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Chipping Operations and Efficiency in Different Operational Environments

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This research analyses the productivity of energy wood chipping operations at several sites in Austria and Finland. The aim of the work is to examine the differences in productivity and the effects of the operational environment for the chipping of bioenergy at the roadside. Furthermore, the study quantifies the effects of different variables such as forest energy assortments, tree species, sieve size and machines on the overall productivity of chipping. The results 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. Furthermore, the different operational environments in both countries, as well as the characteristics of the raw material also seem to have an effect on productivity. In order to improve the chipping productivity, particularly in Central European conditions, all relevant stakeholders need to work jointly to find solutions that will allow a greater variation of chip size. Furthermore, in the future more consideration has to be given to the close interlinkage between the chipper, crane and grapple. As a result, investments costs can be optimized and operational costs and stress on the machines reduced.

Keywords wood-fuel logistics, forest machinery, bioenergy supply
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1 Introduction

The use of forest and agricultural biomass for energy is an increasingly important topic, particularly in light of the recent debate on climate change (IPCC 2007). In the European context, forest biomass offers the largest and most economic potential as a renewable fuel when managed on a sustainable basis (Alakangas et al. 2007, Naabuurs et al. 2007, Asikainen et al. 2008, Röser et al. 2008). With current forest biomass development, the ambitious 20/20/20 targets set by the EU (European Commission 2009) and non-EU countries are a great challenge for the forestry and biomass sector.

One of the biggest challenges to increase the use of forest biomass is the availability and proper use of suitable harvesting technology to meet the growing demand for raw material. Existing, and proven solutions to harvest forest biomass, have to be adapted to new working environments across Europe. For many years, forest operations have been fully mechanized in Scandinavian countries, whereas, in Central Europe, the mechanization process has been much slower (Asikainen et al. 2008). However, mechanization of forest biomass for energy operations is particularly crucial in order to make forest operations economically sustainable. The adaptation of existing harvesting systems from Scandinavia to other parts of Europe to facilitate the recovery of energy biomass through technology and know-how transfer is an ongoing, but challenging process.

The most common supply chain in Scandinavia and Central Europe is based on comminuting the raw material at the roadside (Stampfer and Kanzian 2006, Asikainen et al. 2008). In that system, the harvesting is done with a harvester using the cut-to-length method, while forwarding is done by conventional forwarders designed for roundwood forwarding (Hakkila 2004, Laitila et al. 2007, Laitila 2008). At the roadside, the raw material is chipped with either a truck mounted or tractor-based chipper directly into the chip truck. Only in some cases, for example in the Alps, chips are blown into a pile on the ground (Kanzian et al. 2009). Chipping at a plant or terminal usually results in lower chipping costs, but increases the overall demand on logistics and handling costs, and is often not possible due to high dust and noise emmissions (Kanzian et al. 2009). If chipping is carried out at terminal, loose chips are transported to the heating plant using an ordinary chip truck or tractor trailer. Apart from long distance transportation, chipping is a crucial cost factor in the entire supply chain, and its economic success is largely dependent on an economic chipping operation (Angus-Hankin 1995, Asikainen 1995, Laitila 2008).

In Europe, in the past decade, studies have focused on a wider range of comminution equipment. For example, grinders (Asikainen and Pulkkinen 1998) and integrated equipment, such as in-woods chippers (Vesisenaho 1994, Thor 1996, Hämäläinen 1997, Asikainen and Pulkkinen 1998, Remmler 1999, Spinelli and Hartsough 2001). The use of hand fed chippers has also been investigated, but they are usually limited to small scale operations (Spinelli and Hartsough 2001, Webster 2007). Today, the most commonly used chippers are independent chippers, either self-powered or powered by a tractor or truck, processing raw material at the roadside. Several studies on their use, productivity and systems analysis have been published (Asikainen and Pulkkinen 1998, Feller 2001, Spinelli and Hartsough 2001, Wittkopf 2005, Yoshioka et al. 2005, Lechner et al. 2007, Moskalik and Ostolska 2011). In recent years, the focus of chipping studies has shifted towards the investigation of more specific variables of the chipping operations. For example, van Belle (2006), Spinelli and Hartsough (2001), Spinelli et al. (2011) and Magagnotti and Spinelli (2011) have highlighted the large effect of varying raw material characteristics on the overall chipping productivity, while Nati et al. (2010, 2011) studied the effect of blade wear and sieve size on chipping productivity and fuel consumption. Spinelli and Visser (2009), on the other hand, have investigated the effect of delay times of chipping operations in Italian conditions. Furthermore, Cremer (2009) carried out a comprehensive study on chipping operations in Germany. In Finland, Kärhä (2011a,b) and Pajuoja et al. (2011) recently carried out a number of studies evaluating the performance of various mobile chippers.

There is an important need to identify in which areas the technology and the operational environment should be improved in order to increase the economic and environmental sustainability of forest operations. Therefore, the study aims to investigate differences in chipping productivity at roadside, in different operational environments. Furthermore, the study aims to quantify the effects of different variables, such as, forest energy assortments, sieve size and used technology on productivity.

2 Material and Methods

2.1 Description of the Trials

Different sets of trials were performed in order to have sufficient variability to assess the analysis. In total, 5 sites were analyzed in Finland and 1 in Austria. The time studies in Finland were carried out in Tohmajärvi (62°14´N, 30°20´E), Rääkylä (62°18´N, 29°37´E) and Kitee (62°6´N, 30°8´E) during February, May and November of 2008, respectively. Two additional sites were established in the Kumpu (62°31´N, 29°58´E) municipality and performed in March and June, 2008. All of the trials were performed by the same local chipping entrepreneur. In addition, an Austrian trial was established during August, 2008 at Engelhartszell (48°30´N, 13°44´E), also by a local chipping entrepreneur.

In both countries, the studied chipper was a Kesla C4560 drum chipper, mounted on a trailer and powered by a tractor. Both chippers were equipped with a KESLA 600T crane. In Finland, the tractor was a Valtra S280 with 250 HP, while in Austria a John Deere 7920 with 300 HP was used.

The drum chipper was equipped with a chipping system consisting of 6 staggered knives. A screen was mounted under the drum to ensure a homogenized chip size. A no-stress control device slowed down the movement of the feeding system when the feed orifice was full. When the material was chipped by the blades, chips were sieved, and blown through the ejection system, directly into the container. The commands for maneuvering the crane were positioned in the cabin of the tractor. In all study sites, the chipper was operated by skilled operators.

In order to fulfill the product quality specifications of the respective local markets, the chipper was equipped with an 80×80 sieve in Finland and a 35×35 sieve in Austria. However, in order to better compare results, one load in Austria was chipped using an 80×80 sieve and 3 loads in Finland were chipped using a 35×35 sieve. The chipping equipment was always positioned parallel to the pile to minimize the moving time of the crane. The containers were positioned behind the chipper so that chips could be blown directly into the container.

In Finland, the observation unit was a truck container with a 50 m^3 load volume, whereas in Austria a farm tractor based container with a 25 m^3 load volume was used. Each container was always completely filled with chips. In the five sites in Finland, a total of 27 containers were studied, whereas in Austria, time studies were carried out on a total of 17 containers. After each container was filled it was weighed using certified truck scales.

The raw material consisted of species typically used for energy production in each of the coun-

Table 1. Location of the tests, number of resulting containers, raw material assortments, sieve used in the chipper and main species used. Mean D: estimated mean diameter of the containers.

Country	Location	Containers	Raw material	Mean D	Sieve	Main species
Finland	Kumpu	3	Whole trees	8.2	80×80	Alder
		4	Whole trees	8.4	80×80	Birch (30%) Pine (70%)
		3	Whole trees	10.4	80×80	Birch (80%)
	Rääkkylä	4	Whole trees	7	80×80	Birch (40%) Aspen (40%)
		3	Logging residues	3		Spruce (90%)
	Tohmajärvi	7	Stems	21.9	80×80	Pine
	Kitee	3	Whole trees	9.70	35×35	Alder
Austria	Engelhartszell	6	Whole trees	11.47	35×35	Spruce
		10	Whole trees	15.25	35×35	Beech
		1	Whole trees	15.25	80×80	Beech

tries (Table 1). In Austria, material consisted of whole trees of beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*) with a small amount of un-merchantable trees. In Finland, the raw materials studied were large diameter stems of mainly Scots pine, (*Pinus sylvestris)* with some small amounts of aspen (*Populus tremula*). In Finland, the stems were very homogenous and piled in two large piles in a spacious storage area. Furthermore, whole trees from thinning operations of hardwood, (*Betula pubescens*, *Alnus incana*), mixed hardwood, and softwood (*Pinus sylvestris*, *Picea abies*, *Populus tremula*) were chipped at several roadside storage places. Finally, logging residues originating from a final harvest operation of softwood tops (*Picea abies*) and branches, with some un-merchantable trees, were chipped at the roadside.

Before chipping the dimension of all the piles, percentages of species, and the average diameter of the wood material to be chipped, were measured.

2.2 Data Analysis

A time study was carried out manually using the continuous time method (Harstela 1991). The data was collected using a hand-held data recorder. The accuracy of the data recorder was 0.6 s (1 cm). The effective chipping time (E0) was recorded and sub-divided according to crane movement elements and chipper feed orifice activities. In Finland, observations were carried out by two experienced researchers due to the overlapping of time elements. In Austria, the time study of the feed orifice was carried out by an experienced researcher, and the movement of the crane was video recorded and later analyzed in the laboratory. Moreover, the number of crane loads for each container was counted in order to calculate the size of the boom load.

Considered time element of the crane movements:

- Feeding: placing the material into the feed orifice
- Helping in feeding: additional efforts to ensure consistent feeding
- Waiting for feeding: crane idling
- Boom moving: boom out, grab, and boom in

Considered time elements of the chipper feed orifice activities:

- Chipping: when the feed orifice is full
- Idling: waiting for material to be placed into the feed orifice

The analysis focused on the interaction of the chipper and the crane in order to study their

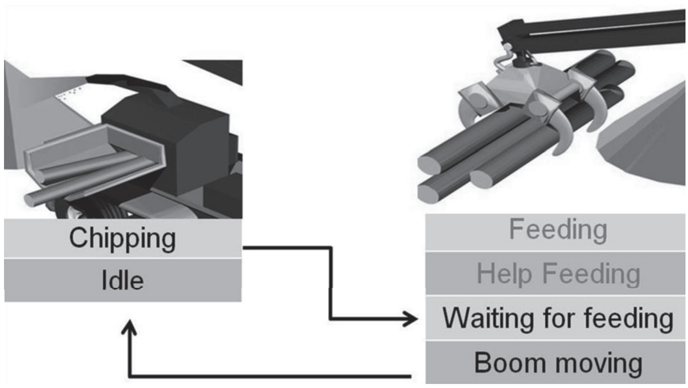

Fig. 1. Description of the interrelationship between chipper and crane. The chipper element “Chipping” is directly related to the element “Waiting for feeding” of the crane: the crane cannot feed the chipper when it is already chipping. “Boom moving” directly affects the chipper: the chipper remains “idle” when the crane is moving material. The two other elements “Feeding” and “Help Feeding” can take place simultaneously to the chipper element “Chipping” and therefore do not directly affect the chipper productivity.

performances and consequently to limit the idle times between them. Cuchet et al. (2004) used a similar approach for the study of a bundling unit. The chipper productivity is potentially affected by factors such as; the size of the sieve used, the sharpness of the knives, tree species, the stem diameter and moisture content of the raw material. Whereas, the crane productivity is potentially affected by the operator, raw material, storage set-up, diameter and the operational environment (e.g. slopes).

However, production and idling are always inter-linked between the two units (Fig. 1). The performance of the chipper has a direct effect on the waiting time of the crane, which has to wait for feeding when the chipper has insufficient capacity to process the wood.

The overall results were analyzed using ANOVA tests in order to find significant differences amongst the different factors. The differences between the material assortments (logging residues, whole trees and stems) were assessed with a Tukey test. Finally, a simple model was constructed for the analysis of the combined effect of the location (i.e. country) and sieve on the productivity, using the whole tree assortments. The model was fitted using restricted maximum likelihood, and the variables were treated as dummy variables. The model followed the equation:

$$p = \beta_0 + \beta_1 SIEVE + \beta_2 FINLAND + \varepsilon \qquad (1)$$

Where p represents the productivity (loose m^3/effective hour), SIEVE is a dummy variable that takes the value 1 when the sieve used was 80×80, and 0 when the sieve used was 35×35. FINLAND is a dummy variable that takes the value 1 if the process took place in Finland, and 0 if it took place in Austria.

3 Results

The average, overall productivity of all the trials was about 85.3 loose m^3 per effective hour. For the crane, about 50% of the time was moving and about 24% feeding, on average. Other operations considered, such as helping in feeding, waiting for the chipper to process, and waiting for other

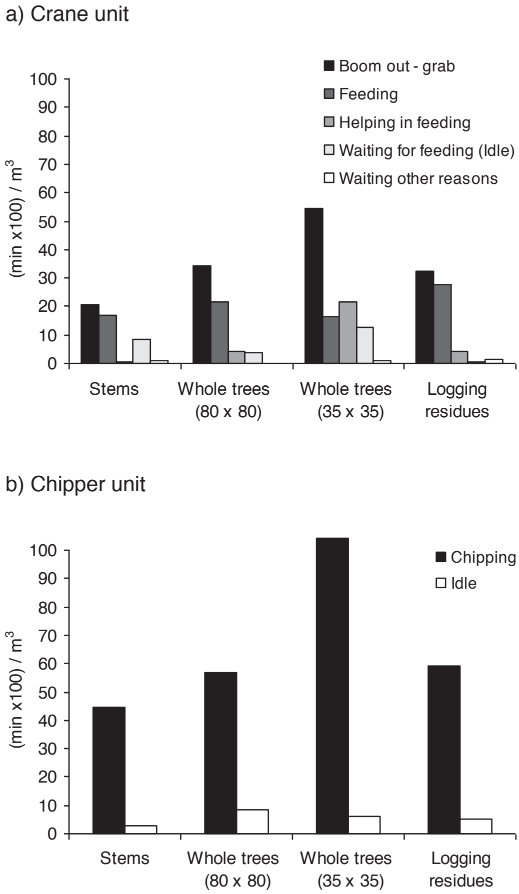

Fig. 2. Shares of time invested in the different operations considered according to raw material assortments.

reasons accounted for 14%, 11% and 1% of the time, respectively. In total, the chipper was in operation about 92 % of the time.

However, these shares presented important differences in regard to the type of raw material, and the sieve used (Fig. 2).

The raw materials affected the percentages of time that the crane was idle ($p<0.001$), whereas, it did not seem to affect the idling of the chipper ($p=0.517$). The time the crane remained idle was proportional to the size and diameter of the material chipped. In the case of the chipper, it remained idle about 8% of the time (Fig. 3). On the other hand, the size of the sieve seemed to have a moderate effect on the crane, ($p=0.031$) and a significant effect on the chipper efficiency

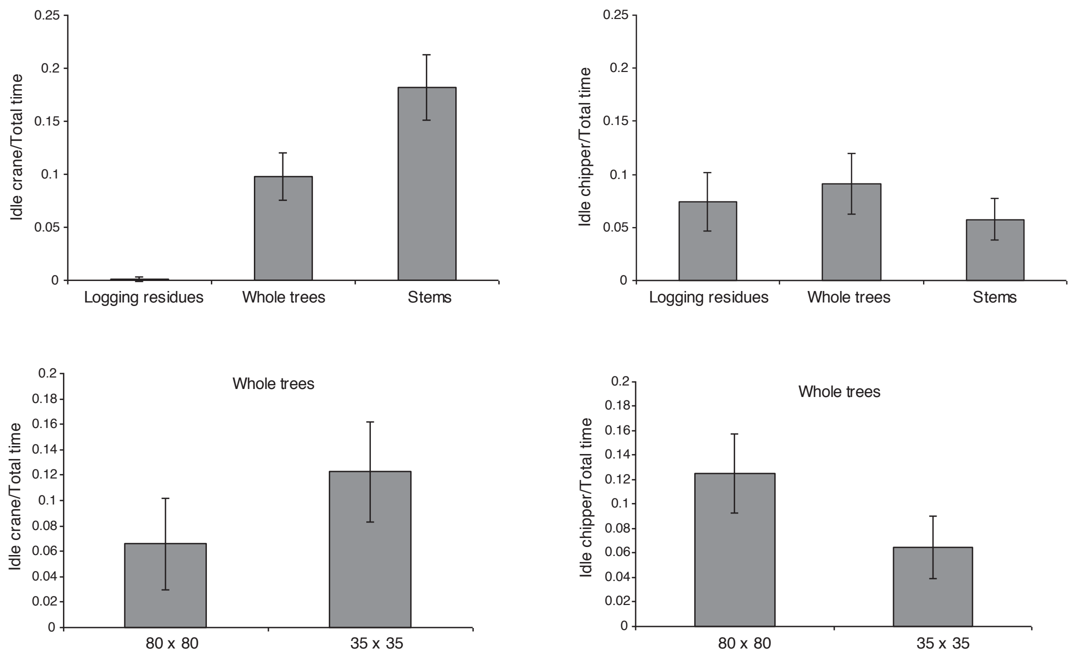

Fig. 3. Average percentages of idle time for the crane (left) and the chipper (right), according to raw material assortment (up) and sieve size (bottom). Error bars represent two times the standard error of every mean.

($p<0.01$). Whereas the share of idle time for the chipper was lower for the 35×35 sieve, the share of idle time in the case of the crane was lower for the 80×80 sieve.

The raw materials and sieve size partially explain the differences in productivity. For the same grapple load size, (linked to the raw material) the smaller sieve resulted in a reduction of productivity of about 47 loose m^3 per effective hour (std error = 3.30). Furthermore, the relationship of the grapple load size and the productivity was independent of the sieve size (Fig. 4). It is notable, that when the 35×35 sieve was used in Finland, the productivities were higher compared to the Austrian conditions. In addition, when using the 80×80 sieve in Austria, the productivities were lower than in the Finnish operations when chipping similar raw material.

The overall productivity of both machines was higher for stems, (Table 2) with no significant differences between logging residues and whole trees (p value = 0.999). The analysis of the sieves, on the overall productivity, revealed average increments of about 60% when the 80×80 sieve

Table 2. Average values of productivity (loose m^3/effective hour) according to raw material assortment, results of the Tukey test (groups a and b) and test of of significance for the accounted differences Standard Errors of the means are provided in parenthesis. Mean diff = mean difference between raw material assortments.

Variable	N	Mean (SE) (a)	Mean (SE) (b)
Whole trees	34	77.93 (2.94)	
Logging residues	3	77.39 (4.78)	
Stems	7		127.96 (4.68)

	Mean diff.	SE	p-value
Logging residues vs stems	–50.60	6.69	<0.001
Whole trees vs stems	–50.02	5.53	<0.001

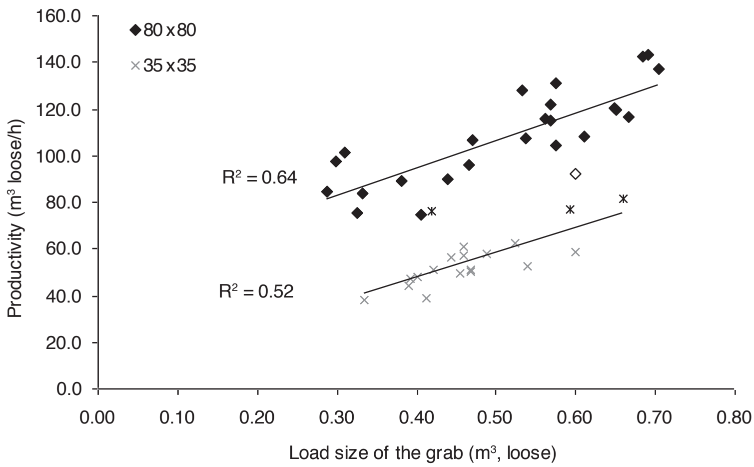

Fig. 4. Productivity according to load size of the grapple, for the two sieves considered. The white dot corresponds to the Austrian test using 80×80 sieves. The darker crosses correspond to the Finnish tests using 35×35 sieves.

Table 3. Overall effects of the sieve and country in the productivity (loose m^3/effective hour). The effects are treated as dummy variables. (Sieve 80×80 versus Sieve 35×35; Finland versus Austria) and the data only includes *whole trees* as raw material. SE = standard error (df = 31).

Variable	Estimate	SE	p-value
Intercept β_0	52.06	2.62	<0.001
"SIEVE" (80×80) β_1	31.32	5.80	<0.001
"FINLAND" β_2	22.97	5.76	<0.001

was used (Table 3). In addition, the statistical analysis showed that the average productivity was about 27% higher in Finnish conditions when the same sieve was used, although, it must be taken into account that the number of replications was very limited. The combination of both factors resulted in increments of around 104% in the Finnish trials.

The time lines of both machines working together revealed the dependence of the two different work elements (crane and chipper). Fig. 5 shows that there are significant differences in the working time of the crane and chipper. Differences are particularly evident in the case of stems and whole trees when the 35×35 sieve was used, where the crane is working considerably less. When chipping logging residues, both the chipper and the crane are working in sync after a slight "adjustment" phase at the beginning of the operations. When chipping whole trees with an 80×80 sieve, the results are mixed. However, in the case of Finland, where more data is available, the data shows that the chipper is working less than the crane.

Finally, concerning the crane cycles, the study showed that stems are most efficient to process when compared to logging residues. This is due to the large grapple load when processing the stems (Fig. 6). The larger grapple load reduces the number of cycles the crane has to carry out. The sieve size also has a large effect on the crane cycles, reducing their numbers considerably due to the long waiting times for the chipper.

4 Discussion

The results show that there are significant differences in how the machines work when comparing different assortments (logging residues, whole

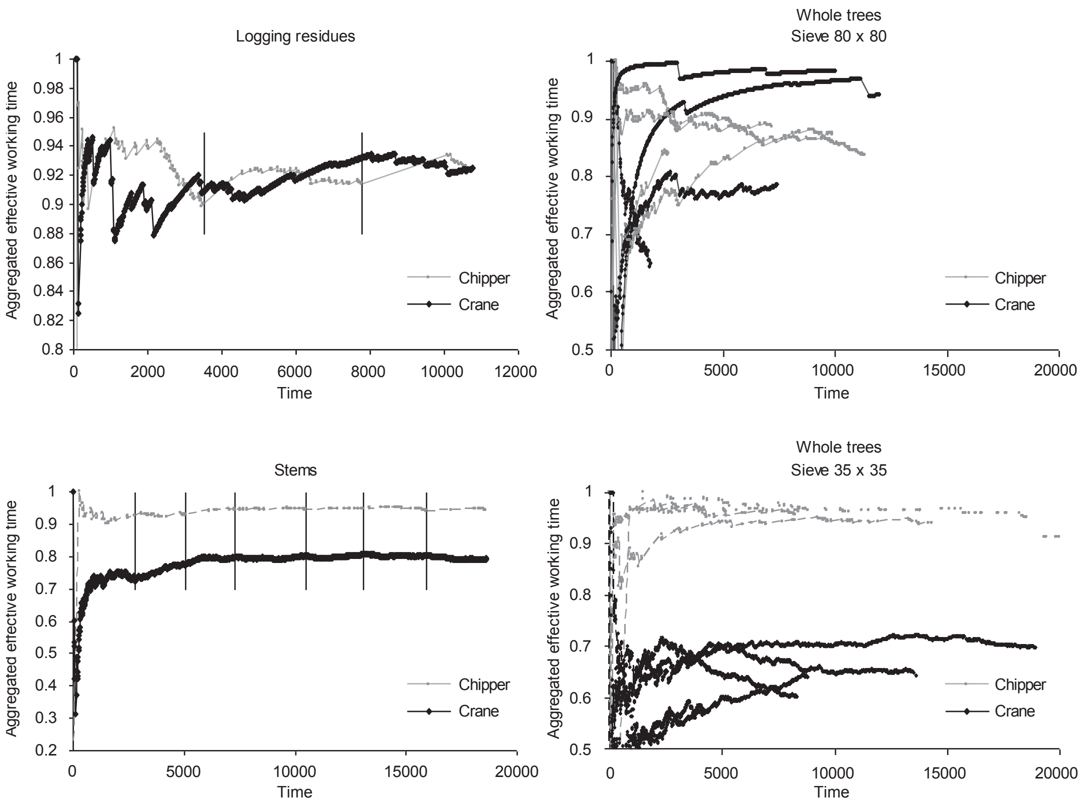

Fig. 5. Cumulative effective working time for the chipper and the crane for the same day and pile of raw material: logging residues (left, up), whole trees with sieves 80×80 (right, up) and 35×35 (right, bottom) and stems (left, bottom). Vertical lines correspond to the containers filled. Time is expressed in cmin (1 minute equals 100 centiminutes).

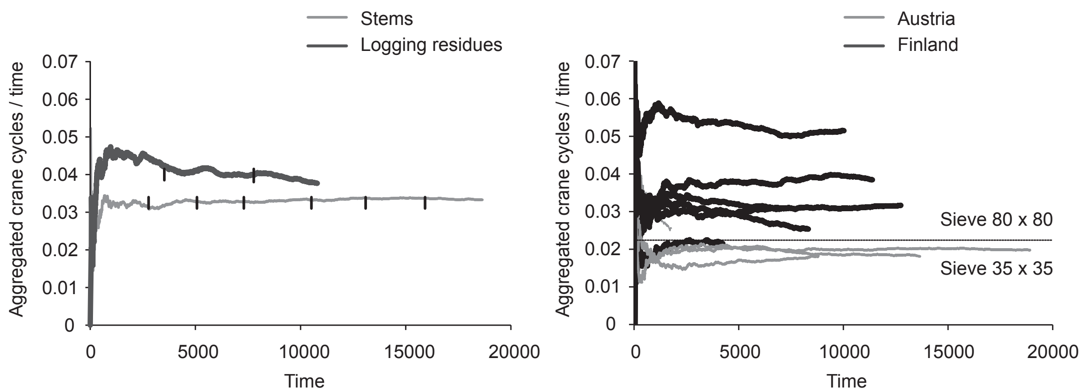

Fig. 6. Cumulative crane cycles for stems and logging residues (left) and for whole trees according to sieve size and country (right). Time is expressed in cmin (1 minute equals 100 centiminutes).

trees from thinnings and stems) and working environments (sieve size, species, organizational setup, operators, storage practices, local conditions and weather), resulting in important differences in productivity. Although, there are many sources of variability that might affect the overall productivity of the chipper, and consequently the analysis of the acquired data, this study focused on the most relevant variables and investigated the inter-linkages within the crane-chipper interaction.

Concerning the trial set up, even though there was some variation in the timing of trials, the effect of seasonal differences on the chipping operation was not observed. Previous studies in Finland found productivity differences in the chipper to be only about 5–8% higher in winter than in summer (Asikainen et al. 2001).

In general, the overall chipping productivities in this study are comparable with those reported in other studies in Central and Northern Europe (Asikainen 1998, Spinelli and Hartsough 2001, Lechner et al. 2007, Spinelli et al. 2011, Kärhä 2011a,b, Pajuoja 2011). The importance of the raw material itself and its dimensions have already been highlighted in previous studies. Spinelli and Hartsough (2001), for example, pointed out the significance of the piece size as one of the key elements of chipping productivity, which was also confirmed by a recent study carried out by Magagnotti and Spinelli (2011). Spinelli et al. (2011) found similar differences to the study presented here, for example, in the chipping productivity of stems vs. branches/whole trees. Van Belle (2006) also concluded that the raw material characteristics have a significant effect on the chipping productivity. Pajuoja (2011) also partly explained large differences of the chipping productivity among different mobile chippers in Finland, by pointing out the differences in the raw material.

Another factor of importance in productivity studies is the potential effect of the operator in the overall efficiency. Although, in the trials studied, all operations were handled by experienced operators, one of the limitations of the study is that there was only one operator in each country, which makes it impossible to isolate the effect of of the operator from other potential country-based effects. Different operators are known to have a large effect on the overall productivity in forest operations due to varying techniques; motoric skills, planning of the work, working experience, and decision-making processes (Ovaskainen et al. 2004). For instance, in a previous study in Finland, the variability concerning idle time due to different operators in harvesting operations accounted for 11.8% of the mean, when expressed as standard deviation, and 4.8% when expressed as a standard error (processed data from Ovaskainen et al. 2004). Similarly, the variability in relative productivity was 18.7% and 7.6%, respectively, for processing 100 dm^3. A similar study on harvesting operations observed the maximum productivity differences between individual operators to be in the range of 20–40%, depending on the complexity of the methods used (Kärhä et al. 2004).

However, it also must be taken into account that the chipping operations reported in this study involve less complex operations than in harvesting studies, and therefore, the differences due to the operator's skills can be assumed to be lower. For instance, in a study on chipper operations, Spinelli and Magagnotti (2010) regarded the operator's effect on commercial operations as secondary, and the between-operator's differences were not significant, resulting in its exclusion from their models. Although the results of this study are not conclusive, since the data is limited, we suggest the possibility that there are factors other than the operator skills that explain the differences between the operations performed in both countries, including, among others, the effect of different topography, common preparation practices, traditions in the organisation of the operations, or specific market demands that determine the working environment.

In fact, besides the potential differences due to the operator's skills, the main reason for the big differences can be attributed to the different sieves used in the trials (Fig. 3). In Southern Germany and Austria, many heating plants demand fine sized chips, from chippers with sieves of 35×35 mm since they result in a more uniform chip. However, in Finland, sieves of 80×80 mm are commonly used. The consequences are significant for the overall chipping productivity of the operations and also in terms of higher fuel consumption when using a smaller sieve. This was also observed by Nati et al. (2010), who noted that the smallest possible sieve size of their chipper (40×40) was not used due to the "tendency to choke the chipper". However, this did not correspond with our results, since an even smaller sieve (35×35) was used without any problems throughout the trial. On the other hand, our study confirmed that sieve size causes a significant reduction in chipping productivity.

Together with the sieve size, the raw material dimension is a key variable when carrying out the chipping operation (e.g. Magagnotti and Spinelli 2011, Spinelli and Hartsough 2001). The results showed that there are large variations in the effective working time of both the chipper and the crane when dealing with different raw materials. These differences are mainly caused by the varying diameters of the different raw material. For instance, when the chipper is fed with small diameter trees, the idle times of the crane are considerably lower when compared to larger dimensioned timber. The results are also in line with Asikainen et al. (2001), who found that the productivity of chipping small diameter trees is higher compared to chipping logging residues.

In this respect, an important strength of the study has been the analysis of the close connection between the chipper and the crane. According to the results, both machines have to be considered as one unit that is significantly dependent on each other. In addition, the grapple load had a large effect on the overall productivity of the operations, and therefore, more attention needs to be paid to the proper grapple size when dealing with varying raw material sources; particularly when chipping whole trees with an 80×80 sieve, a larger grapple would ensure less idle time of the chipper. The situation is opposite when chipping whole trees with a 35×35 sieve. If that assortment represents the largest share of a chipping contractor, the investment in a small crane is sufficient since the crane is idling a lot during the chipping. A smaller crane will also have positive secondary effects on the operation since it should reduce the fuel consumption and the stress on the equipment.

It has to be assumed that there are differences in the performance and in the organization of the activities, and that could be a possible explanation regarding some of the differences in Finland and Austria. However, there are a number of other factors that have an effect on the overall productivity of the operations, including e.g. sharpness of the blades or tree species (Nati et al. 2011, Spinelli et al. 2011). However, these factors were outside the scope of this study.

The study showed that several aspects, from operator skills to different working environments, might also have an effect on the overall productivity of the operations since the productivity of chipping is still higher in the Finnish trials, even when similar sieves were used. In the future, additional trials with different operators and the inclusion of other selected factors (e.g. sharpness of knives), could help to better explain the observed differences and evaluate the performance of the machines in different operational environments. Furthermore, effects on fuel consumption and resulting CO_2 emissions should be analyzed in future studies to mitigate the negative economic consequences of rising fuel prices for chipping entrepreneurs.

A direct outcome of this study can be the improvement of guidelines and advice to entrepreneurs when designing their supply chains and harvesting operations. First, it demonstrates that there would be a clear benefit by trying to improve chipping productivity in Austria, by looking at the different factors mentioned above, or considering the use of 80×80 sieves. At present, Finland has a competitive edge when it comes to the production of wood chips, simply because of longer traditions in using forest energy in heating plants. However, if the status quo is that the customer demands chips of smaller sizes, chipping contractors will have to comply with these demands.

Secondly, entrepreneurs should be aware of the main assortments to be processed before making the decision about which chipper, crane, and grapple they purchase in order to optimize their investment. When small diameter trees are the main source, a crane with a large grapple would be the most suitable choice. However, when dealing with larger diameter timber, the size of the grapple becomes less important, but the productivity of the chipper has to be higher in order to minimize waiting times of the crane.

Further studies may focus on solutions on how the overall operational efficiency of forest biomass supply chains can be improved in different operational environments, by improving the general framework and set-up of chipping operations. Furthermore, the overall economic benefit of, for example, using sharper knives rather than a smaller sieve to produce high quality chips, should be investigated. However, this can only be done using a holistic approach that involves all stakeholders along the supply chain.

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Total of 40 references