The Effect of Raw Material, Cut Length, and Chip Discharge on the Performance of an Industrial Chipper

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Abstract

In this study we examined the effect of specific factors on chipper performance by using a mobile industrial chipper in a real-life commercial setting. The comprehensive experimental design consisted of five replications per each combination of two types of raw material, two chip discharge systems, and two cut lengths (i.e., $5 \times 2 \times 2 \times 2 = 40$ replications). Each replication consisted of a full 18-m^3 trailer load. Cut length was manipulated by using different drum types. When all else was equal, the doubling of cut length resulted in a 50 percent increase of average chip length, a 15 percent increase of net productivity, and a 15 percent decrease in fuel consumption. The handling characteristics of the raw material had a strong impact on chipper productivity, causing variations on the order of 20 percent. The discharge system had no significant effect on fuel consumption or productivity, but it did impact product quality and bulk density. Using a blower allowed increasing bulk density between 4 and 7 percent, whereas the installation of a belt conveyor reduced the incidence of small chips and fine particles by up to 30 percent.

Chipping is an essential element in all modern energy wood supply chains because automated boilers only accept homogeneous fuel particles within specified size limits (Strehler 2000). Also, chipping offers additional benefits in terms of increased load density and improved handling quality (Pottie and Guimier 1985). For these reasons, low-density raw materials should be chipped as early as possible all along the supply chain (Björheden 2008). Mobile chippers are widely popular in Europe because they allow size reduction directly in the forest or at the roadside landing, before transportation (Asikainen and Pulkkinen 1998). Compared with stationary electric chippers, however, mobile chippers are relatively inefficient and have large fuel consumption (Spinelli and Magagnotti 2010a). Recent studies suggest that chipping alone can account for up to 80 percent of the total energy consumption of forest-to-energy supply chains based on in-field chipping. Regardless of exact figures, fuel certainly accounts for a large share of the overall cost incurred by chipping contractors, who are looking for ways to reduce their diesel bills (Granlund 2011).

While much general knowledge is already available about chipper productivity and chipping cost (Spinelli and Hartsough 2001), greater insight is needed on the specifics of chipper performance. This knowledge would allow fine-tuning operations and making a step forward toward optimized deployment. Many elements can be manipulated within machine design and setup, which may have a measurable impact on performance. After knife wear and screen size (Nati et al. 2010), the most important elements may be cut length and the chip discharge system (blower or conveyor). Cut length has been shown to significantly affect productivity and fuel consumption, both in recent (Abdallah et al. 2011) and older (Papworth and Erickson 1966) studies. Chip discharge also seems to have a significant impact on product quality; in particular, blowers may produce a higher amount of fines compared with conveyors due to their aggressive action (Twaddle and Watson 1992). Unfortunately, studies on the effects of cut length and discharge have been conducted on disc chippers only, often in laboratory setups rather than under operational conditions. When producing energy biomass, drum chippers are much more popular than disc chippers and their numbers are increasing along with the demand for wood fuel (Kärhä 2011). Optimization of energy biomass chipping operations would greatly benefit from improved knowledge about the effects of cut length and discharge on the performance of industrial drum chippers under commercial operation conditions. Therefore, the goal of our research was to

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determine the effects of cut length and chip discharge on the productivity, fuel consumption, and product quality obtained from a commercial drum chipper model.

Materials

The mobile chipper used for the experiment was a Pezzolato PTH 1000/1000 (www.pezzolato.it). This machine is a new-generation chipper-truck, with a 400-kW truck engine providing direct drive for the drum chipper and knuckle boom. The chipper features a massive steel drum, which is spun by a robust belt transmission. The infeed consists of a large feeding table with a bottom conveyor that leads to two horizontal feed rollers that push the logs against the drum. Behind the drum, a bottom auger moves the chips to a large propeller fan, which launches them through the evacuation spout. If needed, the blower can be replaced with a rubber belt conveyor. That requires disengaging the propeller fan transmission, moving the spout to the side, applying an extension to the bottom auger, and connecting the conveyor belt assembly. This operation takes about 3 hours, although the newest models are designed for quick conversion and can switch discharge systems in about 30 minutes. Cut length can be changed by manipulating blade offset and adjusting the anvil accordingly. However, this procedure allows only moderate variations of the cut length due to the structural limitations imposed by drum geometry. Larger variations of cutting length can be obtained by replacing the whole drum, and the Pezzolato PTH1000/1000 is designed for accepting different drums according to the target size of the product.

The tests were conducted in July 2012 at the wood yard of the Mombracco chip-fired power station, near the Pezzolato manufacturing plants in Envie, northwestern Italy. For the purpose of the experiment, the same machine was alternately equipped with the blower (Fig. 1) and the belt conveyor (Fig. 2), and with two different drums. One drum was designed for producing standard small-size chips and was mounted with two full-length blades with a cut length of 20 mm (henceforth referred to as ''standard drum''). The second drum was designed for producing large-size industrial chips and was mounted with two staggered half-length blades with a cut length of 42 mm (henceforth ''large drum''). Both drums turned at 630 revolutions per minute.

Figure 1.—The industrial chipper truck using the blower discharge system.

Figure 2.—The industrial chipper truck using the belt conveyor discharge system.

Therefore, the machine was tested in four configurations, resulting from the combinations of drum type and discharge system: standard drum with blower, standard drum with conveyor, large drum with conveyor, and large drum with blower. Each change was performed by factory personnel at their manufacturing plant, ensuring both rapid changeover and correct settings. During all the tests, the machine was operated by the same professional operator, who was also the official driver of the chipper-truck under test. The resizing screen remained the same throughout the experiment, and was a 100 by 100-mm square mesh type.

During the experiment, the machine was alternately fed with two different raw material types: logs and sawmill residues. The former were 2-m-long chestnut (*Castanea sativa* L.) logs. The latter were 2-m-long slabs salvaged from a local sawmill and produced from a mix of beech (*Fagus sylvatica* L.), hybrid poplar (*Populus* × *Euro-americana*), and pine (*Pinus sylvestris* L.). These raw materials were chosen because they are widely available in the area and are often used for chip production.

The experiment consisted of five replications per each combination of raw material, chip discharge, and drum type (i.e., $5 \times 2 \times 2 \times 2 = 40$ replications). Work was divided into four batches, each corresponding to one combination of chip discharge and drum type, as previously described. For each batch, the machine was fed alternately with the two material types, starting with the chestnut logs. New knives were installed before starting a new batch, so that each set of knives processed 10 replications. Each replication consisted of one trailer load of chips. The same 18-m^3 trailer was used for all replications.

Methods

Product output was determined by taking the full trailer to the certified weighbridge available on site. The weighbridge had a rated accuracy of 20 kg. Bulk volume output was obtained by measuring the internal volume of the trailer (18 m^3) and by visually estimating the volume of any mounds or voids on the trailer top. One 500-g sample was collected from each replication in order to determine moisture content and particle size distribution. Each 500-g sample was obtained after reduction of a larger sample assembled by mixing subsamples collected at different points from the chip heap left after trailer dumping. Moisture content was determined with the gravimetric method, according to European standard CEN/TS 14774-2. Fresh weight was determined on-site with a portable scale, immediately after sample collection. Particle size distribution was determined with the oscillating screen method, using four sieves to separate into five chip length classes: >63 mm (oversize particles), 63 to >45 mm (large-size chips), 45 to >16 mm (medium-size chips), 16 to 3 mm (small-size chips), and <3 mm (fines). Each fraction was then weighed with a precision scale. The average chip size was obtained as the weighed average of the central value in each size class by the percent incidence of the class itself.

Time input was determined with a Husky Hunter handheld computer (Husky Computers Ltd. 1991), running the Siwork3 dedicated time study software (Kofman 1995). Both productive and delay time were measured, but the analysis was conducted on productive time only in order to avoid the confounding effect of delay time, which is typically erratic (Spinelli and Visser 2009). Use of the handheld computer allowed easy separation of actual chipping time and chipper waiting time, the latter defined as the time the chipper was momentarily turning idle because the loader could not feed it fast enough (Röser et al. 2012). Separation was conducted in order to avoid the risk that the faster chipping possibly achieved with one of the wood types could be masked by the resulting expansion of loader waiting time, if the loader was the weak link in the process. The analysis was then conducted separately with and without the inclusion of loader waiting time, to gauge the effect of loader performance on chipper productivity. Exclusion of loader waiting time defined theoretical productivity, whereas inclusion defined net productivity.

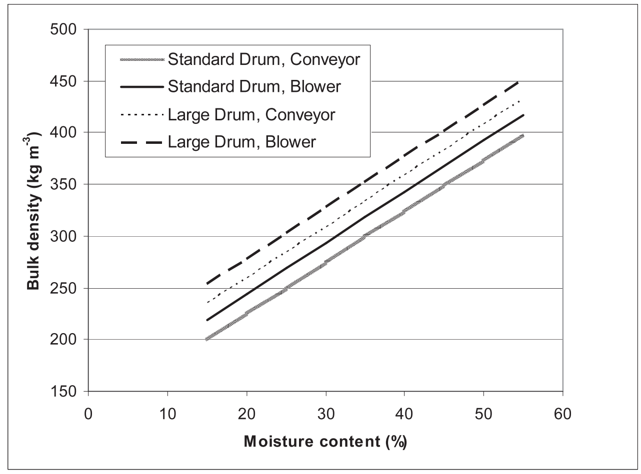
Fuel input was measured for each replication, by refilling the diesel tank with a fuel pump accurate to 0.1 dm^3, after parking the truck on the same level spot. Fuel consumption was the gross fuel consumption for the chipper and the loader because both were powered by the same engine.

Results

The analysis of material type detected a significant difference in the moisture content of logs and sawmill residues. The average moisture content (wet base) was 41.5 percent for the logs and 27.0 percent for the sawmill residues. This difference was statistically significant at the 5 percent level ($P < 0.0001$).

Even if all machine configurations processed the same proportion of logs and residue loads, the material fed to the large drum treatment was significantly dryer than that fed to the standard drum treatment, resulting in an average moisture content of 31 and 37 percent, respectively. This may have biased some of the results, decreasing the power of the experiment. In order to remove the unbalanced influence of moisture content, we focused subsequent analyses on performance indicators referring to dry matter (e.g., fuel consumption per ovendry tonne [odt]).

Figure 3 shows the effect of moisture content, drum type, and discharge system on the bulk density of chip loads. Moisture content had a dominant effect, but the other factors also had a significant influence on bulk density. The analysis confirmed the expected packing action of the blower, which produced a moderate (from 4% to 7%) but statistically significant increase in bulk density. Drum type exerted an even stronger effect, with loads produced by the large drum being between 8 and 17 percent denser than loads produced by the standard drum. This difference was statistically significant.



BD = a + b MC + c B + d SD			Count = 40	R^2 = 0.659
Parameter	Coefficient	Std. Error	t-Value	P-Value
a	160.680	19.823	8.106	<0.0001
b	4.942	0.570	8.664	<0.0001
c	18.886	10.988	1.719	0.0943
d	-34.337	11.757	-2.920	0.0060
Where: BD = Bulk Density; MC = Moisture Content; B = Dummy Blower (1 if Blower, 0 if Conveyor); SD = Dummy Standard Drum (1 if Standard Drum, 0 if Large Drum)				

Figure 3.—Relationship between moisture content and bulk density.

Particle size distribution and mean chip size were closely related to drum type, discharge system, and raw material type (Table 1). Drum type determined cut length and had the strongest effect by far. Use of the large drum produced a significantly longer chip and a 50 percent reduction in the incidence of fines. The discharge system had a minor but significant effect on particle size. Using a conveyor instead of a blower led to a substantial reduction in the proportion of particles in the two smallest size classes. The incidence of fines decreased from 4.3 to 2.9 percent. Raw material type also affected particle size, with sawmill residues producing coarser chips than logs. However, material type had no effect on the incidence of oversize and fine particles.

Fuel consumption varied around 3 liters odt^{-1}. It was significantly affected by drum type and by the total amount of chips processed with the same set of knives, assumed as an indicator of blade wear and used as a covariate in the statistical analysis. Contrary to expectation, the discharge system had no effect on fuel consumption (Table 2), nor did material type, once the effect of moisture content was removed by comparing the measurement to the ovendry tonne. Figure 4 shows the relationship between fuel consumption, drum type, and the total amount of wood processed with the same set of knives. We also introduced the interaction of the two independent variables into the explanatory models without any significant model improvement. After processing 50 odt, fuel consumption was between 24 and 29 percent higher than it was when the knives were new. Opting for a larger chip size cut fuel consumption by 15 percent, or by 0.5 liter odt^{-1}.

Both theoretical and net productivity were affected by drum type and by the total amount of chips processed with

Table 1.—Particle size distribution and mean chip length.[a]

	Effect:														
	Drum type					Discharge system					Material type				
	Mean incidence (%)					Mean incidence (%)					Mean incidence (%)				
	Large	Standard	*F*	*P*	%SS	Blower	Conveyor	*F*	*P*	%SS	Logs	Sawmill	*F*	*P*	%SS
Particle size (mm)															
>100	1.3	0.3	1.196	0.2822	3.0	0.4	1.3	0.824	0.3709	1.9	0.9	0.7	0.014	0.9070	0.0
100–>63	2.4	0.3	6.584	0.0152	13.8	0.8	1.9	2.820	0.1028	6.0	0.7	2.0	3.022	0.0918	6.4
63–>45	6.3	2.0	27.990	<0.0001	28.3	2.8	5.5	7.261	0.0111	7.3	3.3	5.0	13.898	0.0007	14.0
45–>16	59.5	36.2	180.634	<0.0001	50.3	45.0	50.7	11.681	0.0017	3.2	39.9	55.8	86.444	<0.0001	24.1
16–>8	20.1	38.6	173.556	<0.0001	54.2	31.7	27.0	12.534	0.0012	2.5	36.2	22.6	91.149	<0.0001	28.4
8–3	8.0	17.7	188.792	<0.0001	56.5	15.0	10.7	36.262	<0.0001	10.8	15.3	10.4	45.962	<0.0001	13.8
<3	2.3	4.9	30.236	<0.0001	35.7	4.3	2.9	6.062	0.0194	7.1	3.7	3.4	1.326	0.2580	1.4
Mean length (mm)	27.7	18.3	117.263	<0.0001	38.0	20.9	25.1	23.152	<0.0001	7.5	20.7	25.4	29.309	<0.0001	9.5

[a] *F* value, *P* value, and SS obtained from the analysis of covariance; %SS = % of the sum of squares for the specific variable and factor.

the same set of knives. Material type also had a significant effect on productivity (Table 2). The effect of material type was stronger and more significant for net productivity than it was for theoretical productivity. Again, the discharge system had no significant effect. Figure 5 shows the relationship between net productivity, drum type, and the total amount of wood processed with the same set of knives. After processing 50 odt, net productivity was between 25 and 35 percent lower than it was when the knives were new. Opting for a larger chip size boosted net productivity by 16 percent.

Discussion

No other studies have tried to isolate the effect of specific factors on chipper performance by using real-life commercial equipment and settings. Previous studies of this type were less realistic because they used only a few kilograms of wood for each repetition and were often conducted inside a laboratory using model chippers. This study showed that wood moisture content is extremely difficult to control when the tests are performed under real field conditions, as already reported by Spinelli et al. (2011). When the experiment uses hundreds of tonnes, it is difficult not to hit moisture gradients in the wood store. We believe that this major difficulty was effectively overcome in our analysis by using dry matter as the unit measure for mass.

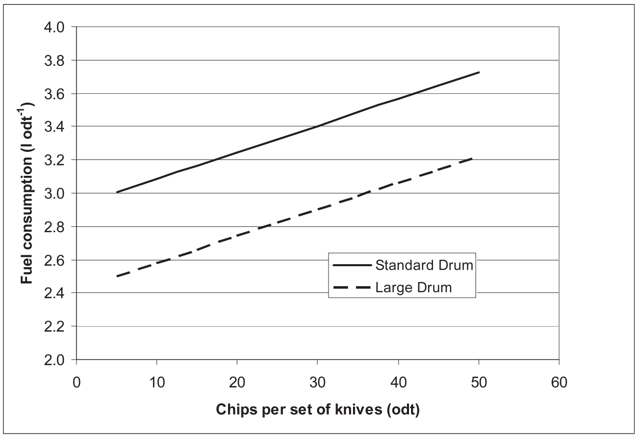
The direct relationship between particle size and bulk density may surprise many practitioners, who are used to the lower bulk density of coarse hog fuel compared with finer chips. However, chips and hog fuel fragments have different shapes. With hog fuel fragments, one dimension (length) is much larger than the other two, which favors accidental structuring that results in low density (Jensen et al. 2004). Chips have a much more regular shape, which strongly reduces the chances for structuring. Chips behave somewhat like granulate particles, which pack better when they are larger (Gluba et al. 2004). Therefore, it is important to distinguish the effect of shape from the effect of size: regular shape and larger size result in a higher bulk density. The visual estimation of the excess and defective chip volumes on the trailer tops reduced the accuracy of the bulk density figures. While our figures are realistic, they must still be viewed with some caution.

Blowers accelerate chips, packing them harder than belt conveyors do. The aggressive action of a blower tends to crack cut particles, generating a larger proportion of small chips and fines. In this respect, the difference between the two discharge systems was smaller than expected, possibly due to the double auger conveyor mechanism that moved chips from under the drum casing regardless of the blower or the belt conveyor being used. The auger conveyor also tended to abrade the chips. It is likely that the difference would have been higher if the belt conveyor was placed right under the drum casing and the chips just fell onto the belt. This same reason may have contributed to the absence of any significant relationship between fuel consumption and discharge system.

Table 2.—Fuel consumption and productivity.[a]

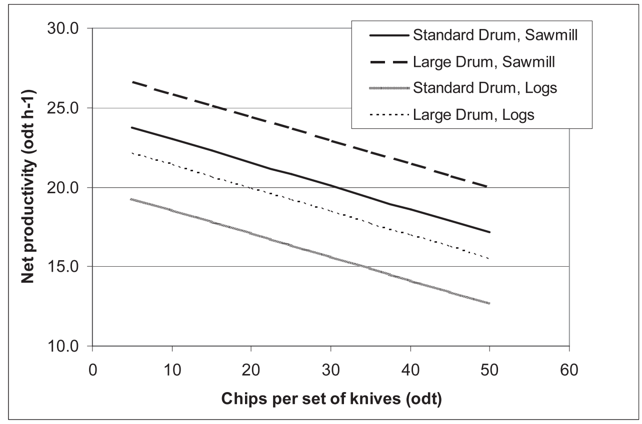
	Effect:														
	Drum type					Discharge system					Material type				
	Large	Standard	*F*	*P*	%SS	Blower	Conveyor	*F*	*P*	%SS	Logs	Sawmill	*F*	*P*	%SS
liters odt^{-1}	2.8	3.3	15.425	0.0004	24.0	3.0	3.1	1.976	0.1686	3.1	3.0	3.0	0.695	0.4103	1.1
odt h^{-1} theor	26.6	22.8	13.496	0.0008	18.4	23.8	25.6	0.135	0.7156	0.2	23.5	25.9	7.320	0.0105	10.0
odt h^{-1} net	21.9	19.2	7.167	0.0112	10.4	19.9	21.2	0.105	0.7474	0.2	18.4	22.7	17.748	0.0002	25.8

[a] odt h^{-1} theor = productivity in ovendry tonnes, calculated after removing loader waiting time; odt h^{-1} net = productivity in ovendry tonnes, calculated while including loader waiting time; *F* value, *P* value, and SS obtained from the analysis of covariance; %SS = % of the sum of squares for the specific variable and factor. As a term of reference, the %SS of the variable ''chips per set of knives (odt)'' was 17.5 percent for liters odt^{-1}, 23.5 percent for odt h^{-1} theor, and 12.9 percent for odt h^{-1} net.



FC = a + b CSK + c SD			Count = 40	R^2 = 0.339
Parameter	Coefficient	Std. Error	t-Value	P-Value
a	2.421	0.155	15.612	<0.0001
b	0.016	0.005	2.976	0.0051
c	0.504	0.131	3.856	0.0004
Where: FC = Fuel Consumption; CSK = Chips per set of knives; SD = Dummy Standard Drum (1 if Standard Drum, 0 if Large Drum)				

Figure 4.—Relationship between fuel consumption, knife wear, and drum type.



NP = a + b CSK + c SD + d L			Count = 40	R^2 = 0.371
Parameter	Coefficient	Std. Error	t-Value	P-Value
a	27.328	1.555	17.571	<0.0001
b	-0.147	0.049	-2.975	0.0052
c	-2.841	1.179	-2.410	0.0212
d	-4.476	1.187	-3.770	0.0006
Where: NP = Net productivity; CSK = Chips per set of knives; SD = Dummy Standard Drum (1 if Standard Drum, 0 if Large Drum); L = Dummy Logs (1 if logs, 0 if sawmill residues)				

Figure 5.—Relationship between net productivity, knife wear, drum, and material type.

From visual observation, it appeared that the work environment was much more dusty when using the blower. Our analysis did not account for the quantity of fines dispersed in the air and may have underestimated the difference between blower and belt conveyor, if the former dispersed more fines than the latter. Further research should determine the difference in dispersed fine particles, which is extremely relevant to operator safety and in general to chipping in settled areas (Magagnotti et al. 2013).

Drum type drives cut length, which is logically associated with chip quality, fuel consumption, and productivity. A longer cut length corresponds to fewer cuts per unit mass. That results in a lower specific consumption and a faster feeding rate, i.e., higher productivity. The strong effect of drum type on productivity and fuel consumption is combined with the effect of blade wear, which is even stronger: drum type can determine changes on the order of 15 to 20 percent, whereas blade wear can affect productivity and fuel consumption by 25 to 35 percent. If the main goal is increasing productivity and/or decreasing fuel consumption, then reducing blade wear should be the primary target. In fact, previous studies indicate that fuel consumption can increase up to 50 percent as a result of blade wear (Nati et al. 2010). This study returned slightly lower figures because the knives were replaced after processing 10 loads without waiting for their blades to be completely dull. If the knives had been used for a longer time, fuel consumption would have increased further.

Material type affects productivity and particle size, but not fuel consumption per dry unit. The effect is stronger on net productivity than on theoretical productivity, meaning that differences between materials increase when loader handling is included in the calculation. That may indicate that the effect of material type originates from its handling characteristics (Spinelli and Magagnotti 2010b). Both assortments were 2 m long, but while sawmill residues were straight, relatively homogeneous, and generally well aligned, logs were often crooked, heterogeneous, and entangled. That made them difficult to ''digest'' for the feeding rollers (i.e., negative effect on theoretical productivity, which excluded loader time), and even more difficult to handle for the loader (i.e., negative effect on net productivity, including loader time). The slower feed rate may explain why logs generated smaller chips compared with sawmill residues.

In general, the fuel consumption levels recorded in this study are compatible with those reported by previous chipper studies. An almost perfect match is obtained with the 2.7 to 3.6 liters odt^{-1} reported for an industrial chipper powered by a 260-kW independent engine (Spinelli et al. 2011). A similar study conducted on a much smaller chipper (58 kW) returned a higher fuel consumption, between 3.4 and 4.2 liters odt^{-1} (Spinelli et al. 2012). That difference could be explained with scale efficiency.

As to the productivity levels, readers must be aware that the figures in this study refer to net chipping productivity and are calculated for chipping time only, excluding all accessory work time and delays (Björheden et al. 1995). In particular, delays can represent up to 50 percent of a chipper's scheduled work time (Spinelli and Visser 2009). Inclusion of accessory work time and delays will not only reduce machine productivity but may also reduce the eventual differences between treatments.

Conclusions

All else being equal, doubling cut length through the installation of a new drum results in a 50 percent increase of average chip length, a 15 percent increase of net productivity, and a 15 percent decrease of fuel consumption. The handling characteristics of the raw material have a strong impact on chipper productivity, causing variations on the order of 20 percent. The discharge system has no significant effect on fuel consumption or productivity, but it does impact product quality and bulk density. Using a blower allows increasing bulk density between 4 and 7 percent, whereas the installation of a belt conveyor reduces the incidence of small chips and fine particles by up to 30 percent. This knowledge can be used to fine-tune chipping operations, moving one more step towards optimization.

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