2013a, 2013c) showed that the proportion of small chips increased dramatically with the shortest cut length setting (7 mm). Installing a piece breaker allowed maximizing the incidence of small chips, which reached 70% of the total mass when the piece breaker was used in combination with the shortest cut length setting. Reducing cut length determined a substantial decrease of productivity (ca. 30%), and an even higher increase of specific fuel consumption (ca. 50%). All strategies to reduce chip size also resulted in increasing the incidence of fines.

Power and energy consumption are lower when processing with a larger cutterhead diameter (Kuljich et al. 2015). These parameters were also greater when cutting frozen logs compared with unfrozen logs.

Experiments made with a model helical chipper have shown that the infeed angle has a huge impact on chip quality parameters. Furthermore, power requirement and energy consumed are decreasing with increasing infeed angle. The results seem to be extraordinary since increasing infeed angles lead to decreasing chip sizes being produced (Wegener et al. 2015).

3.1.4.3 Screens and sieves

For optimal combustion, the fuel should have a low content of fine particles (Kons et al. 2015), which can be achieved by screening or sieving. A newly designed mobile screening device achieved an average productivity of 1.9 odt/h, corresponding to screening costs of 28.5 €/odt (Spinelli et al. 2011a). This figure was lower than the price increase obtained by upgrading the industrial chips to residential user standards. The economic value of such screening depends heavily on the costs of the refining process and the value/utility of the separated fine particles. Laitila and Nuutinen (2015) evaluated the significance of screening to guarantee sufficient quality when processing stump fuel. On the other hand, Kons et al. (2015) and Eliasson et al. (2015a) found that the sieve size had no significant effects on particle size distribution and ash content.

The replacement of the standard wide mesh screen with a narrower screen causes decreasing productivity and increasing fuel consumption (Nati et al. 2010). Röser et al. (2012) revealed that there are significant differences in the chipping productivity in Austria and Finland, which are largely based on the use of different sieve sizes. The use of narrower 80 mm × 80 mm sieves on Scots pine material does not seem to offer any benefit compared to 100 mm × 100 mm from the chip quality point of view (Laitila and Routa 2015).

Nati et al. (2015) tested the use of a trommel screen originally designed for compost materials to reject oversize particles from hog fuel. The study consisted in screening material previously comminuted by a convertible crusher, designed to use both hammers and knives. Trommel screen productivity varied between 4.2 t/h, and 5.2 t/h of oven dry material. Screening hog fuel derived from pallets was respectively 30% and 40% less productive than screening fuel derived from logs and residues.

3.1.5 Operator effect and impacts on human health

»Operator effect« has a strong impact on operational chipper performance, due to individual differences in technique, motor skills, work-planning capacity, decision-making abilities and general experience (Ovaskainen et al. 2004, Röser et al. 2012, Mola-Yudego et al. 2015).

Comminution is often performed with large, powerful machines, capable of generating much noise. In turn, high noise levels may have negative impacts on the health and comfort of workers, and of the people living in the surroundings of a wood fuel yard (Kühmaier et al. 2014). A study of Spinelli et al. (2016a) demonstrated that the chipper generated more noise than the grinder, due to its better ability to process wood and to transmit more energy into it. Since the chipper was equipped with less working tools and turned slower than the grinder, it generated its noise peaks at lower frequency bands. Nuutinen et al. (2015) and Poje et al. (2015) recorded an average noise level of a grinder of about 82 dB(A), which is more than the limit level of 80 dB(A). The main source of noise was the powerful diesel engine, followed by the chipper drum: they generated the highest noise levels in the 100–200 Hz and the 20–50 Hz frequency ranges, respectively. Tractor-trailer chippers have higher noise levels than truck-mounted chippers (Rottensteiner et al. 2013).

During chipping, machine operators are exposed to whole-body vibration bearing a risk to health (Rottensteiner et al. 2013). Truck-mounted chippers have higher vibration values than tractor-trailer chippers. The highest vibration levels were recorded while driving on the forest road and the second highest during chipping. Chipping hardwood produced higher vibration magnitudes than chipping softwood. Nevertheless, the exposure limit values set by the EU were usually not exceeded. The International Agency for Research on Cancer (IARC) has classified hardwood dust as a human carcinogen (IARC 1995). Magagnotti et al. (2013) determined the exposure of chipper operators to inhalable wood dust. Exposure to dust varied widely with wood conditions and machine productivity, and only occasionally exceeded the occupational exposure limit of 5 mg/m^3. Operators working inside a cab were three times less exposed than operators working outside.

3.2 Transportation and logistics

3.2.1 Selecting suitable transportation modes

Manzone and Balsari (2015) compared tractor + trailer and trucks in terms of working time, working rate, fuel consumption, energy costs and economic costs. In Northern Scotland, forest chips can be delivered starting from approximately 20 €/MWh within a 50 km transportation distance when chipping is at roadside. If the transportation distance is 100 km, wood chips could be delivered at approximately 23 €/MWh (Röser et al. 2011). Time studies related to on-road transportation were made by Laitila et al. (2009); they compared the terminal handling time. The mean loading and unloading time of bundles per truck load was 46% higher compared to that of conventional 5 m pulpwood. Vainio et al. (2009) also developed transportation costs to a very detailed level. Fuelwood is usually transported by trucks but there is also a growing medium or long distance transportation of energy wood by railways or waterways (Tahvanainen and Anttila 2011, Wolfsmayr et al. 2016). According to a study of Tahvanainen and Anttila (2011), for distances shorter than 60 km, truck transportation of loose residues and end-facility comminution was the most cost-competitive chain. Over longer distances, roadside chipping with chip truck transportation was the most cost-efficient option. When the transportation distance went from 135 to 165 km, train-based transportation offered the lowest costs. The most cost-competitive alternative for long-distance transport included a combination of roadside chipping, truck transportation to the terminal and train transportation to the plant. A MILP model was developed by Rauch and Gronalt (2011), comprising decisions on modes of transportation and spatial arrangement of terminals. An increase of energy costs results in a procurement cost increase. While domestic waterways become more important because of the energy cost increase, rail only does so. One way to decrease procurement costs would be to reduce the share of empty trips with truck and trailer. Routing influences the modal split considerably, and the truck transport share increases from 86% to 97%, accordingly. Increasing forest fuel imports by large CHPs lowers domestic competition and enables smaller plants to cut their procurement costs.

Sukhanov et al. (2013) came to the conclusion that in Northwest Russia the collection of logging residues for chipping is cost-effective if the distance to the customer is less than 100 km. The use of logs for the production of forest chips is economically more feasible, compared with the use of residues. In this case, forest chips can be transported up to 150 km (Gerasimov and Karjalainen 2013). The cost-efficiency of waterway transportation operations related to forest chips in Finland's Lake Saimaa region was studied by Karttunen et al. (2012) using practical demonstrations and discrete-event simulation. The waterway supply chain of forest chips was cost-competitive to road transport by truck after 100–150 km.

3.2.2 Improving the efficiency of fuelwood transportation

The factors influencing transporting efficiency and cost are payload, loading and unloading time, transporting distance, hourly costs and operational delays, such as waiting and auxiliary times. Transportation of logs is usually the most efficient transport system, causing less cost than transporting bundles and residues (Bergström and Di Fulvio 2014). Maximum permitted weights of truck transport differ in Europe with a range of 31 to 60 tonnes (Table 2) IRU (2017), ITF (2017). The presented limits can be higher for restricted road networks, the first or last leg of transport, intermodal/combined/container transport or for the transport of special goods (e.g wood).

Table 2 Comparison of maximum vehicle gross weights in European countries

Weight limits, tonnes	Countries (ISO code)
31	CY
36	AM
38	AZ, BY
40	AT, BA, BG, CH, DE, ES, FR, HR, LT, LV, MD ME, MK, MT, PL, PT, RO, RS, SI, SK, TR, UA
42	GR
44	AL, BE, EE, GB, GE, IE, IS, IT, LU, RU
48	CZ
50	NL
56	DK
60	FI, NO, SE

In Finland, the laws providing the physical dimensions of freight transport vehicles were changed and the new legislation enables higher gross weights as well as larger load capacities. Laitila et al. (2016) dealt with the determination of the most cost-effective vehicle type. The 69-tonne truck-trailer was a feasible choice when the payload was not limited by the bulk weight of the forest industry by-products. With heavier forest industry by-products, such as sawmill wood chips and bark, the 76-tonne truck-trailer was the most feasible choice. The results showed clearly that the transporting costs associated with using the new type truck-trailers were lower than those for conventional 60-tonne truck-trailers in all assortments.

Increased use of forest biomass for energy and rising transportation costs are forcing biomass suppliers towards better moisture content management (Pasila 2013, Routa et al. 2016, Sosa et al. 2015). Kühmaier et al. (2016) found that the transport of wood chips causes a cost advantage of 0.32–0.49 €/m^3 loose if the moisture content can be reduced from 55 to 35%. Erber et al. (2016) has shown that moisture content management increased truckload volume utilisation by 25%

and transported calorific value by 48%. The number of truck trips for transportation was reduced by 20%.

Stump parts are bulky and it is impossible to achieve full tonnages on trucks and trailers even though the load space is completely full. Grinding the stumps at the landing and sieving of the produced chips has the potential to increase load weights and reduce both the amount of contaminants and the transport costs. Transport payloads increase substantially, but according to a case study of Anerud et al. (2016), a transport distance of 110 km is needed before the coarse grinding system provided lower cost than the standard system with transports of stump parts and grinding at the heating plant.

3.2.3 Coordination of supply processes

Forest fuel has to be converted into chips before delivery to the customer and the demand for forest fuel varies over the year depending on temperature. To balance the chipping and transportation capacities over time, it is important to manage inventory levels at terminals. An optimisation model developed by Flisberg et al. (2012) provides decision support for questions regarding the choice of technology for chipping, where to perform the chipping operations, and the allocation of different assortments to heating plants. It is important to maximise the proportion of effective work time in relation to scheduled work time. Currently, the effective work time is often less than 50 per cent of scheduled work time, due to chip transports using the chipper, waiting for chip trucks, and other delays. Increased chipper utilisation requires greater coordination between the chipper and the chip trucks transporting the produced chips to the customer. Eliasson et al. (2015b) have simulated supply systems to examine how transport distance, number of trucks, shift scheduling and chip buffers affect the system costs for a high-performance chipper system. Spinelli et al. (2014b) compared chipping operations of residues at the roadside landing or at the yarder pad, the latter inaccessible to heavy road vehicles, by carefully reflecting interaction delays between individual units along the chain. Chipping at the pad with a chipper and two shuttles was the best compromise solution of low supply cost and fuel consumption. Machine activity based controlling offers a new way to increase efficiency and productivity. A study of Holzleitner et al. (2013) aims to monitor the forest fuel supply processes via fleet management equipment. Large data sets were automatically and efficiently gathered with little effort by drivers and operators. Data management was conducted in a pre-configured database that contained pre-defined reports.

3.2.4 Economic assessment of supply chains

Several studies have analysed the efficiency and costs of supply chains for different operating conditions. Valente et al. (2014) made a comparative analysis of Norwegian and Italian supply chains. In Norway, the supply chain is more mechanised than in Italy, which explains the higher productivity. Laitila (2008) calculated the procurement costs of six whole tree chips supply chains. The harvesting system based on the harvester with an accumulating felling head was the cheapest, while the harwarder system was the most expensive. The procurement costs of fuel chips made from delimbed stemwood and whole trees for another case study in Finland (Laitila et al. 2010) were 49.1 and 41.8 €/m^3, respectively. Belbo and Talbot (2014) and Gustavsson et al. (2011) analysed widely applied supply chains producing forest fuel from whole trees from energy thinnings. Results showed that the most expensive chain (roadside bundling, roadside storage, terminal storage and delivery using timber truck) was 23% more costly than the cheapest chain (roadside chipping and direct transport to conversion plant with container truck). In economic terms, the transport of forest residues by truck and trailer presents the highest cost followed by chipping and processing of trees. These three operations are responsible for approximately 80% of the total costs (Ferreira et al. 2014). Cost-supply curves can be used to support the planning of heating plant investments (Anttila et al. 2011). Bergström and Di Fulvio (2014) analysed the effect of future harvesting and handling technologies on the cost and energy efficiency of supply chains. If boom-corridor thinning technologies, optimised bundle-harvesters and load-compression devices are developed, costs are reduced on average by 12–27%, and 11–30% less energy is required when compared with current systems.

Linear programming models have been developed to study the logistics and determine the best setup for bioenergy chains (e.g. Kanzian et al. 2009, Velazquez-Marti and Fernandez-Gonzalez 2010, Van Dyken et al. 2010, Kanzian et al. 2013). The focus of the work of Van Dyken et al. (2010) was to represent the relationship between moisture and energy content of different kinds of biomass and to handle long-term processes in the optimisation like passive drying effects. A spatial decision support tool based on LP (Linear Programming) developed by Sosa et al. (2015) uses drying curves to assess the moisture content, weight and energy content of biomass. The model helps solve the best spatial allocation for the demanded wood products by optimising the number of trucks required to satisfy the demand at power and mill plants whilst still applying the volume and payload weight constraints.

Gronalt and Rauch (2007) evaluated different supply lines for the woody biomass from forest to plants by calculating the system cost for a number of alternative configurations. Especially, they compared central chipping against a local approach. A partial equilibrium model for the forest chips market in Finland was developed and demonstrated by Kallio et al. (2011). Since the supply of stumps and logging residues is tied to roundwood harvests, reaching the target seems unrealistic without investments in the new production capacity of the forest industry.

3.2.5 Environmental assessment of supply chains

Kühmaier and Stampfer (2012) developed a computer-based decision support tool to assist stakeholders in identifying the most suitable fuelwood supply chain. The tool considers a number of criteria, such as energy efficiency, nutrient balance, stability and vitality of the remaining stand and soil, contribution margin, supply guarantee, employment rate and working safety. Kanzian et al. (2013, 2016) have formulated a multi-criteria optimisation problem (MOP), whereby the profit must be maximised and the CO_2 emissions have to be minimised. In an effort to minimise CO_2 emissions, 30% of the woody biomass should be delivered chipped from the terminals and more than 50% chipped directly from forest. By changing the weight to maximise the profit, CO_2 emissions will only increase by 4.5%, whereas the profit more than doubles. Murphy et al. (2016) developed an optimisation model, which ensures minimal GHG emissions. Based on forest growth simulations, a set of realistic forest biomass supply chains for Bavarian forestry conditions were modelled (Klein et al. 2016). Total GHG emissions are estimated for the Bavarian forestry sector indicating a share of 0.41% in the total GHG emissions of Bavaria. Most decisive parameters are forest road maintenance, biomass harvesting, forwarding and biomass transport. Tree species, age class, wood assortment and site quality also notably influence GHG emissions.

Life cycle assessment (LCA) was used in several studies (Whittaker et al. 2011, Murphy et al. 2016, Klein et al. 2016, De la Fuente et al. 2017) to evaluate biomass-to-energy systems to reduce environmental impacts during production and transportation. Typically used impact categories are global warming, acidification, eutrophication, and energy demand. Mechanised forest harvesting generates more greenhouse gas (GHG) emissions than motor-manual harvesting. The main sources of GHG emissions are truck transportation and chipping (Galezia 2013, Ferreira et al. 2014, De la Fuente et al. 2017). The lower bulk density of wood chips means that transportation energy requirements and GHG emissions are higher compared with round wood logs and brash bales, suggesting that chipping should occur near the end-user (Whittaker et al. 2011). CO_2 emissions for supply chains have been calculated by several authors (e.g. Eriksson 2008, Whittaker et al. 2011, Valente et al. 2014, De la Fuente et al. 2017). Although forest roads were constructed, their relative contributions to the overall energy requirements and GHG emissions are small (Whittaker et al. 2011). The ratio between the extra fossil energy input to harvest biomass on the one hand and the possible energy output from the wood chips on the other hand varied between 0.7% and 1.3% (Vangansbeke et al. 2015).

4. Discussion and conclusion

Strategies and measures to increase the efficiency of fuelwood supply systems have been a topic of research ever since the development of industrial forest fuelwood supply systems started. The focus and trends have undergone changes over time but the challenges remained more or less the same. The coordination of fuelwood supply processes is complex, the costs for harvesting are high and the revenues from forest biomass are low. In mountainous areas, limited space on forest roads and strong limitation in available transport routes are additional challenges.

When introducing industrial fuelwood supply, the major research topics were the assessment of ecological risks, the coordination of individual processes and improvement of transport efficiency. Stampfer and Kanzian (2006) already mentioned that the position of the chipper within the work chain influences the efficiency of the supply chain and determines the type of biomass that will be transported. Direct chipping of the material into trucks results in operational delays in the order of 20%. If chipping and transportation is carried out independently, then additional costs occur for chip loading. Röser et al. (2012) emphasised that more consideration has to be given to the close interlinkage between the chipper, crane and grapple in the future. The optimal positioning of the comminution process within the supply chain is still an important research question to reduce delays caused by a lack of coordination between expensive machines. It was proven by several authors that the characteristics of the raw material have a strong effect on chipper performance and product quality. The most significant parameters are tree parts (logs, residues, bundles etc.), volume of the material to be chipped, tree species and moisture content.

One of the latest research trends was the improvement of chipper design with a special focus on knifes as well as screens and sieves configuration. The machine type on which the chipper is mounted, the grapple load of the crane as well as in-feed and evacuation systems have an effect on the overall productivity. Di Fulvio et al. (2015) have tested hybrid systems, which store excess energy from a diesel engine during periods of low loading for use during peak loading times. Knife configuration is more productive than a hammer configuration. The impact of knife wear, knife angle, moving speed, drum spinning speed on productivity and product quality has been assessed by several studies during the last 5 years. It was probably the most investigated research trend in the recent past. For optimal combustion, the fuel should have a low content of fine particles (Kons et al. 2015), which can be achieved by screening or sieving. The use of narrower screens improves the product quality but decreases productivity and increases fuel consumption. Therefore, recommendations for optimal screen sizes should be defined for different areas of application and quality requirements. Noise and vibration have been identified as the most relevant parameters influencing the human health during chipping operations. The information produced in these studies is important because it raises awareness about the higher noise impact of a chipper, so that appropriate countermeasures can be taken (additional distance, noise-attenuation and shielding measures, etc.) (Spinelli et al. 2016b).

Due to spatial distribution, low mass density, low energy density and low bulk density, the transportation of forest fuel is crucial for economic and ecological efficiency (Wolfsmayr and Rauch 2014). The question of efficient production of wood chips is tightly connected to the reduction of transportation costs. In the past, this problem was overcome by keeping transportation distances very short. With the recent boom in bio-energy and construction of larger bio-energy power plants, the total woody fuel needs within a region have increased, and the required supply region has become larger. Transportation distances and costs have increased accordingly (Asikainen et al. 2001). Transportation by railways or waterways (Tahvanainen and Anttila 2011, Wolfsmayr et al. 2016) has become a valuable alternative. Intermodal transport, however, has not been studied in the past and, therefore, future research requirements have been identified (Wolfsmayr and Rauch 2014). The best possible utilisation of the vehicle capacity will become a key factor for remaining competitive. The capacity for trucks can be improved through higher payloads, increased on-truck load density, reduced loading and unloading time, smaller transporting distance, as well decreased hourly costs and operational delays (Stampfer and Kanzian 2006). Operational delays can be minimised by balancing the chipping and transportation capacities and inventory levels at landings and terminals. Linear programming models have been developed to study the logistics and determine the best setup for forest fuel chains (e.g. Kanzian et al. 2009, Velazquez-Marti and Fernandez-Gonzalez 2010, Van Dyken et al. 2010, Kanzian et al. 2013).

In recent years, the assessment of ecological impact is becoming more and more important. Life cycle assessment (LCA) was used in several studies (Whittaker et al. 2011, Murphy et al. 2016, Klein et al. 2016, De la Fuente et al. 2017) to evaluate biomass-to-energy systems to reduce environmental impacts. It is expected that this topic will also become one of the main future research trends because of recently defined climate protection targets. The focus is not only climate change but also water and soil protection, which will probably become more important.

5. References

Abdallah, R., Auchet, S., Méausoone, P. J., 2014: A dynamic measurement of a disc chipper cutting forces. Biomass and Bioenergy 64: 269–275.

Anerud, E., von Hofsten, H., Eliasson, L., 2016: An alternative supply system for stump biomass – coarse grinding combined with sieving of the produced hog fuel. International Journal of Forest Engineering 27(2): 109–114.

Anttila, P., Asikainen, A., Laitila, J., Broto, M., Campanero, I., Lizarralde, I., Rodriguez, F., 2011: Potential and supply costs of wood chips from forests in Soria, Spain. Forest Systems 20(2): 245–254.

Asikainen, A., Ranta, T., Laitila, J., 2001: Large-scale forest fuel procurement. In: Pelkonen, P., Hakkila, P., Karjalainen, T., Schlamadinger, B. Woody Biomass as an Energy Source – Challenges in Europe, European Forest Institute (EFI): 73–78.

Assirelli, A., Civitarese, V., Fanigliulo, R., Pari, L., Pochi, D., Santangelo, E., Spinelli, R., 2013: Effect of piece size and tree part on chipper performance. Biomass and Bioenergy 54: 77–82.

Belbo, H., Talbot, B., 2014: Systems analysis of ten supply chains for whole tree chips. Forests 5(9): 2084–2105.

Bergström, D., Di Fulvio, F., 2014: Comparison of the cost and energy efficiencies of present and future biomass supply systems for young dense forests. Scandinavian Journal of Forest Research 29(8): 793–812.

COM/2014/015: Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A policy framework for climate and energy in the period from 2020 to 2030.

De la Fuente, T., González-García, S., Athanassiadis, D., Nordfjell, T., 2017: Fuel consumption and GHG emissions of forest biomass supply chains in Northern Sweden: a comparison analysis between integrated and conventional supply chains. Scandinavian Journal of Forest Research 32(7): 568–581.

De Meyer, A., Cattrysse, D., Rasinmäki, J., Van Orshoven, J., 2014: Methods to optimise the design and management of biomass-for-bioenergy supply chains: A review. Renewable and Sustainable Energy Reviews 31: 657–670.

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.

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.

Eisenlauer, M., Teipel, U., 2016: Comminution of woody renewable resources. Chemie-Ingenieur-Technik 88(7): 948–957.

Eliasson, L., von Hofsten, H., Johannesson, T., Spinelli, R., Thierfelder, T., 2015a: Effects of sieve size on chipper productivity, fuel consumption and chip size distribution for open drum chippers. Croatian Journal of Forest Engineering 36(1): 11–18.

Eliasson, L., Eriksson, A., Mohtashami, S., 2015b: Analysis of factors affecting productivity and costs for a high-performance chip supply system. Applied Energy 185: 497–505.

Erber, G., Kanzian, C., Stampfer, K., 2016: Modelling natural drying of European beech (*Fagus sylvatica* L.) logs for energy based on meteorological data. Scandinavian Journal of Forest Research 31(3): 294–301.

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, L. N., 2008: Comparative analyses of forest fuels in a life cycle perspective with a focus on transport systems. Resources, Conservation and Recycling 52(10): 1190–1197.

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.

Eskandarpour, M., Dejax, P., Miemczyk, J., Péton, O., 2015: Sustainable supply chain network design: An optimization-oriented review. Omega 54: 11–32.

Facello, A., Cavallo, E., Magagnotti, N., Paletto, G., Spinelli, R., 2013a: The effect of knife wear on chip quality and processing cost of chestnut and locust fuel wood. Biomass and Bioenergy 59: 468–476.

Facello, A., Cavallo, E., Spinelli, R., 2013b: Chipping machines: Disc and drum energy requirements. Journal of Agricultural Engineering 44(2): 378–380.

Facello, A., Cavallo, E., Magagnotti, N., Paletto, G., Spinelli, R., 2013c: The effect of chipper cut length on wood fuel processing performance. Fuel Processing Technology 116: 228–233.

Ferreira, J. V., Viana, H., Esteves, B., Cruz Lopes, L. P., Domingos, I., 2014: Life cycle assessment of residual forestry biomass chips at a power plant: A Portuguese case study. International Journal of Energy and Environmental Engineering 5(2–3): 1–7.

Flisberg, P., Frisk, M., Rönnqvist, M., 2012: FuelOpt: A decision support system for forest fuel logistics. Journal of the Operational Research Society 63(11): 1600–1612.

Gałezia, T., 2013: Analysis of selected methods effectiveness of wood biomass harvesting for energy purposes. Silva Balcanica 14(1): 94–101.

Gerasimov, Y., Karjalainen, T., 2013: Energy wood resources availability and delivery cost in Northwest Russia. Scandinavian Journal of Forest Research 28(7): 689–700.

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.

Gold, S., Seuring, S., 2011: Supply chain and logistics issues of bio-energy production. Journal of Cleaner Production 19(1): 32–42.

Gronalt, M., Rauch, P., 2007: Designing a regional forest fuel supply network. Biomass and Bioenergy 31(6): 393–402.

Gustavsson, L., Eriksson, L., Sathre, R., 2011: Costs and CO_2 benefits of recovering, refining and transporting logging residues for fossil fuel replacement. Applied Energy 88(1): 192–197.

Holzleitner, F., Kanzian, C., Höller, N., 2013: Monitoring the chipping and transportation of wood fuels with a fleet management system. Silva Fennica 47(1): 1–11.

IARC 1995: IARC monographs on the evaluation of carcinogenic risks to human. Wood dust and formaldehyde. Vol. 62. Lyon: IARC.

IRU, 2017: Weights and dimensions good transport. Retrieved from www.iru.org/resources/tools-apps/infocentre [15/12/2017].

Isaksson, P., Gradin, P. A., Hellström, L. M., 2013: A numerical and experimental study regarding the influence of some process parameters on the damage state in wood chips. Holzforschung 67(6): 691–696.

ITF, 2017: Permissible Maximum Weights of Lorries in Europe. Retrieved from www.itf-oecd.org/node/19217 [15/12/2017].

Kallio, A. M. I., Anttila, P., McCormick, M., Asikainen, A., 2011: Are the Finnish targets for the energy use of forest chips realistic-Assessment with a spatial market model. Journal of Forest Economics 17(2): 110–126.

Kanzian, C., Holzleitner, F., Stampfer, K., Ashton, S., 2009: Regional energy wood logistics - Optimizing local fuel supply. Silva Fennica 43(1): 113–128.

Kanzian, C., Kühmaier, M., Zazgornik, J., Stampfer, K., 2013: Design of forest energy supply networks using multi-objective optimization. Biomass and Bioenergy 58: 294–302.

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(8): 3404–3413.

Karttunen, K., Väätäinen, K., Asikainen, A., Ranta, T., 2012: The operational efficiency of waterway transport of forest chips on Finland's lake Saimaa. Silva Fennica 46(3): 395–413.

Kent, T., Kofman, P., Coates, E., 2011: Harvesting wood for energy. Cost-effective woodfuel supply chains in Irish forestry. COFORD Report: 98 p.

Klein, D., Wolf, C., Schulz, C., Weber-Blaschke, G., 2016: Environmental impacts of various biomass supply chains for the provision of raw wood in Bavaria, Germany, with focus on climate change. Science of the Total Environment 539: 45–60.

Kons, K., Bergström, D., Di Fulvio, F., 2015: Effects of sieve size and assortment on wood fuel quality during chipping operations. International Journal of Forest Engineering 26(2): 114–123.

Kováč, J., Krilek, J., Mikleš, M., 2011: Energy consumption of a chipper coupled to a universal wheel skidder in the process of chipping wood. Journal of Forest Science 57(1): 34–40.

Krajnc, M., Dolšak, B., 2014: The influence of drum chipper configuration on the quality of wood chips. Biomass and Bioenergy 64: 133–139.

Kühmaier, M., Kanzian, C., Stampfer, K., 2014: Identification of potential energy wood terminal locations using a spatial multicriteria decision analysis. Biomass and Bioenergy 66: 337–347.

Kühmaier, M., Stampfer, K., 2012: Development of a multicriteria decision support tool for energy wood supply management. Croatian Journal of Forest Engineering 33(2): 181–198.

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

Kuljich, S., Hernández, R. E., Blais, C., 2015: Effects of cutterhead diameter and log infeed position on energy requirements of a chipper-canter. Wood and Fiber Science 47(4): 399–409.

Kuptz, D., Hartmann, H., 2015: The effect of raw material and machine setting on chipping performance and fuel quality – a German case study. International Journal of Forest Engineering 26(1): 60–70.

Laitila, J., 2008: Harvesting technology and the cost of fuel chips from early thinnings. Silva Fennica 42(2): 267–283.

Laitila, J., Nuutinen, Y., 2015: Efficiency of integrated grinding and screening of stump wood for fuel at roadside landing with a low-speed double-shaft grinder and a star screen. Croatian Journal of Forest Engineering 36(1): 19–32.

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): 1–19.

Laitila, J., Niemistö, P., Väätäinen, K., 2016: Productivity of multi-tree cutting in thinnings and clear cuttings of young downy birch (*Betula pubescens*) dominated stands in the integrated harvesting of pulpwood and energy wood. Baltic Forestry 22(2): 116–131.

Laitila, J., Heikkilä, J., Anttila, P., 2010: Harvesting alternatives, accumulation and procurement cost of small-diameter thinning wood for fuel in Central Finland. Silva Fennica 44(3): 465–480.

Laitila, J., Kärhä, K., Jylhä, P., 2009: Time consumption models and parameters for off- and on-road transportation of whole-tree bundles. Baltic Forestry 15(1): 105–114.

Magagnotti, N., Nannicini, C., Sciarra, G., Spinelli, R., Volpi, D., 2013: Determining the exposure of chipper operators to inhalable wood dust. Annals of Occupational Hygiene 57(6): 784–792.

Manzone, M., Balsari, P., 2015: The energy consumption and economic costs of different vehicles used in transporting woodchips. Fuel 139: 511–515.

Marchi, E., Magagnotti, N., Berretti, L., Neri, F., Spinelli, R., 2011: Comparing terrain and roadside chipping in mediterranean pine salvage cuts. Croatian Journal of Forest Engineering 32(2): 587–598.

Mizaras, S., Sadauskiene, L., Mizaraite, D., 2011: Cost and profitability of biofuel chipping in *Alnus incana* stands in Lithuania. Scandinavian Journal of Forest Research 26(2): 154–160.

Mola-Yudego, B., Picchi, G., Röser, D., Spinelli, R., 2015: Assessing chipper productivity and operator effects in forest biomass operations. Silva Fennica 49(5): 1–14.

Murphy, F., Sosa, A., McDonnell, K., Devlin, G., 2016: Life cycle assessment of biomass-to-energy systems in Ireland modelled with biomass supply chain optimisation based on greenhouse gas emission reduction. Energy 109: 1040–1055.

Nati, C., Magagnotti, N., Spinelli, R., 2015: The improvement of hog fuel by removing fines, using a trommel screen. Biomass and Bioenergy 75: 155–160.

Nati, C., Spinelli, R., Fabbri, P., 2010: Wood chips size distribution in relation to blade wear and screen use. Biomass and Bioenergy 34(5): 583–587.

Nuutinen, Y., Petty, A., Bergström, D., Rytkönen, M., Di 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.

Nuutinen, Y., Laitila, J., Rytkönen, E., 2015: Grinding of stumps, logging residues and small diameter wood using a CBI 5800 grinder with a truck as a base machine. Baltic Forestry 20(1): 176–188.

Ovaskainen, H., Uusitalo, J., Väätäinen, K., 2004: Characteristics and significance of a harvester operators' working technique in thinnings. International Journal of Forest Engineering 15(2): 67–77.

Pasila, A., 2013: Changes, challenges and opportunities in the wood energy supply chain. Agronomy Research 11(2): 529–532.

Patterson, D. W., Hartley, J. I., Pelkki, M. H., 2011: Size, moisture content, and British thermal unit value of processed in-woods residues: Five Case Studies. Forest Products Journal 61(4): 316–320.

Picchi, G., Eliasson, L., 2015: Chip truck utilization for a container handling chipper truck when chipping logging residues and the effect of two grapple types on chipping efficiency. International Journal of Forest Engineering 26(3): 203–211.

Pochi, D., Civitarese, V., Fanigliulo, R., Spinelli, R., Pari, L., 2015: Effect of poplar fuel wood storage on chipping performance. Fuel Processing Technology 134: 116–121.

Poje, A., Spinelli, R., Magagnotti, N., Mihelic, M., 2015: Exposure to noise in wood chipping operations under the conditions of agro-forestry. International Journal of Industrial Ergonomics 50: 151–157.

Ranta, T., Rinne, S., 2006: The profitability of transporting uncomminuted raw materials in Finland. Biomass and Bioenergy 30(3): 231–237.

Rauch, P., Gronalt, M., 2011: The effects of rising energy costs and transportation mode mix on forest fuel procurement costs. Biomass and Bioenergy 35(1): 690–699.

Röser, D., Sikanen, L., Asikainen, A., Parikka, H., Väätäinen, K., 2011: Productivity and cost of mechanized energy wood harvesting in Northern Scotland. Biomass and Bioenergy 35(11): 4570–4580.

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.

Rottensteiner, C., Tsioras, P., Neumayer, H., Stampfer, K., 2013: Vibration and noise assessment of tractor-trailer and truck-mounted chippers. Silva Fennica 47(5): 1–14.

Routa, J., Asikainen, A., Björheden, R., Laitila, J., Röser, D., 2013: Forest energy procurement: State of the art in Finland and Sweden. Wiley Interdisciplinary Reviews: Energy and Environment 2(6): 602–613.

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.

Sosa, A., Acuna, M., McDonnell, K., Devlin, G., 2015: Managing the moisture content of wood biomass for the optimisation of Ireland's transport supply strategy to bioenergy markets and competing industries. Energy 86: 354–368.

Spinelli, R., Visser, R., 2009: Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy 33(3): 429–433.

Spinelli, R., Ivorra, L., Magagnotti, N., Picchi, G., 2011a: Performance of a mobile mechanical screen to improve the commercial quality of wood chips for energy. Bioresource Technology 102(15): 7366–7370.

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

Spinelli, R., Cavallo, E., Facello, A., Magagnotti, N., Nati, C., Paletto, G., 2012a: Performance and energy efficiency of alternative comminution principles: Chipping versus grinding. Scandinavian Journal of Forest Research 27(4): 393–400.

Spinelli, R., Cavallo, E., Facello, A., 2012b: A new comminution device for high-quality chip production. Fuel Processing Technology 99: 69–74.

Spinelli, R., Magagnotti, N., 2013: Performance of a small-scale chipper for professional rural contractors. Forest Science and Practice 15(3): 206–213.

Spinelli, R., Magagnotti, N., 2014a: Determining long-term chipper usage, productivity and fuel consumption. Biomass and Bioenergy 66: 442–449.

Spinelli, R., Magagnotti, N., 2014b: Using disposable chipper knives to decrease wood fuel processing cost. Fuel Processing Technology 126: 415–419.

Spinelli, R., Glushkov, S., Markov, I., 2014a: Managing chipper knife wear to increase chip quality and reduce chipping cost. Biomass and Bioenergy 62: 117–122.

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.

Spinelli, R., Cavallo, E., Eliasson, L., Facello, A., Magagnotti, N., 2015: The effect of drum design on chipper performance. Renewable Energy 81: 57–61.

Spinelli, R., Eliasson, L., Magagnotti, N., 2016a: Increasing wood fuel processing efficiency by fine-tuning chipper settings. Fuel Processing Technology 151: 126–130.

Spinelli, R., Magagnotti, N., Deboli, R., Preti, C., 2016b: Noise emissions in wood chipping yards: Options compared. Science of the Total Environment 563–564: 145–151.

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.

Sukhanov, Y., Seliverstov, A., Gerasimov, Y., 2013: Efficiency of forest chip supply systems in Northwest Russia. Advanced Materials Research 740: 799–804.

Tahvanainen, T., Anttila, P., 2011: Supply chain cost analysis of long-distance transportation of energy wood in Finland. Biomass and Bioenergy 35(8): 3360–3375.

Vainio, P., Tokola, T., Palander, T., Kangas, A., 2009: A GIS-based stand management system for estimating local energy wood supplies. Biomass and Bioenergy 33(9): 1278–1288.

Valente, C., Spinelli, R., Hillring, B. G., Solberg, B., 2014: Mountain forest wood fuel supply chains: Comparative studies between Norway and Italy. Biomass and Bioenergy 71: 370–380.

Van Dyken, S., Bakken, B. H., Skjelbred, H. I., 2010: Linear mixed-integer models for biomass supply chains with transport, storage and processing. Energy 35(3): 1338–1350.

Vangansbeke, P., Osselaere, J., Van Dael, M., De Frenne, P., Gruwez, R., Pelkmans, L., Gorissen, L., Verheyen, K., 2015: Logging operations in pine stands in Belgium with additional harvest of woody biomass: Yield, economics, and energy balance. Canadian Journal of Forest Research 45(8): 987–997.

Velazquez-Marti, B., Fernandez-Gonzalez, E., 2010: Mathematical algorithms to locate factories to transform biomass in bioenergy focused on logistic network construction. Renewable Energy 35(9): 2136–2142.

Wegener, J. K., Frerichs, L., Kemper, S., Sümening, F., 2015: Wood chipping with conical helical blades – Practical experiments concerning the impact of the infeed angle on the power requirement of a helical chipper. Biomass and Bioenergy 80: 173–178.

Whittaker, C., Mortimer, N., Murphy, R., Matthews, R., 2011: Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass and Bioenergy 35(11): 4581–4594.

Wolfsmayr, U. J., Rauch, P., 2014: The primary forest fuel supply chain: A literature review. Biomass and Bioenergy 60: 203–221.

Wolfsmayr, U. J., Rauch, P., Gronalt, M., Merenda, R., Longo, F., 2016: Evaluating primary forest fuel rail terminals with discrete event simulation: A case study from Austria. Annals of Forest Research 59(1): 145–164.

Yoshida, M., Berg, S., Sakurai, R., Sakai, H., 2016: Evaluation of chipping productivity with five different mobile chippers at different forest sites by a stochastic model. Croatian Journal of Forest Engineering 37(2): 309–318.

Received: March 07, 2017
Accepted: December 15, 2017

Authors' addresses:

Martin Kühmaier, PhD. *
e-mail: martin.kuehmaier@boku.ac.at
Gernot Erber, PhD.
e-mail: gernot.erber@boku.ac.at
University of Natural Resources
and Life Sciences Vienna
Department of Forest and Soil Sciences
Institute of Forest Engineering
Peter Jordan Strasse 82
1190 Vienna
AUSTRIA

* Corresponding author