EFFECTS OF CUTTERHEAD DIAMETER AND LOG INFEED POSITION ON ENERGY REQUIREMENTS OF A CHIPPER-CANTER

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Abstract. Effects of chipper-canter cutterhead diameter and log infeed position on maximum power and energy consumption during processing of black spruce logs were evaluated. Two cutterhead diameters (661.5 and 448.7 mm) combined with three infeed positions or vertical distance from the cutterhead axis center to the bedplate on which the log was supported were studied. A mean angle of attack of the chipping edge was calculated for each infeed position. Linear cutting speed was fixed at 23.5 m/s. Rotation speed and feed speed were adjusted to obtain a nominal chip length of 25.4 mm. Fourteen logs for each cutting condition were transformed in frozen and unfrozen wood temperatures. The results showed a significant effect of cutterhead diameter and wood temperature on maximum power and energy consumption. Power and energy consumption were lower when processing with the 661.5-mm compared with the 448.7-mm cutterhead diameter. These parameters were also greater when cutting frozen logs compared with unfrozen logs. Although cutting action of the chipping edge was the principal contributor to energy consumption when processing with a chipper-canter, its angle of attack had a negligible effect on this consumption. This happened because of an opposite effect of the knife path length (arc formed by engagement of the knife into the log). These results gave useful information for estimating changes in power and energy consumption within the studied range of infeed positions (or angles of attack of the chipping edge) and cutterhead diameters.

Keywords: Energy consumption, chipper-canter, infeed position, attack angle.

INTRODUCTION

Sawmills account for 45% of the energy use in the Canadian wood products industry. As seen in the industry in general, sawmills are decreasing the use of fossil fuels and increasing the use of electricity and wood waste to meet their energy needs. Between 1990 and 2012, energy use in the Canadian sawmill sector increased by 37%, whereas greenhouse gas emissions declined by 33%. Thus, the contribution of electricity and wood waste increased from 57% in 1990 to 78% in 2012 (Nyboer and Bennett 2014). While

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electricity is required to operate the electric motors that run most equipment, wood waste is generally used in boilers to generated steam to dry lumber (Gopalakrishnan et al 2012). Therefore, improving electrical efficiency at each phase of the sawmill transformation process is certainly desirable.

A decrease of electrical consumption can directly affect sawmill operation costs and therefore increase profitability. Proper selection of an electrical motor based on cutting power requirements of each machining center is essential to achieve electrical efficiency. It is also important to be aware of cutting parameter effects on power consumption of each machine. Because of the rigorous work environment under which sawmill equipment operates (especially in northern countries), it is also critical to schedule regular maintenance.

Energy requirements during wood machining can be estimated from the power demanded by the tool, the length of the workpiece, and the feed speed (Koch 1964). The power demanded is positively related to the wood cutting forces. Forces applied by the tool are affected by factors related to feeding, cutting tool, and workpiece (Koch 1964). Wood characteristics such as species, basic density, dimensions, grain direction with respect to the tool edge, and presence of knots or decay affect the wood mechanical properties and, consequently, the cutting force requirements. Furthermore, the temperature of logs in northern countries becomes critical during winter. The mechanical strength of wood is greater at temperatures below zero especially in greater MC conditions (Gerhards 1982; Mishiro and Asano 1984; Mishiro 1990; Hernández et al 2014b). Also, the geometry of the cutting tool affects the forces generated during wood machining. For example, forces increase as the rake angle decreases during orthogonal cutting (Woodson and Koch 1970; Stewart 1977, 1991; Woodson 1979; Koch 1985; Kuljich et al 2013; Hernández et al 2014a).

In eastern Canada, chipper-canters are the most common breakdown machine installed at sawmills. These machines transform, in a single operation, small- and medium-diameter logs into cants and chips with very low sawdust production. Cants are then processed to obtain studs and other members used for structural purposes. Chips obtained are destined for the pulp and paper industry. Although machining using a chipper-canter generates quite satisfactory production, some of its technical aspects could be improved. The decrease of variability in the chip size distribution, increase in surface quality of cants, and decrease of the energy requirements are among the most important.

Studies on the technical aspects of improving chipper-canter performance have been principally focused on controlling the thickness of chips produced (Hernández and Quirion 1993, 1995; Hernández and Boulanger 1997; Hernández and Lessard 1997). Recently, Hernández et al (2010, 2014a) and Kuljich et al (2013) investigated the effects of certain cutting parameters on surface quality. A significant result showed that an increase in the canting knife rake angle from 35 to 65° produced a significant decrease in cutting forces and improved surface quality of the cants produced (Kuljich et al 2013; Hernández et al 2014a).

The cutting action of chipper-canters is often associated with orthogonal cutting, in which the cutting edge is perpendicular to the relative motion of the tool and the workpiece. The surface generated is a plane parallel to the original work surface. The most common chipper-canter used in eastern Canada has a conical-shaped cutterhead fitted with uniformly distributed knife holders, each with a bent knife and a knife clamp (Fig 1). The bent knife has two cutting edges that are joined at an angle: a longer or chipping edge and a shorter or canting edge. In some cases, the bent knife is replaced by a dual knife set. The cutting work is performed by the simultaneous action of both cutting edges. The chipping edge severs a slice to produce chips, and the canting edge smooths the cant. The feed per knife ensures the thickness of the slice and the length of the chips. The chips are mainly produced by splitting or shear failure parallel to the grain. This action is also provided by the knife clamp, placed in the back of the knife.

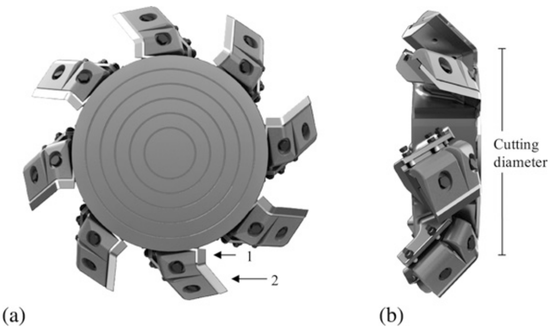

Figure 1. Front (a) and side (b) views of a conical-shaped cutterhead fitted with eight uniformly distributed knife holders, each with a bent knife and a knife clamp. The bent knife had two cutting edges that were joined at an angle: 1) the shorter edge smoothed the cant (canting edge) and 2) the longer edge severed a slice to produce chips (chipping edge) (Courtesy of DK-SPEC Inc.).

Therefore, the energy required for cutting is a sum of contributions of different actions (described by order of importance). Cutting the slice of wood by the chipping edge is probably the action that demands the most energy. This edge cuts the log across its end grain. For this, the knife has to compress wood perpendicularly to sever the slice by shearing perpendicular to the grain or near to it. Shear strength perpendicular to the grain is very great. The canting edge smooths the log surface when cutting across the side grain. The fibers in that case are not crosscut and are separated by their side. Thus, the forces generated at the chipping edge should be greater than the ones generated at the canting edge. As subsequently explained, the orientation of both knife edges with respect to the grain is also involved in this process, as it varies through the cutting path (Fig 2). The presence of knots can, nonetheless, considerably increase the forces generated on the canting edge. According to Hernández (2014), cutting forces during crosscutting white spruce knots can increase up to eight times compared with the ones produced in nearby wood. The impact of the wood slice against the knife clamp (fragmentation) also contributes to energy consumption. Finally, the friction between the wood slice, knife, and knife clamp and the acceleration of the chips are also actions that contribute to the energy requirements of processing a log with a chipper-canter.

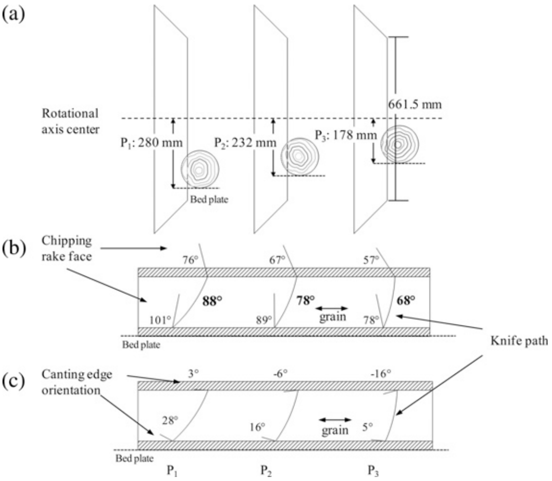

Figure 2. (a) The three log infeed positions, (b) mean angle of attack of the chipping edge (in bold), and (c) cutting orientation of the canting edge for each log infeed position when chipping with the larger cutterhead tested (661.5 mm of cutting diameter).

The aim of this study was to investigate the performance of chipper-canters with different configurations in terms of energy requirements. Thus, the effects of cutterhead diameter and position in which the logs are fed into the machine on energy consumption were evaluated when milling black spruce logs in frozen and unfrozen conditions. Log infeed position affects the orientation in which the knives cut into the wood.

MATERIALS AND METHODS

Testing Material

Tests were carried out with 84 stems of black spruce [*Picea mariana* (Mill) B.S.P.] that came from the region of Mauricie in central Quebec. This tree is one of the most important boreal species in eastern Canada and is part of the spruce-pine-fir wood group, which is widely used for construction applications and in the pulp and paper industry (Zhang and Koubaa 2008). The stems were freshly debarked and crosscut into 2.80-m logs. The crosscutting position was chosen to have a small end diameter of 152.4 mm, which yielded a mean taper of 6.6 mm/m. The logs were without crook or visible decay and had straight grain and concentric growth rings. Logs obtained were stored green at −30°C to maintain MC until the day of log transformation.

Specific Gravity (SG) and MC Measurements

Two 100-mm-thick disks from each end of the log were first cut to prepare specimens for physical tests. The two extreme disks were used to measure sapwood thickness. The other two were used to assess mean SG and MC of both sapwood and heartwood at the time of log transformation. SG was reported as oven-dry weight and green volume ratio. A sample of sapwood and another of heartwood were obtained from each disk to yield a total of 336 samples. All samples were 30 mm wide and 100 mm long. Thickness of samples varied depending on sapwood thickness of individual logs.

Log Transformation

Logs were processed with a prototype chipper-canter equipped with one cutterhead manufactured by DK-SPEC (Quebec, Canada) that had the shape of a shallow truncated cone (Fig 1). The cutterhead was fitted with eight or six (depending of their diameter) uniformly distributed knife holders, each of them with a bent knife and a knife clamp. The experiment consisted of processing 2.40-m-long black spruce logs using two cutterheads with 661.5 and 448.7 mm of inner cutting diameter. For each cutterhead, logs were fed at three infeed positions or height positions. This position is defined by the vertical distance from the cutterhead axis center to the bedplate on which the log is supported (Fig 2a). The cutting orientations of the chipping and canting edges with respect to the wood grain, during the cutting action, were calculated for each log infeed position. In the case of the chipping edge, the angle (or cutting orientation) of its rake face with respect to the grain was called angle of attack. The mean angle of attack was the average angle between the entrance and exit of the log (Table 1; Fig 2b). The cutting orientations of the chipping and canting edge changed during the cutting path on the log and depended on the infeed position (Fig 2b-c). In addition, at a given moment, the two cutting edges cut the wood at different orientations. In general, the canting edge cut nearly across the side grain (tendency to a 0-90° cutting mode), whereas the chipping edge cut across the end grain (tendency to a 90-90° cutting mode) (Fig 2b-c).

The knife angle of the chipping edge was 33°, with a rake angle of 47.7° and a clearance angle of 9.3°. These angles were calculated in a section view obtained by taking an imaginary cut through the chipping knife (using SolidWorks software, Madison, WI). The section view was parallel to the infeed direction and corresponded to the position at which the knife was working with a cutting width of 25.4 mm. The knife clamp angle was 30°, and the distance from the knife

Table 1. Cutting orientation of chipping and canting edges with respect to the grain for each infeed position.

Cutting diameter[a] (mm)	Infeed position[b] (mm)	Attack angle of chipping edge[c]			Cutting orientation of canting edge[c]		Knife path length[d] (mm)
		Entrance	Exit	Mean	Entrance	Exit	
448.7	199	67	103	85	−7	29	141
	174	60	93	77	−14	19	129
	148	54	85	69	−20	11	122
661.5	280	76	101	88	3	28	148
	232	67	89	78	−6	16	130
	178	57	78	68	−16	5	120

[a] Distance between the junction point of the canting and chipping edges of two opposite knives.

[b] Vertical distance from the center of the rotational axis of the cutterhead to the bedplate on which the log is supported.

[c] See Fig 2.

[d] Length of arc formed by engagement of the knife into the log.

clamp edge to the knife edge was 22 mm. The knife angle of the canting edge was 30°, with a rake angle of 59° and a clearance angle of 1°. All knives were freshly ground before the experiment to minimize the effect of tool wear on chip size and surface quality.

Cutting width was held constant at 25.4 mm (along the log) to decrease the effects of log taper and cutting height on wood fragmentation. Five clamps in the carriage held the log in place to decrease vibration during fragmentation. Linear cutting speed was set at 23.5 m/s and calculated at the junction point between the canting and chipping edges of the knife. Rotation speed and feed speed were adjusted to obtain a nominal chip length of 25.4 mm. Cutting parameters for all studied conditions are shown in Table 2.

The study was done in two steps to simulate seasonal differences during log transformation (frozen and unfrozen wood conditions). Fourteen logs were processed for each cutting condition. Log temperature was measured at two uniformly distributed points at a depth of 25 mm with a digital thermometer to the nearest 0.1°C. The log was always fed with the small end first, and it was machined flat on one side at frozen wood conditions (−25°C). The other side was processed after the log was at room temperature (18°C, unfrozen side). As soon as the log was transformed, all chips produced were collected in plastic bags. The cants were wrapped in polyethylene and stored in a −5°C freezer along with the chip bags for further analysis.

Power and Energy Consumption Measurements

The prototype chipper-canter was equipped with a three-phase induction motor rated at 111.9 kW and with a nominal efficiency of 95.8%. A power analyzer 1735 Power Logger (Fluke, Everett, WA) was connected to the input of the electrical motor driving the cutterhead. The input voltage and current, active power, and energy were recorded at this point. The data were collected using an acquisition frequency of 10.24 kHz at averaging intervals of 0.5 s for 7 s. The maximum power and energy consumption during each cut were determined with the Power logger software (http://en-us.fluke.com/support/software-downloads/). Cutting time for each log varied according to the diameter of the cutterhead: 0.95 and 1.04 s for the 448.7- and 661.5-mm cutterheads, respectively. Then, energy consumption for each cut was calculated by subtracting the unload energy from the total energy measured. Equally, the specific cutting energy (energy consumed for removing a unit of wood volume) was also estimated for each cutting condition. Thus, specific cutting energy is the ratio between energy consumption (Wh) and volume of wood (m^3) removed or transformed into chips by each cut.

Estimation of Volume of Wood Transformed into Chips

Figure 3 shows the elements used to estimate the volume of wood transformed into chips. This volume was estimated by adding 12 equal portions of the log (for higher precision). First, the area of

Table 2. Cutting parameters of the chipper-canter during log transformation.

Cutting diameter[a] (mm)	Cutterhead weight (kg)	Unload power (W)	Number of knives	Infeed position[b] (mm)	Mean attack angle of chipping edge[c]	Nominal linear cutting speed[d] (m/s)	Rotation speed (rpm)	Feed speed (m/min)	Angular velocity (rad/s)	Nominal chip length (mm)
448.7	202.5	3878	6	199	85	23.5	1000	152	104.7	25.4
				174	77					
				148	69					
661.5	321.8	3345	8	280	88		679	138	71.1	
				232	78					
				178	68					

[a] Distance between the junction point of the canting and chipping edges of two opposite knives.

[b] Vertical distance from the center of the rotational axis of the cutterhead to the bedplate on which the log is supported.

[c] See Fig 2.

[d] Calculated at the junction point of the canting and chipping edges of the knife.

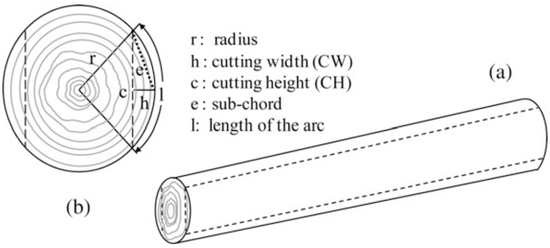

Figure 3. (a) The part of the log transformed into chips and (b) the elements used to estimate the volume of wood transformed into chips.

the slab transformed into chips was calculated using the formula for the area of a segment (as) of the circle:

$$\text{as} = 0.5\, lr - 0.5\, c(r - h) \tag{1}$$

where c and h are cutting height and cutting width, respectively. These parameters were measured at 11 equidistant points on the log. Cutting width was measured before log processing, and cutting height was measured after processing. Then, length of the arc (l) and radius of the log (r) were calculated at each portion of the log as follows:

$$l = \frac{8e - c}{3} \tag{2}$$

$$r = \frac{c^2 + 4h^2}{8h} \tag{3}$$

To calculate the length of the arc, the subchord (e) was first estimated as follows:

$$e = 0.5\sqrt{c^2 + 4h^2} \tag{4}$$

Finally, to estimate the volume of each portion, the area of the 12 slab portions was multiplied by the length of the log portion and added to get the total volume of wood transformed into chips.

Statistical Analyses

Statistical analyses were performed by means of the SAS package version 9.3 (SAS Institute 2010). A multivariate analysis of variance (MANOVA) was first performed to test if the physical properties were equal among the six groups of logs used for testing the cutting conditions studied. SG and MC of sapwood and heartwood, mean thickness of sapwood, and wood volume removed during each cut were the variables tested. Then, a split-plot analysis of variance (ANOVA) was used to evaluate the maximum power, energy consumption, and specific cutting energy variation of each cutting condition. Cutterhead diameter and angle of attack of the chipping edge were the sources of variation as main plots, and the temperature condition (frozen and unfrozen wood) was the source of variation as the subplot. Angle of attack was nested within cutting diameter because this parameter was specific to each cutterhead (Table 2). The raw data were first transformed using a logarithmic transformation. Also, the SG of wood, mean thickness of sapwood, and wood volume transformed into chips were added as covariates when they were significant to the model. Means were compared with the least squares means statement at a 95% confidence level. The normality of the data were verified using the Shapiro–Wilk test.

RESULTS AND DISCUSSION

The first MANOVA (not shown) revealed that the six groups of logs used for the cutting conditions studied were equivalent in terms of their physical properties. Thus, mean values of SG and MC of sapwood and heartwood, thickness of sapwood, and wood volume transformed into chips during each cut were similar for all groups of logs. Mean SG was 0.445 for sapwood and 0.438 for heartwood. The difference was not statistically significant. However, the MC of sapwood (125%) and heartwood (38%) were statistically different. The thickness of sapwood and wood volume removed during each cut were on average 15 mm and 0.0048 m^3, respectively.

The ANOVA showed that the electrical performance of the motor driving the cutterhead was significantly affected by cutterhead diameter and temperature condition (frozen or unfrozen wood) (Table 3). This analysis also found a significant effect of SG, mean thickness of sapwood, and wood volume transformed into chips during each cut on the motor electrical performance. As expected, a positive relationship was found between those parameters and maximum power

Table 3. *F* values obtained from ANOVA for maximum power and energy consumption analyses.

Source of variation	Maximum power	Energy consumption
	F value	
Wood SG	33.75**	24.54**
Mean thickness of sapwood	—	9.31**
Wood volume removed	49.12**	53.54**
Cutterhead diameter	111.78**	68.92**
(Angle of attack [diameter])	1.74$^{\text{n.s.}}$	3.69**
Temperature condition	185.66**	263.37**
Diameter*condition	0.00$^{\text{n.s.}}$	3.07$^{\text{n.s.}}$
Angle*diameter*condition	0.98$^{\text{n.s.}}$	0.98$^{\text{n.s.}}$

* Statistically significant at the 5% probability level; ** statistically significant at the 1% probability level; $^{\text{n.s.}}$ not statistically significant.

and energy consumption. For instance, as more material was transformed, the cutting forces increased, and therefore, maximum power and energy consumption also increased. Equally, energy consumption increased as SG increased (Papworth and Erickson 1966). Also, the effect of sapwood thickness became more important when transforming frozen wood, especially at higher MC conditions.

Maximum power was statistically significantly affected by cutterhead diameter and temperature condition (frozen or unfrozen wood) (Table 3). Thus, maximum power was 18% higher when processing with a 448.7-mm cutterhead diameter (51.1 kW) compared with a 661.5-mm cutterhead (43.3 kW) (Table 4). This can be explained by the fact that part of the required energy for processing the log was provided by the electrical motor and part by the mechanical energy (or kinetic energy) stored in the cutterhead. The rotational kinetic energy (KE) can be expressed in terms of moment of inertia (I) and angular velocity (w) (Giambattista et al 2004) as follows:

$$\mathrm{KE} = \frac{1}{2} I w^2 \tag{5}$$

As a first approximation, if the cutterhead is then considered as being a solid truncated cone (Figs 1b and 2a), the moment of inertia can be calculated as follows:

$$I = \frac{3}{10} M \left(\frac{R^5 - r^5}{R^3 - r^3} \right) \tag{6}$$

where M is mass of the truncated cone, R is radius of the bigger end, and r is radius of the smaller end (Singh 2013). Kinetic energy and momentum of inertia were directly proportional to the cutterhead weight. Assuming that the mechanical losses were equal on both systems and that the cutterheads rotated at constant rates, the 661.5-mm cutterhead needed less power to continue to rotate at a constant rate compared with the smaller cutterhead because of the greater mechanical energy of the system provided by the greater weight of the 661.5-mm cutterhead (Table 2). This is consistent with the values of unload power measured during the experiment. Unload power was 3.3 kW for the 661.5-mm cutterhead and 3.9 kW for the smaller cutterhead (448.7 mm) (Table 2).

The temperature condition significantly affected maximum power and energy consumption (Table 3). The maximum power required for processing frozen logs (52.2 kW) was 24% higher than for unfrozen logs (42.2 kW) (Table 4). Similarly, the energy consumption was 23% higher when transforming frozen wood compared with unfrozen wood (Table 5). Papworth and Erickson (1966) reported an increase of 8-10% in the specific cutting power when disk chipping frozen spruce logs compared with unfrozen logs. The difference between frozen and unfrozen conditions depended on wood temperature and MC variations. It is well known that wood becomes in fact more resistant as temperature decreases

Table 4. Mean values of maximum power required for fragmentation of black spruce logs.

Cutting diameter	Maximum power (W)			Temperature condition	Maximum power (W)		
448.7 mm	51074[a]	(537)[b]	A[c]	Unfrozen wood	42210	(532)	B
661.5 mm	43292	(540)	B	Frozen wood	52156	(535)	A

[a] Mean of 84 replicates.

[b] Standard error of the mean in parentheses.

[c] Means within a column followed by a different letter are significantly different at 5% probability level.

Table 5. Mean values of energy consumption and specific cutting energy.

Temperature condition	Energy consumption (Wh)			Specific cutting energy (Wh/m^3)		
Unfrozen wood	8.6[a]	(0.1)[b]	B[c]	1782	(21)	B
Frozen wood	10.6	(0.1)	A	2220	(21)	A

[a] Mean of 84 replicates.
[b] Standard error of the mean in parentheses.
[c] Means within a column followed by a different letter are significantly different at 5% probability level.

below 0°C, especially for MC above the fiber saturation point (FSP) (Hernández et al 2014b). The proportion of liquid water freezes, expands, and increases wood strength (Mishiro and Asano 1984; Mishiro 1990). Thus, as wood strength increases, energy consumption also increases. During wood fragmentation, splitting, shear parallel to the grain, and bending properties are involved at different degrees (McLauchlan and Lapointe 1979; Hernández and Quirion 1993, 1995; Hernández and Lessard 1997; Hernández et al 2014b; Cáceres et al 2015). Thus, for black spruce sapwood (139% MC), Hernández et al (2014b) reported an increase of about 151%, 106%, and 74% in shear strength, modulus of rupture (MOR), and modulus of elasticity (MOE), respectively, for a temperature decrease from 0 to −30°C. Also, splitting strength was 286% greater at −20 than at 0°C.

Energy consumption was also significantly affected by the angle of attack of the chipping edge. However, the *F* value of this effect was very low compared with the other sources of variation considered in the analyses (Table 3). In fact, energy consumption was only statistically higher when processing logs with the bigger cutterhead at 68° attack angle (178 mm of infeed position). The energy required with the other angles of attack (78 and 88°) was similar for this cutterhead. Also, energy consumption was statistically similar for the three angles of attack used for the 448.7-mm cutterhead diameter (Fig 4).

The low effect of angle of attack on energy consumption was probably because its effect was offset by the influence of the path length of the knife engagement with the log. Energy consumption should increase as the distance from log entry position to cutterhead rotation axis decreases. Angle of attack of the chipping edge varied through the cutting path on the log (Fig 2b). Thus, angle of attack of the chipping edge also varied with infeed position. If a mean angle of attack is considered, as the distance from the cutterhead rotation axis to the bedplate increases, the mean angle of attack also increases (Fig 2b). Chip fragmentation will occur more by splitting at the lower log infeed position (because of the higher angle of attack). As the infeed position approaches the cutterhead rotation axis, the angle of attack decreases, producing chips by longitudinal shear failure because of a higher parallel compression component. Because shear strength is normally greater than splitting strength, energy consumption should increase as the infeed position of the log approaches the rotation center or as the angle of attack of the chipping edge decreases.

As indicated previously, the effect of the attack angle was probably offset by the fact that as the infeed position approached the rotation center, the knife path length decreased (Table 1). The knife path length is the length of the arc formed by the engagement of the knife into the log (Fig 2b-c). Thus, for a cutterhead diameter of 448.7 mm, as the angle of attack decreased from 85 to 69°, the knife path length decreased

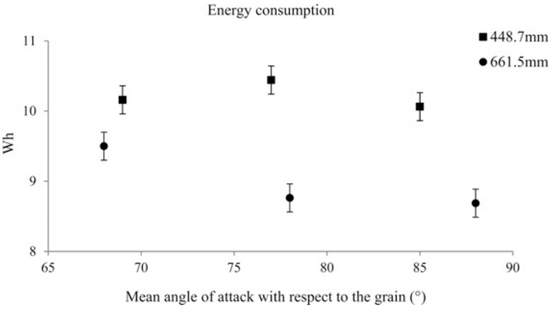

Figure 4. Effect of angle of attack of the chipping edge on energy consumption for the two diameters of cutterheads tested (448.7 and 661.5 mm).

from 141 to 122 mm. Similarly, for the greater cutterhead diameter (661.5 mm), the decrease of the angle of attack from 88 to 68° produced a decrease of knife path length from 148 to 120 mm (Table 1). Thus, if the amount of work (W) depends on force and the distance that it is applied, a longer knife path would generate a greater amount of work if the same force was applied. However, as the angle of attack increases, the resistance of wood decreases. A lower force generated would be counterbalanced by a longer knife path when cutting with a greater cutting angle and vice versa. Therefore, the effect of angle of attack on energy requirements was offset by the effect of the knife path length. This reasoning is similar to that applied to explain the effect of saw blade projection on the cutting power of circular saws (Koch 1964).

Conversely, the greater energy value observed when processing with the larger cutterhead at 68° of attack angle (178 mm of infeed position) can be attributed to the particular orientation of the canting edge of the bent knife during cutting. When processing logs with this particular angle of attack, the orientation of the canting edge with respect to the grain varied between about $-16°$ at the entry point into the log to 5° at the exit from the log (Table 1; Fig 2c). The low exit angle produced an important edge tear out along the edge of the cant, which probably increased average energy consumption. Small exit angles increase the unit shear stress component across the grain along the edge of the log or as the knife edge exits from the log (Stewart 1985). For the other cutting conditions, the exit angle was always greater than 11°. Also, as the exit angle increases, only one point of the canting edge crosses the exit edge of the log at a time, which should generate a cleaner cut (Stewart 1985). Furthermore, the length of the tear-out exceeded in many cases the nominal chip length (or feed per knife), which was set at 25.4 mm. The resulting chips were hence bigger, which could also contribute to the increase of energy consumption.

Specific cutting energy was also calculated for each cutting condition. This parameter represents the energy (Wh) necessary to chip a cubic meter of wood. Specific cutting energy was significantly affected by the temperature condition (unfrozen and frozen wood). Thus, the specific cutting energy was 25% higher when processing frozen wood (2220 Wh/m^3) compared with unfrozen wood (1782 Wh/m^3). In addition, as for energy consumption, the effect of attack angle on specific cutting energy was negligible (not shown) because of the opposite effect of the knife path length.

A complementary test was made to determine the potential increase in energy requirements when transforming logs with a smaller cutterhead (345.2 mm of cutting diameter). Nine unfrozen black spruce logs were processed at the same cutting speed (23.5 m/s) and cutting width (24.5 mm) as the previous experiments. In contrast, rotation speed (1319 rpm) and feed speed (201 m/min) were adjusted to obtain a nominal chip length of 25.4 mm. Maximum power was 57.1 kW and energy consumed was 10 Wh for this cutterhead. These values were 44.9 kW and 8.8 Wh for the 448.7-mm cutterhead and 39.5 kW and 8.3 Wh for the 661.5-mm cutterhead, respectively. Thus, maximum power and energy consumption were 45% and 20%, respectively, greater for the smallest cutterhead compared with the largest one.

In this experiment, comparison between cutterhead diameters was made at a constant chip length (25.4 mm) and cutting rate (23.5 m/s). Taking into account the perimeter of the cutterhead, the number of knives was 6 and 8 for the 448.7- and 661.5-mm diameter cutterheads, respectively. Feed speed and rotational speed had to be changed between cutterhead diameters (Table 2). If we had maintained a constant feed speed (152 m/min), the energy requirements for the 661.5-mm cutterhead would have been even lower than what we found (Table 4). This happened because the 661.5-mm cutterhead had a higher moment of inertia (23.7 kg·m^2) because of its higher weight (Table 2). Increasing feed speed from 138 to 152 m/min would increase the angular velocity from 71.1 to 78.3 rad/s. The kinetic energy would increase from 16.7 to 20.2 Wh (Table 6), which decreases the energy requirements. Therefore, the difference in energy requirements between the two cutterheads (661.5 and

Table 6. Moment of inertia (I) and kinetic energy (KE) estimations.

Cutting diameter (mm)	Cutterhead weight (kg)	Number of knives	Nominal linear cutting speed (m/s)	Rotation speed (rpm)	Feed speed (m/min)	Angular velocity (rad/s)	Moment of inertia[a] (estimated) (Kg·m^2)	Kinetic energy[b] (estimated) (Wh)
448.7	202.5	6	23.5	1000	152	104.7	7.9	12.0
661.5	321.8	8	23.5	679	138	71.1	23.7	16.7
661.5	321.8	8	25.9	748	152	78.3	23.7	20.2
345.2	101.0	6	18.0	997	152	104.4	2.6	4.0

[a] Calculated using $I = \frac{3}{10}M\left(\frac{R^5 - r^5}{R^3 - r^3}\right)$ (6).

[b] Calculated using $\mathrm{KE} = \frac{1}{2}Iw^2$ (5).

448.7 mm) would be even more pronounced and would be lower for the 661.5-mm cutterhead. Furthermore, the kinetic energy for a smaller cutterhead (345.2 mm) would be much higher because of lower weight (101 kg) compared with the 448.7- and 661.5-mm cutterheads (Table 6). Thus, an increase in cutterhead diameter and/or weight decreases energy requirements.

The F values shown in Table 3 indicate that wood temperature condition and cutterhead diameter were the principal sources of variation affecting maximum power and energy consumption when transforming black spruce logs with a chipper-canter. The angle of attack of the chipping edge had a low influence on those parameters. From a practical point of view, this means that the cutterhead diameter will directly affect sawmill electrical energy consumption and therefore production costs. These data can also be useful for chipper-canter manufacturers. A proper cutterhead size selection can lead to a decrease in the size and cost of the electrical motor used to drive it. In eastern Canada, it is common to use integrated machines equipped with conical cutterheads of small diameters. The cutting diameter of these cutterheads is in the range of 240 and 355 mm. Although the use of smaller cutterheads is convenient because of the compact size, manufacturers should pay attention to the selection of the cutterhead configuration and cutting parameters.

This study showed the important effect of the chipper-canter cutterhead diameter on its energy requirements. However, it was focused only on the electrical performance of the motor driving the cutterhead. A next step would be to study the energy and power consumption of the electrical motor driving the infeed system as a function of angle of attack of the chipping edge (infeed position) of the knife. Global energy consumption could be further decreased taking this factor into account. Rotation of the cutterhead could contribute to the feeding energy by processing at low log infeed positions (high angles of attack of the chipping edge). However, this must be done while limiting the risk of acceleration of logs associated with the climb milling (or down milling) situation.

CONCLUSIONS AND RECOMMENDATIONS

This study showed that cutterhead diameter and temperature condition (frozen and unfrozen wood) significantly affected the maximum power and energy consumption during fragmentation of black spruce logs with a chipper-canter. These parameters were higher when processing with the smaller cutterhead diameter (448.7 mm) compared with a 661.5-mm cutterhead. Also, maximum power and energy consumption were greater when milling frozen logs compared with unfrozen logs. Although the cutting action of the chipping edge was the principal contributor to energy requirements when processing with a chipper-canter, its angle of attack had a negligible effect on energy consumption and specific cutting energy. This happened because of an opposite effect of the length of the knife path (arc formed by the engagement of the knife into the log) on these energy requirements. The use of cutterheads of greater diameters could decrease production costs of chipper-canters and increase profitability of sawmills.

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REFERENCES

Cáceres CB, Hernández RE, Koubaa A (2015) Effects of the cutting pattern and log provenance on size distribution of black spruce chips produced by a chipper-canter. Eur J Wood Wood Prod 73(3):357-368.

Gerhards CC (1982) Effect of the moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects. Wood Fiber Sci 14(1):4-36.

Giambattista A, Richardson B, Richardson R (2004) Torque and angular momentum. Pages 255-308 *in* College Physics. McGraw-Hill, New York, NY.

Gopalakrishnan B, Mardikar Y, Gupta D, Jalali SM, Chaudhari S (2012) Establishing baseline electrical energy consumption in wood processing sawmills for lean energy initiatives: A model based on energy analysis and diagnostics. Energy Eng 109(5):40-80.

Hernández RE (2014) L'usinage au CRMR: Un allié pour le développement de nouveaux produits (in French). Le Monde Forestier 28(7):20.

Hernández RE, Boulanger J (1997) Effects of the rotation speed on the size distribution of black spruce pulp chips produced by a chipper-canter. Forest Prod J 47(4):43-49.

Hernández RE, Kuljich S, Koubaa A (2010) Effect of cutting width and cutting height on the surface quality of black spruce cants produced by a chipper-canter. Wood Fiber Sci 42(3):273-284.

Hernández RE, Lessard J (1997) Effects of the cutting width and cutting height on the size distribution of black spruce pulp chips produced by a chipper-canter. Forest Prod J 47(3):89-95.

Hernández RE, Llavé AM, Koubaa A (2014a) Effects of cutting parameters on cutting forces and surface quality of black spruce cants. Eur J Wood Wood Prod 72(1):106-117.

Hernández RE, Passarini L, Koubaa A (2014b) Effects of temperature and moisture content on selected wood mechanical properties involved in the chipping process. Wood Sci Technol 48(6):1281-1301.

Hernández RE, Quirion B (1993) Effects of a chipper-canter knife clamp on the quality of chips produced from black spruce. Forest Prod J 43(9):8-14.

Hernández RE, Quirion B (1995) Effects of knife clamp, log diameter, and species on the size distribution of pulp chips produced by a chipper-canter. Forest Prod J 45(7/8): 83-90.

Koch P (1985) Utilization of hardwoods growing on southern pines sites, Vol 2. Agric handb 605. USDA For Serv Southern Forest Exp Stn, New Orleans. 1123 pp.

Koch P (1964) Wood machining processes. Ronald Press, New York, NY. 530 pp.

Kuljich S, Hernández RE, Llavé AM, Koubaa A (2013) Effects of cutting direction, rake angle, and depth of cut on cutting forces and surface quality during machining of balsam fir. Wood Fiber Sci 45(2):195-205.

McLauchlan TA, Lapointe JA (1979) Production of chips by disc chippers. Pages 15-32 *in* Chip quality monograph. Joint Textbook Committee of the Paper Industry (TAPPI), Atlanta, GA.

Mishiro A (1990) Effect of freezing treatments on the bending properties of wood. Bull Tokyo Univ For 82: 177-189.

Mishiro A, Asano I (1984) Mechanical properties of wood at low temperatures. Effect of moisture content and temperature on the bending properties of wood II. Moisture content beyond the fiber-saturation point. Mokuzai Gakkaishi 30(4):277-286.

Nyboer J, Bennett M (2014) Energy use and related data: Canadian wood products industry 1990, 1995 to 2012. The Canadian industrial energy end-use data and analysis centre. Simon Fraser University, Burnaby. 28 pp.

Papworth RL, Erickson JR (1966) Power requirements for producing wood chips. Forest Prod J 16(10):31-36.

SAS Institute (2010) SAS package version 9.3. SAS Institute, Cary, NC.

Singh KK (2013) Textbook of dynamics. PHI Learning Private Limited, New Delhi. 397 pp.

Stewart HA (1985) Determining face-milling radial rake angle to reduce exit edge tear-out in yellow poplar. Forest Prod J 35(7/8):57-58.

Stewart HA (1991) Importance of clearance angles, particularly with small rake angles. Forest Prod J 41(10): 73-75.

Stewart HA (1977) Optimum rake angle related to selected strength properties of wood. Forest Prod J 27(1):51-53.

Woodson GE (1979) Tool forces and chip types in orthogonal cutting of southern hardwoods. Res Paper SO-146. USDA For Serv Southern Forest Exp Stn, New Orleans. 77 pp.

Woodson GE, Koch P (1970) Tool forces and chip formation in orthogonal cutting of loblolly pine. Res Paper SO-52. USDA For Serv Southern Forest Exp Stn, New Orleans. 25 pp.

Zhang SY, Koubaa A (2008) Black spruce. Pages 1-28 *in* Softwoods of eastern Canada: Their silvics, characteristics, manufacturing, and end-uses. Special Publication SP-526E. FPInnovations, Quebec, Canada.