Towards Strand Production in Primary Log Breakdown: Effects of the Counter-Knife and Temperature on Size Distribution of Jack Pine Strands

Irsan Alipraja,[a,c,]* Roger E. Hernández,[a] Claudia B. Cáceres,[a] and Ahmed Koubaa [b]

Effects of counter-knife and wood temperature were studied relative to the size distribution of Jack pine strands processed by a strander-canter. Studied factors included the counter-knife angle (60°, 75°, 90°, and 105°) and the distance between the edges of the counter-knife and knife (6 mm, 11 mm, and 16 mm). The nominal cutting speed was fixed at 25 m/s. Rotation and feed speeds were adjusted to obtain a target strand length of 102 mm, while the target strand thickness was 0.9 mm. The stranding process was performed under two log temperatures, *i.e.*, -13.4 °C (frozen condition) and 18.6 °C (unfrozen condition). Results showed that the proportion of strands, fines, pin chips, and strands' width were affected by the counter-knife angle and wood temperature. The proportion of strands and the mean strand width increased as the counter-knife angle decreased, while conversely, the proportion of fines and pin chips decreased. Frozen logs produced narrower strands and more fines and pin chips than unfrozen logs. The highest strand proportion, lowest fines and pin chips proportions, and wider strands were obtained with a counter-knife angle of 60° for frozen wood and 75° for unfrozen wood.

DOI : 10.15376/biores.17.2.2632-2651

Keywords: Strander-canter; Counter-knife; Stranding; Strand geometry; Jack pine

*Contact information: a: Centre de Recherche sur les Matériaux Renouvelables, Département des Sciences du Bois et de la Forêt, Université Laval, Pavillon Gene H.-Kruger, 2425 Rue de la Terrasse, G1V 0A6, QC, Canada; b: Université du Québec en Abitibi-Témiscamingue, 445 boul. de l'Université Rouyn-Noranda QC J9X 5E4; c: Department of Forest Products, Faculty of Forestry, IPB University, Jl. Ulin, Kampus IPB Darmaga Bogor 16680, Indonesia; *Corresponding author: roger.hernandez@sbf.ulaval.ca*

INTRODUCTION

The forest products sector plays an important part in the Canadian economy. In 2019, this sector contributed up to CAN $23.7 billion to the nominal gross domestic product and an export product value of around CAN $33 billion (NRCAN 2020). Wood product manufacturing is the leading sub-sector that accounted for approximately 44% of the forest sector contribution, followed by the pulp and paper industry (38%). Sawmills are well known as the principal suppliers for most of the forest products industry since that is where the first transformation of wood is carried out after being harvested from the forest. In Canada, particularly in Eastern Canada, most of the processing of the softwood logs in sawmills is carried out by chipper-canters followed by circular saws. This machine is designed to transform logs into lumber and chips, in a single operation, with very low sawdust production (Hernández and Quirion 1995; Hernández and Boulanger 1997; Hernández and Lessard 1997). On average, the lumber recovery from Canadian sawmills is around 43 to 51%, while 33 to 38% of the log volume is converted into pulp chips (Liu *et al*. 2009; UNECE/FAO 2010; Ghafghazi *et al*. 2017). Specifically, in Eastern Canada, the lumber recovery may reach up to 60%, depending on the log diameter and the type of machinery used (Spelter and Alderman 2005). As a by-product, wood chips have an important economic value for sawmills, contributing to 10 to 15% of total sales (FAO 1976;

Nagubadi and Zhang 2006; Zhang and Nagubadi 2006). Pulp and paper mills have been the main consumer of the wood chips from sawmills (Gouvernement du Québec 2016). Several sawmills even sell 100% of their chips to the industry, while up to 60% of pulp mill chip supply comes from the sawmills (Gardner Pinfold Consultants 2019). This shows the inter-dependent economy between sawmills and pulp and paper industries.

Nonetheless, the migration of the consumers to electronic media, the use of recycled paper, the increase of production costs, and the competition with pulp production from other countries has caused the Canadian pulp and paper industry to continue to decline. Since 2010, although fluctuating, productions of Canadian wood pulp and paper have tended to decrease (NRCAN 2019). Compared to 2010, domestic production of wood pulp, newsprint, and printing and writing paper in 2019 decreased 17%, 42%, and 36%, respectively. These conditions affect the employment field and gross domestic product and cause other problems, especially related to the oversupply of wood chips as raw materials. Sawmills might be forced to limit the production of large volumes of chips that are being produced. According to Salmon (2018), in 2017, there were 144.500 oven-dry metric tons of unsold wood chips of Spruce-Pin-Fir group in Quebec’s sawmill yards, which was almost four times higher than in 2014. Exports could be a short-term solution. However, a new production capacity (*i.e.*, either wood pulp or bioenergy/pellets) needs to be adjusted to make the sawmill industry survive. If not, sawmills must inevitably reduce chip production in the future.

One possible solution to solve the overproduction of pulp chips is producing raw materials for other uses, such as bioenergy or composite panels. Oriented strand board (OSB) is one of the promising composite panels made from wood strands. OSB is experiencing very high growth throughout the world, especially in North America. Oriented strand boards are widely used in residential structures and have also been introduced in some furniture markets (Spelter *et al*. 2006; Iswanto *et al*. 2010; Jin *et al*. 2016). Thus, strands production by sawmills may provide two advantages: (1) for the sawmill, this can be a beneficial alternative income while solving the problem of excess pulp chip production; and (2) for OSB mills, this type of strands could offer a potential source of raw materials.

Strand geometry is the main parameter that affect properties and the OSB manufacturing process (Geimer and Price 1978; Barnes 2000; Iswanto *et al*. 2010; Mirski *et al*. 2019). Strand geometry has a greater impact on OSB performance than the wood species itself (Beck *et al*. 2009). Strand dimensions directly affect the porosity between strands during mat formation (Dai *et al*. 2005). As length and width increase while thickness decreases, the porosity decreases, which leads to more complete contact around the strand edges. Thus, longer and thinner strands are suitable to obtain better panel properties.

However, the effect of strand width on panel properties appears to be associated with those of length and thickness. Combined with the length, the width of the strands has an effect on their alignment during mat formation (Chen *et al*. 2008). Strands between 19 mm and 38 mm wide had better alignment than those narrower or wider than these values. Panels with strand alignment between 0 and 20° in the main axis showed three times higher flexural properties than those aligned between 20 and 40° (Chen *et al*. 2008). Narrow strands have more tendency to rotate, which could increase the misalignment and porosity. Meanwhile, very wide strands tend to cross the orienter disk, and while being carried across the top of the orienters they tend to fall through the orienter over a wider distance.

The dimensions of strands produced under industrial conditions usually range between 50 to 150 mm in length, 0.3 to 1.3 mm in thickness, and 13 to 25 mm in width (Geimer and Price 1978; Van *et al*. 2019). These dimensions may differ between OSB mills depending on the applied machining parameters. Several studies reported that the mean dimensions of commercial strands were around 25 mm wide, 100 mm long, and 0.7 mm thick (Dai *et al*. 2007, 2008), while others have 16 mm wide, 60 mm long, and 0.6 mm thick strands (Kruse *et al*. 2000).

Another factor that affects the quality of OSBs is the volume of fines. These particles are typically kept in the mixture to reduce costs in board manufacturing, but their presence affect the mat structure and the board properties (Barnes 2000; Han *et al*. 2006, 2007). According to Barnes (2000), the proportion of fines on OSB should be less than 10%. However, Han *et al*. (2006) reported that increasing fines on the core layer of panels to a maximum volume of 20% increased internal bond strength. The modulus of elasticity (MOE) and modulus of rupture (MOR) varied little in the parallel direction and slightly decreased in the perpendicular direction. As a result, fines could be used as filling material in the core layer where the panel's density is low. However, the dimensional stability of panels decreased as the fines content increased.

Given that strand dimensions and fines have a great effect on OSB properties, research on the performance of strander machines should be encouraged. The main challenge of this study was to explore the production of strands by a chipper-canter, henceforth called strander-canter, with acceptable geometry and minimum amount of fines and pin chips. Since stranding and pulp chipping processes have different cutting actions, a new cutterhead was designed. Several technical aspects affecting the stranding, such as machining parameters (knife angle, counter-knife setting, cutting speed, *etc*.) and log conditions, need to be evaluated.

The purpose of this study was to evaluate the effects of the counter-knife angle and the edge distance between knife and counter-knife on the quality of strands produced by a strander-canter from frozen and unfrozen logs. The quality of strands was evaluated using the proportion of strands, fines, and pin chips and the strand length, thickness, and width.

EXPERIMENTAL

Materials

The tests were carried out with freshly felled Jack pine (*Pinus banksiana* Lamb.) logs coming from Abitibi-Témiscamingue, Quebec Province, Canada. This tree is one of the most important boreal species in Canada and makes up part of the SPF (spruce-pine-fir) wood group, which is widely used in the pulp and paper industry and construction applications (Zhang and Koubaa 2008).

The logs selected for this study were relatively straight, freshly debarked, with no visible defects, and cut at 2.4 m long. The mean small end diameter of logs was 160 mm. Two opposite sides of the logs were selected. The first one was processed under frozen conditions, while the second was machined under unfrozen conditions (Fig. 1a). The length, diameter, and the number of knots with a diameter of more than 10 mm of logs were measured. The logs were wrapped with plastic and stored green in a freezer at -19 °C to reduce the loss of moisture content (MC) until testing.

Methods

Specific gravity (SG) and MC measurements

One 25 mm thick disk was cut from each end of the log to measure physical properties. The limit between the sapwood and heartwood was marked on the cross-section of the discs. The thickness of the sapwood was then measured at three points within the part of the disc to be transformed into strands (Fig. 1b).

A sample of 25 mm (axial direction) x 20 mm (tangential direction) x 20 mm (radial direction) were then cut from each side of cutting width. The MC was reported as the ratio between the sample's weight of water and oven-dry weight, while SG was determined as the oven-dry weight divided by the sample's green volume.

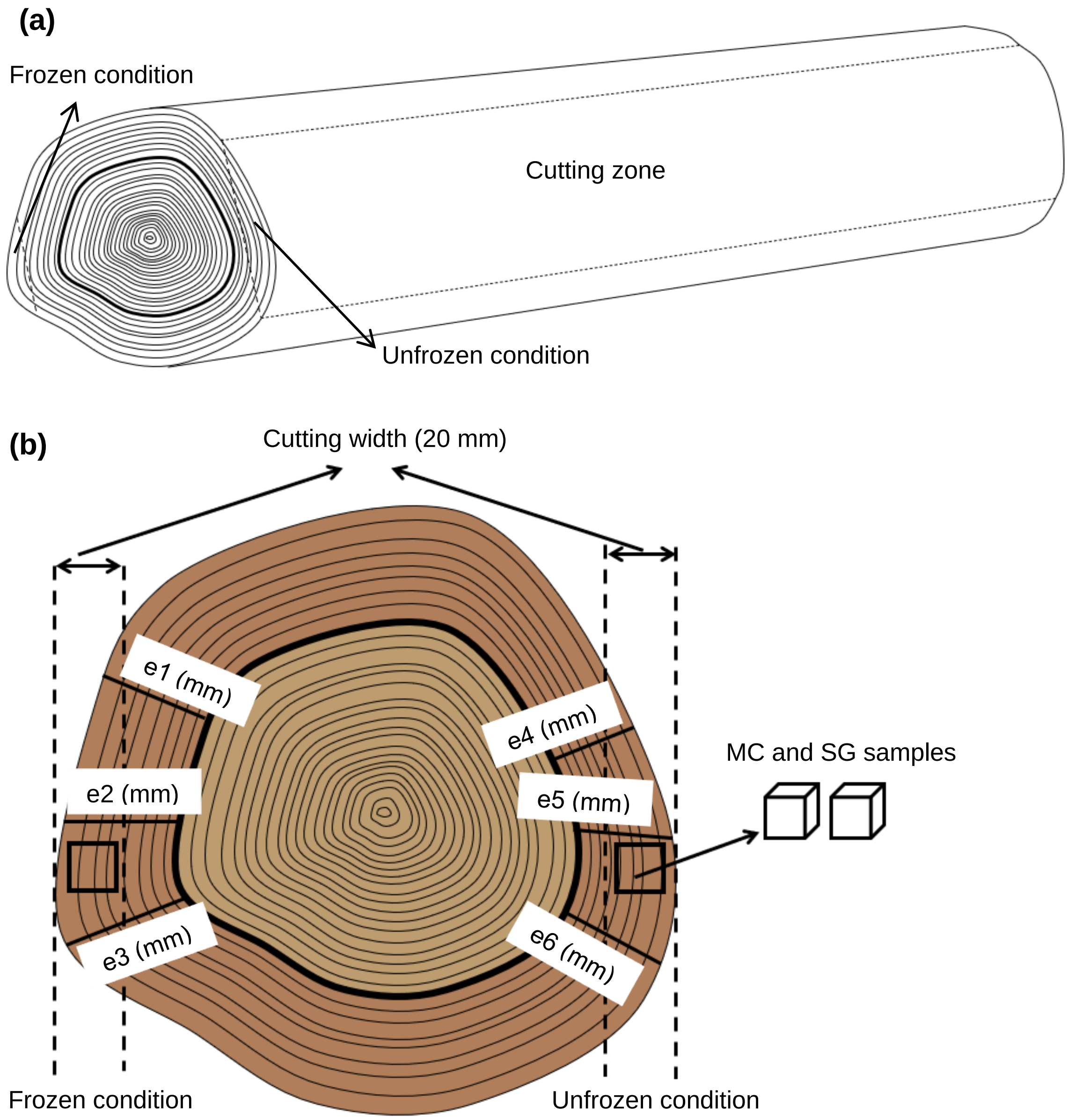


Fig. 1. (a) Cutting zones and (b) sapwood thickness, MC, and SG measurement scheme

Log properties were then analyzed to separate the logs into nine equivalent groups of 15 logs. The properties of logs used in this study are shown in Table 1.

Table 1. Characteristics of Jack Pine Logs from Abitibi-Témiscamingue

Diameter (mm)	208.8 (11.1)[a]
Length (mm)	2321 (1.2)
Taper (mm/m)	9.9 (53)
Sapwood Thickness (mm)	34.2 (24)
Moisture Content (%)	113.8 (18)
Specific Gravity	0.468 (8)
[a]The number in parentheses is the coefficient of variation (%)	

Log transformation

Logs were processed with a laboratory strander-canter equipped with one experimental cutterhead manufactured by DK-SPEC (Quebec, Canada), having the form of a truncated cone. The cutterhead had an inner diameter of 900 mm and was fitted with 33 straight knives installed to cut slices across the grain. These knives were radially offset by 0.9 mm to obtain slices of this thickness. A counter-knife was mounted on the rake face of each knife with a certain distance between its edge and the cutting knife-edge (Fig. 2b). The counter-knife should generate the strands' width by causing the slice to break by transverse bending. The knife angle was 30°, with a rake angle of 59° and a clearance angle of 1°. Four counter-knife angles (60°, 75°, 90°, and 105°) and three distances between the edges of the counter-knife and knife (6 mm, 11 mm, and 16 mm) were studied. All knives were freshly ground to minimize the effect of tool wear on strand size. The strander-canter was equipped with a hydraulic feed carriage that held the log fixed during fragmentation.

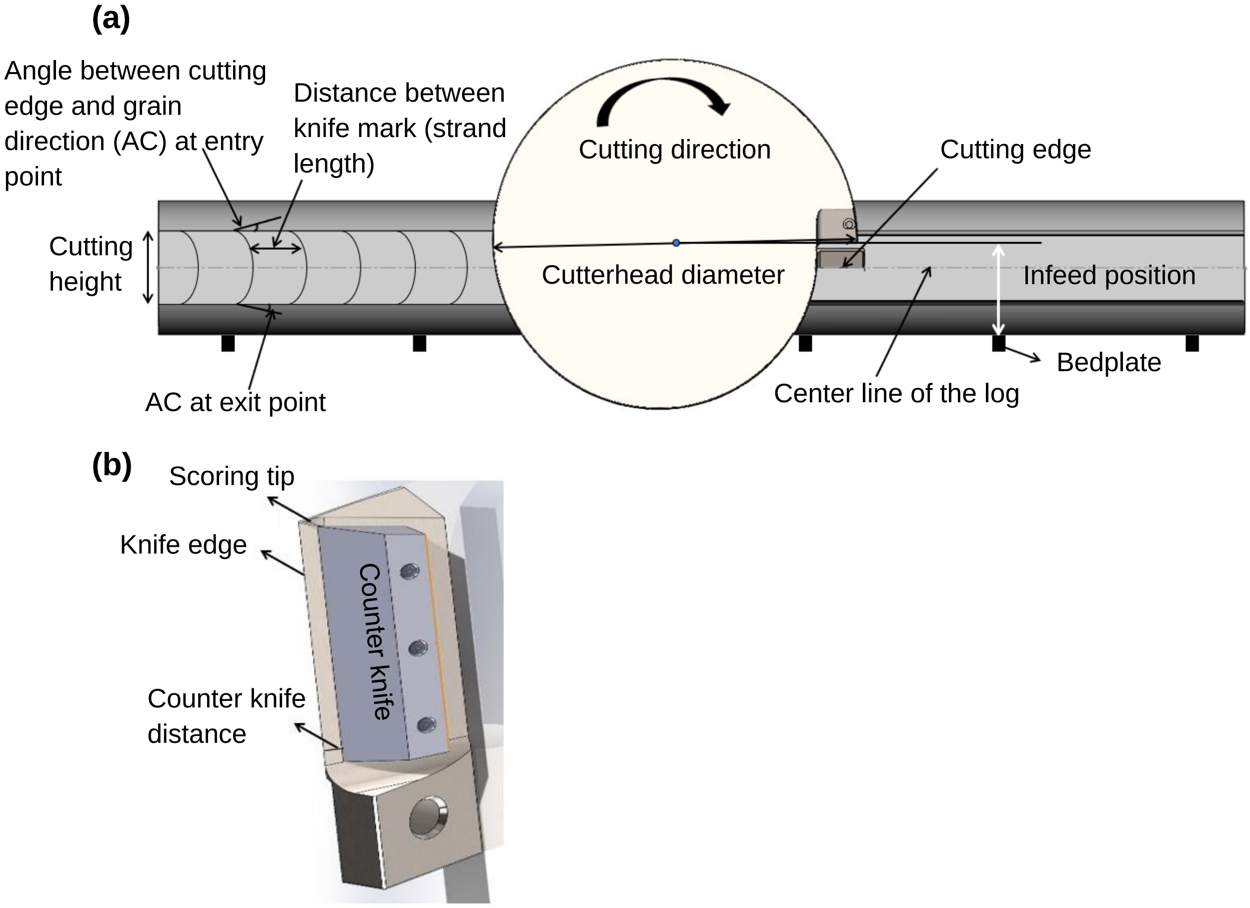


Fig. 2. (a) Cutting scheme on strander-canter and (b) knife and counter-knife assembly showing the distance between their edges

The vertical position of the cutterhead was controlled to obtain a given log infeed position. The vertical distance from the cutterhead axis to the bedplate, on which the log is supported, defines this position. The log infeed position was determined so that the cutting edge was parallel to the wood grain in the middle of each knife cutting path or in the center of the cutting height (0-90° cutting mode). This was done by simulation using software (Solidworks, Waltham, MA, USA) (Fig. 2a).

The cutting width was held constant at 20 mm along the log to reduce the effects of the log taper and cutting height on wood fragmentation. Five clamps in the carriage held the log firmly in place to minimize vibration during the log fragmentation. The rotation speed of the cutterhead was 427 rpm, and the feed speed was 42.6 m/min. This resulted in a cutting speed of 25 m/s and produced a nominal strand length of 102 mm. The cutting parameters for all studied conditions are shown in Table 2.

The study was carried out in two steps to simulate seasonal temperature differences during log processing. The same log was machined on one side under frozen condition and on the opposite side in an unfrozen one. A small hole (with diameter ±2 mm) was made with a drill at the distance ±30 cm from each end of the logs. The depth of the hole was 20 mm, which corresponded to the cutting width. The temperature was measured by using a digital thermometer to the nearest 0.1°C. The logs were always fed with the small end first, and they were machined flat on one side under the frozen condition. Logs were then left overnight indoors and processed the next day (unfrozen side). The mean temperature for frozen and unfrozen side were -13.4°C and 18.6°C, with a standard error of 0.1°C and 0.2°C, respectively. Cants produced were wrapped with a plastic film and stored again in the freezer. As soon as each log was transformed, all particles obtained were collected in plastic bags and stored for subsequent analysis.

Table 2. Principal Cutting Parameters of the Strander-Canter during Fragmentation

Counter-knife Angle (Frozen Condition)	60°	75°	90°
Counter-knife Angle (Unfrozen Condition)	75°	90°	105°
Edge Distance[1]	6 mm	11 mm	16 mm
Cutting Speed [2]	25 m/s		
Mean Cutting Width	20 mm		
Nominal Strand Length	102 mm		
Nominal Strand Thickness	0.9 mm		

[1] distance between the knife edge and the counter-knife edge
[2]calculated at the diameter of the cutterhead (900 mm)

High-speed photography

A MotionPro Y4-S3 (IDT, Tallahassee, FL, USA) equipped with a 35-mm/f 1.4 lens (Kowa, Nagoya, Japan) evaluated the mechanism of strand formation. The stranding was observed from different angles with a field of view of about 35 x 35 cm and focusing on the knives' rake face. Videos were taken at 3000 frames per second and an exposure of 80 to 90 µs. The images were acquired at maximum resolution (1024 x 1024 pixels) with a pixel depth of 24 bit. The cutting action of knives was recorded during strander-canting of one log per treatment under frozen and unfrozen conditions.

Measurement of strand dimensions

All particles were air-dried for 21 days up to about 9.5% MC to facilitate their separation. They were first screened for 15 min with a LabTech (Tampa, FL, USA) classifier (similar to the Williams classifier), which sorts particles by width and length and is more efficient in separating the smallest chip classes. The LabTech classifier retained the following chip classes: fines (material that passed a 4.8-mm-diameter screen hole), pin chips (material that passed a 9.5-mm-diameter screen hole and retained in a 4.8-mm-diameter screen hole), and strands (chips retained in screens of 9.5, 15.9, 22.2, 28.6, 45 mm, and 70 mm hole diameter). All chip classes were expressed as the percent weight of the total chips.

Since the Williams classifier is not well adapted for long particles, the dimensions of the strands were measured semi-manually. A total of 100 strands, taken proportionally from each LabTech screen classifier, were chosen randomly for each condition studied. The strands were scanned using an Epson Expression 1640XL scanner (Epson, Los Alamitos, CA, USA). The images were then changed into 8-bit color, thresholded, and analyzed with Image-J 1.53a software. The following parameters defined strand dimensions: length (longest axis of the strand parallel to the grain), width (mean of five measurements perpendicular to the grain), and thickness (measured with a micrometer to the nearest 0.01 mm).

Statistical analyses

Data were analyzed using Rstudio desktop software version 1.3.1093 (Boston, MA, USA). A multivariate analysis of variance (MANOVA) tested if the physical properties of nine groups of logs used in this study were similar. The SG, MC, sapwood thickness, number of knots, diameter and length of logs were the variables tested.

Raw data for strand length, thickness, and width analyses were evaluated with the BoxCox method to show the fitted transformation if required. A factorial design with a mixed model analysis of covariance (ANCOVA) was then applied to the experiment. Counter-knife angle, counter-knife distance, and temperature were the main sources of variation. The counter-knife angle was nested within temperature since values of this angle differed between the two log conditions. The effect size of each parameter studied was estimated by the eta squared value. The effect size reflects the proportion of variance in the dependent variables that is associated with each of the main effects and the interaction (Tabachnick and Fidel 2001). This proportion allow to interpret descriptively how each variable behave in the model. The eta squared value was calculated by the ratio between the sum of squares of each effect and the sum of squares total.

A MANCOVA was performed using the Aitchison approach for the fines and pin chips proportions (Aitchison 1982). A center log-ratio transformation (CLR) was applied to the raw data. For both analyses, the number of knots, SG, MC, the cutting volume, and the strand width were used as covariates. Only significant covariates were kept in the model. An ANCOVA was then done individually for each proportion. The Shapiro-Wilk and the kurtosis tests verified the normality of data, and the graphical analysis of residuals verified the homogeneity of variance.

RESULTS AND DISCUSSION

The MANOVA (not shown) revealed that the mean values of SG, MC, and thickness of sapwood and the number of knots and diameter of logs were similar for the nine groups of logs. The mean sapwood thickness was 34.2 mm with a coefficient of variation (CoV) of 24%, which indicates that the cutting width used (20 mm) involved mainly this type of wood. Means of SG and MC for sapwood were 0.468 (CoV = 8%) and 113% (CoV = 18%), respectively. The mean of SG was within the range of SG (0.406 to 0.443) and was reported in previous studies conducted in Quebec province (Jessome 2000; Zhang and Koubaa 2008).

According to Spelter *et al*. (1996), the pressure required during processing to achieve good board properties is related to the ratio of board SG to wood SG. A ratio of 1.3:1.0 provides a rough guide to determine if a species is suitable. Commodity-grade OSB panels are made in an SG range of 0.61 to 0.64, thus requiring a wood SG not much greater than 0.480. The Jack pine logs studied, therefore, fall within the desired SG range.

Strand Formation on the Strander-Canter

The cutting action for making strands in this experiment was similar to a disk flaker or a peeling machine. Knives tended to work in a 0 to 90° cutting mode, although the angle of orientation between the cutting edge and the wood grain varied slightly along the cutting path of the knife. According to Leney (1960), a continuous veneer on a 0 to 90° peeling mode is produced, involving mainly two strains: compression strain on the veneer face and a tension one on the knife rake face side or back of the veneer. These two strains should also be involved during the stranding process.

The formation of strands by a strander-canter is shown in Fig. 3 by a sequence of high-speed photographs. At the beginning of the cutting process, the knife penetrated log nearly parallel to the grain with a positive oblique angle (Fig. 3a). As the wood cells in the cutting path were severed and separated by the cutting edge, the formed strand-sheet moved upward along the rake face of the knife.

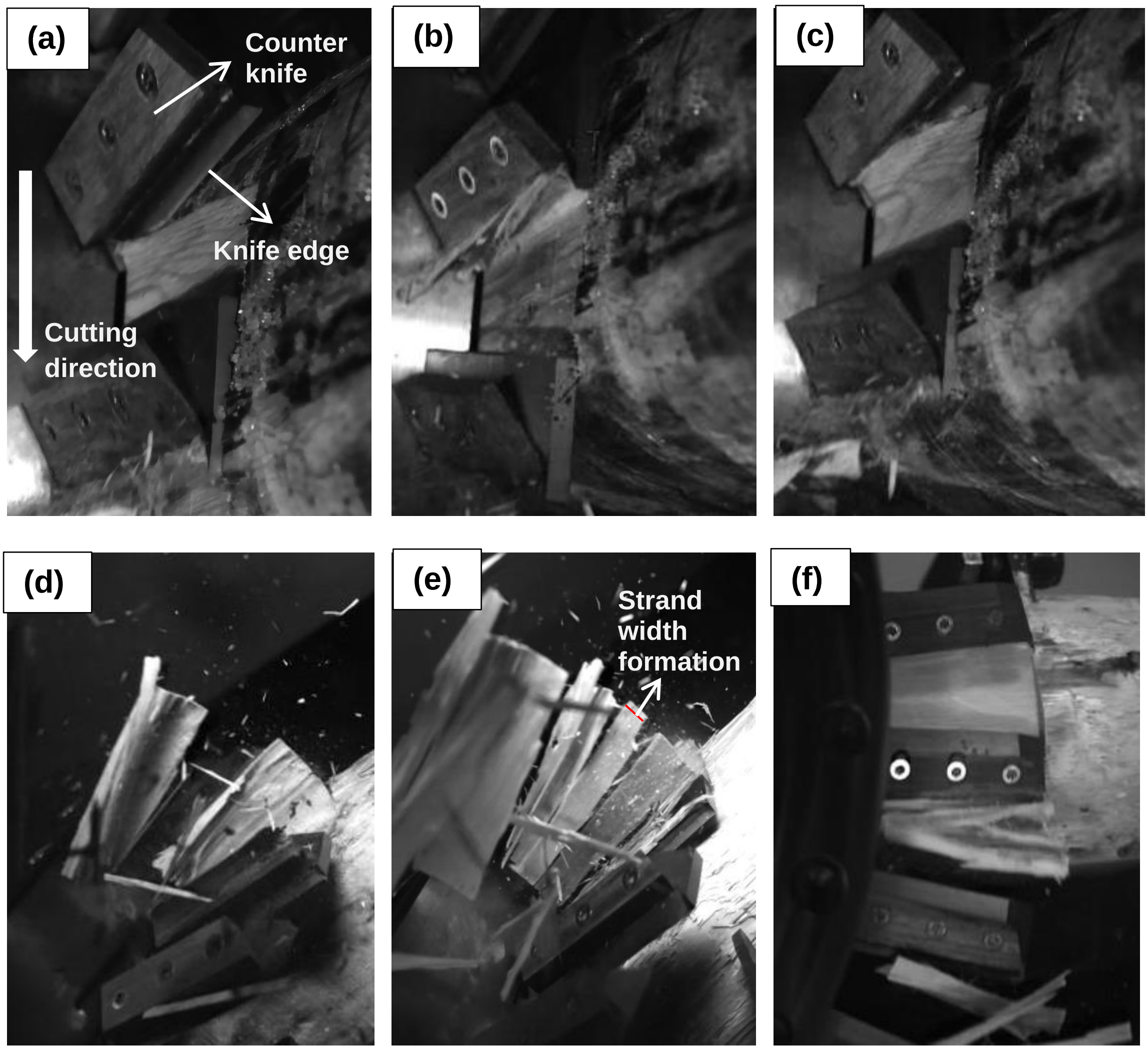


Fig. 3. The sequence of formation of strands of unfrozen wood by a strander-canter. Side view: (a) knife penetration, (b) strand-sheet bending process, (c) exit point of cutting; Bottom view: (d) strand-sheet bending process, (e) strand width formation at the exit point of cutting; Front view: (f) strand length formation

The strand-sheet began to bend as a cantilever beam. This bending deformation of wood tissue created a zone of tensile stress at the rake face of the knife (loose side) and another of compression stress on the side away from the knife (tight side, Fig. 4). Preliminary tests, performed on unfrozen logs and knives without counter-knife, mainly produced continuous strand-sheets, whose width corresponded to the entire cutting height (similar to the peeling action). It is known that the internal cutting stresses occurring in the sheet are dependent on the knife angle. The stresses produced by a knife angle of 30° were not great enough to generate strand width formation by transverse tension fractures. Cutting under frozen conditions increased the frequency of strand-sheet tension fractures, although most of the resulting strands were still too wide.

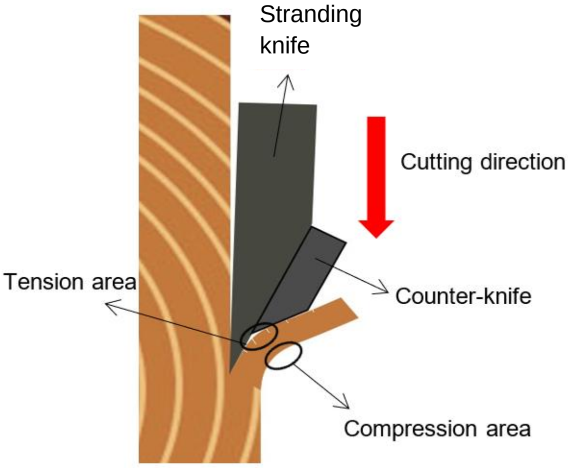


Fig. 4. Illustration of the stranding process at the middle of the logs (0 to 90° cutting)

When a counter-knife was added, the compression and tensile stresses increased significantly as the strand-sheet bent further when passing through this piece (Fig. 3b, d). At this point, the bending stress depends on the angle and the distance of the counter-knife. As the counter-knife angle increased, the bending stress should increase. This stress increases the frequency of checking in the loose side of the strand sheet, leading to its complete fracture with the production of strands with a given width. Moreover, the scoring tip inserted into the knife assembly cut the strands into the desired length by shearing across the grain (Fig. 3f).

On the other hand, the angle between the knife cutting edge and the grain direction (AC) can play a role in the strand production. The AC varies through the cutting path of the knife and depends on the cutterhead diameter and log infeed position (Fig. 2a). This position was chosen to have an AC of 0° at the middle of the knife path (0 to 90° cutting mode). The bending of the strand-sheet at this position occurred exactly perpendicular to the grain, which facilitated splitting and strand width generation. Given the cutterhead diameter used, AC varied between ± 10° within the cutting path at the maximum cutting height (for the mean diameter of logs of 208 mm). The strand-sheet was not bent across the grain at these positions, as seen on the upper knife in Fig. 3c. As a result, the frequency of wood splitting may be higher in the middle of the strand sheet.

The chipping-canting process in sawmills only cut some part of logs to make the wood square. In the experiment, the cutting width used was 20 mm. Thus, the stranding process mainly involved tangential or flat cutting. Failures in the strand sheets due to the bending stress occurred mainly by ray tissues, in the longitudinal-radial plane. The radial tissues are the weakest parts in the wood structure, which makes strand-sheet splitting easier.

Proportion of Strands, Fines, and Pin Chips

The strands proportions ranged from 40% to 71% and 68% to 90% for frozen and unfrozen wood, respectively, depending on the stranding conditions. Compared to performances of some industrial disk flakers (Malanit *et al.* 2005; Stiglbauer *et al.* 2006;

Wan-Mohd-Nazri *et al.* 2011; Xing *et al*. 2017), the proportion of strands obtained from the strander-canter were relatively lower for frozen logs. However, for unfrozen logs, the better conditions produced generally higher volumes of strands than disk flakers. The same tendency was observed when the present results were compared to drum flaking productions (Price and Lehmann 1979; Feng and Knudson 2007). However, aside from the type of machine, comparisons among studies are difficult because different cutting parameters, wood species, log pre-treatments, and wood moisture contents are involved.

The ANCOVA showed that the wood temperature (WT), counter-knife angle (CKA), and counter-knife distance (CKD), as well as their interactions affected the proportion of strands produced by the strander-canter (Table 3). The covariates moisture content (MC) and cutting volume (CV) also significantly affected the proportion of strands. According to the Eta squared values, the wood temperature had the highest effect on the strand proportion, which accounted for around 54.6% of the strand yield variation, followed by the impact of the counter-knife angle (19.8%). The influences of WT, CKA, and CKD on strand proportion are shown in Fig. 5. The proportion of strands increased as CKA decreased. A decrease of CKA reduced the frequency of wood fractures during the stranding process, thus producing wider strands and lower proportions of small particles. At the same CKA, stranding at the unfrozen wood condition (18.6 °C) produced 1.5 to 2 times more strands than at the frozen condition (-13.4 °C). According to Table 4, the higher proportions of strands were obtained using a CKA of 60° for frozen wood and 75° for unfrozen wood. At these values of CKA, the influence of CKD was not statistically significant. Therefore, the proportions of the three distances for these CKAs were pooled. Thus, the highest proportions of strands obtained were 68% for frozen wood and 88% for unfrozen wood.

The bending stress on the strand-sheet increases as CKA increases, which will increase the frequency of wood fractures, generating narrow strands. The formation of narrow strands led to fines and pin chips, which were the small elements produced during stranding. Pin chips are slightly larger than fines and have few contaminants, while fines may contain particles of bark and other contaminants (Fakhri 2005). Fines are not favorable for OSB mills because they are prone to overdrying, consume a large amount of resin, and reduce the strength of panels (Stiglbauer *et al*. 2006; Banerjee *et al*. 2007). Therefore, the production of these particles need to be reduced at the source.

The ANCOVA showed that the wood temperature, counter-knife angle, and counter-knife distance, as well as their interactions, affected the proportion of fines and pin chips (Table 3). According to the Eta squared values, the wood temperature had the highest effect on these particles, followed by the counter-knife angle effect.

Table 3. F-values and Eta Squared Obtained from the ANCOVAs for Proportion of Fines, Pin Chips, Strands, and Strand Width

Source of Variation	F Value			Eta Squared		
	Fines	Pin Chips	Strands	Fines	Pin Chips	Strands
Knots	7.4**	5.1*	ni	0.011	0.003	ni
MC	5.3*	6.2*	11.2***	0.008	0.004	0.007
SG	ni	18.7***	ni	ni	0.012	ni
CV	31.8***	71.9***	91.4***	0.047	0.045	0.057
CKA	22.0***	121.4***	79.1***	0.129	0.307	0.198
CKD	8.6***	9.2***	17.9***	0.025	0.011	0.022
WT	282.7***	721.4***	877.1***	0.414	0.453	0.546
CKD x CKA	2.9**	3.5***	4.2***	0.034	0.018	0.021
CKD x WT	3.1*	4.5*	7.5***	0.009	0.006	0.009
*** statistically significant at 0.001 probability level; **statistically significant at 0.01 probability level; *statistically significant at 0.05 probability level; ni: not included						

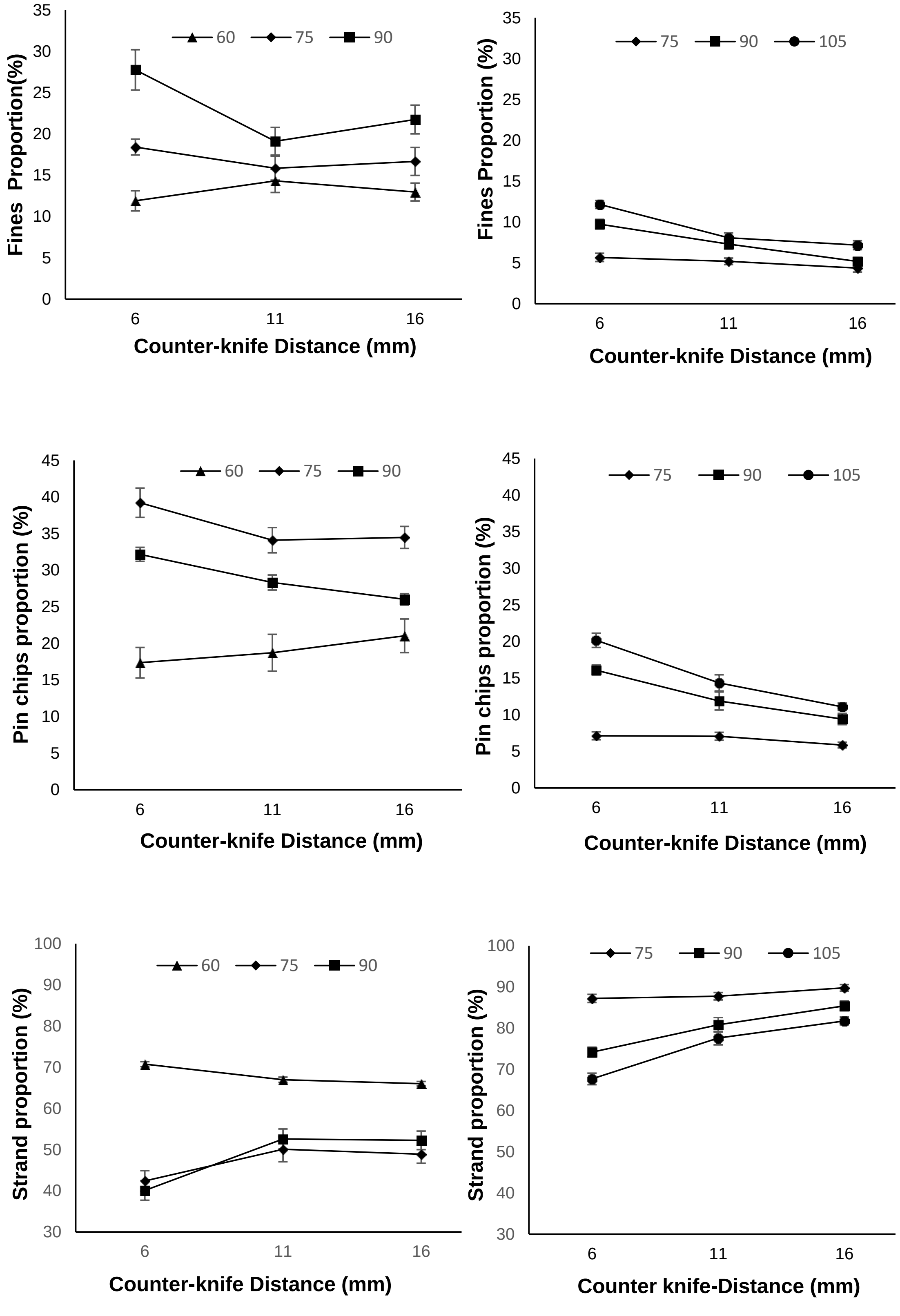
Table 4. Means of Fines, Pin Chips, and Strand Proportions, and Width Strand by Wood Condition, CKA, and CKD

Wood Condition	CKA	CKD	Fines (%)	Pin Chips (%)	Strand (%)	Strand Width (mm)
Frozen	60	6	$11.9_{(1.2)}^{A}$	$17.4_{(1.1)}^{AB}$	$70.7_{(2.1)}^{A}$	$12.8_{(0.7)}^{A}$
	60	11	$14.3_{(1.4)}^{AB}$	$18.7_{(1.3)}^{A}$	$67.0_{(2.5)}^{A}$	$12.8_{(1.0)}^{AB}$
	60	16	$13.0_{(1.1)}^{A}$	$21.0_{(1.8)}^{AB}$	$66.0_{(2.3)}^{A}$	$12.4_{(0.8)}^{AB}$
	75	6	$18.4_{(1.0)}^{AB}$	$39.2_{(2.0)}^{E}$	$42.4_{(2.5)}^{BC}$	$7.2_{(0.3)}^{CD}$
	75	11	$15.9_{(1.5)}^{A}$	$34.1_{(1.7)}^{DE}$	$50.0_{(3.0)}^{B}$	$8.2_{(0.6)}^{CD}$
	75	16	$16.7_{(1.7)}^{AB}$	$34.5_{(1.5)}^{DE}$	$48.8_{(2.2)}^{BC}$	$9.9_{(0.3)}^{B}$
	90	6	$27.8_{(2.4)}^{C}$	$32.1_{(1.0)}^{CD}$	$40.1_{(2.4)}^{C}$	$6.4_{(0.3)}^{D}$
	90	11	$19.1_{(1.7)}^{AB}$	$28.3_{(1.0)}^{C}$	$52.6_{(2.4)}^{B}$	$7.2_{(0.3)}^{CD}$
	90	16	$21.8_{(1.7)}^{BC}$	$26.0_{(0.8)}^{BC}$	$52.2_{(2.3)}^{B}$	$8.1_{(0.3)}^{C}$
Unfrozen	75	6	$5.7_{(0.5)}^{AB}$	$7.1_{(0.5)}^{A}$	$87.2_{(1.0)}^{AB}$	$19.9_{(1.0)}^{A}$
	75	11	$5.2_{(0.4)}^{AB}$	$7.1_{(0.5)}^{A}$	$87.7_{(0.9)}^{A}$	$18.0_{(0.8)}^{ABC}$
	75	16	$4.3_{(0.5)}^{A}$	$5.9_{(0.5)}^{A}$	$89.8_{(0.8)}^{A}$	$18.2_{(0.5)}^{AB}$
	90	6	$9.7_{(0.6)}^{BC}$	$16.1_{(0.7)}^{CD}$	$74.2_{(1.2)}^{CD}$	$13.6_{(0.5)}^{DEF}$
	90	11	$7.3_{(0.6)}^{ABC}$	$11.9_{(1.2)}^{BC}$	$80.8_{(1.8)}^{BC}$	$14.9_{(0.9)}^{DEF}$
	90	16	$5.2_{(0.5)}^{A}$	$9.4_{(0.8)}^{B}$	$85.4_{(1.2)}^{AB}$	$15.9_{(0.51)}^{BCD}$
	105	6	$12.1_{(0.5)}^{C}$	$20.2_{(1.0)}^{D}$	$67.7_{(1.4)}^{D}$	$12.4_{(0.6)}^{F}$
	105	11	$8.1_{(0.6)}^{ABC}$	$14.3_{(1.1)}^{BCD}$	$77.6_{(1.6)}^{C}$	$12.9_{(0.6)}^{EF}$
	105	16	$7.2_{(0.6)}^{ABC}$	$11.1_{(0.5)}^{BC}$	$81.7_{(0.9)}^{BC}$	$15.4_{(0.4)}^{CDE}$

Means within a column followed by the same letter are not significantly different at the 5% probability level for frozen and unfrozen logs separately. Standard errors of means in parentheses

Contrary to the strand behavior, fines and pin chips increased as the angle of the counter-knife increased (Fig. 5). Processing logs in the frozen state (-13.4 °C) generated up to 4 and 5 times more fines and pin chips, respectively than when processing them in the unfrozen state (18.6 °C). It is known that the presence of ice inside the wood increases its brittleness, which makes wood tend to break rather than bend when it passes by the counter-knife (Spelter *et al*. 1996; Stiglbauer *et al*. 2006; Gaete-Martinez *et al*. 2008). According to Table 4, the lowest proportions of fines and pin chips were obtained using a CKA of 60° for frozen wood and 75° for unfrozen wood, regardless of the CKD. The effect of CKD on fines and pin chips was only significant at a CKA of 90° or higher. Thus, the edge of the counter-knives can be placed between 6 and 16 mm from the knife-edge without affecting fines and pin chips production. The best angles of the counter-knives obtained for reducing the fines and pin chips were the same that came out to maximize the production of strands. At these values of CKA, the proportions of the three distances for these CKAs were pooled. Thus, the lowest proportions of fines and pin chips were 13% and 19% for frozen wood, and 5% and 7% for unfrozen wood, respectively (Table 4). In general, the amount of fines produced from stranding process ranges between 20% and 40% (Cafferata 2003; Fakhri *et al*. 2006; Lau *et al*. 2007). Some studies report proportions lower than 10% (Stiglbauer *et al*. 2006; Xing *et al*. 2017). This variation can be attributed to the use of different types of machines, machining parameters, wood species, wood temperatures, and the variable hole size of screens used to separate the fines. In any case, the best conditions obtained here gave volumes of fines smaller or similar to those reported in previous studies.

On the other hand, the amount of fines and pin chips obtained from the strander-canter were relatively higher than those normally produced by a chipper-canter (Cáceres *et al*. 2015, 2016). This is due to the different cutting modes used by the two processes. As mentioned before, chipper-canter pulp chips are principally produced by parallel splitting once knives cut the wood obliquely to the grain. In contrast, the strands in this study were mainly obtained by a 0 to 90° cutting action, where the edge knife is oriented along the grain and the cutting direction is perpendicular to the grain. Moreover, because knives are arranged to obtain relatively thin strands (0.9 mm), this thickness also favored the production of more fines and pin chips.



(a) (b)

Fig. 5. Effects of counter-knife angle and counter-knife distance on fines, pin chips, and strand proportions for (a) frozen wood (-13.4 °C) and (b) unfrozen wood (18.6 °C)

The formation of fines and pin chips was studied by high-speed video images (Fig. 6). The analysis showed that the fines and pin chips were mainly produced under three situations: (1) with the knives cutting the external parts of the log (Fig. 6a), (2) during the strand width formation (Fig. 6b), and (3) by the scoring tip of the knife (Fig. 6c). Thus, knives cutting at the log surfaces only cut small portions of wood due to the natural shape and irregularities of logs (Fig. 6a). This barely generated fines and pin chips. The number of fines and pin chips produced at this stage may depend on the quality of logs after debarking, surface MC, and the log diameter and taper. As the cutting width increased, the number of strands produced increased. At this stage, fines and pin chips were produced when the thin slice broke along the grain to be separated into strands (Fig. 6b). Simultaneously, the scoring edge of the knife cut the wood by shearing across the grain at the end of the cutting path, also generating fines and pin chips (Fig. 6c). As discussed later, these three cutting situations could also reduce the length of strands.

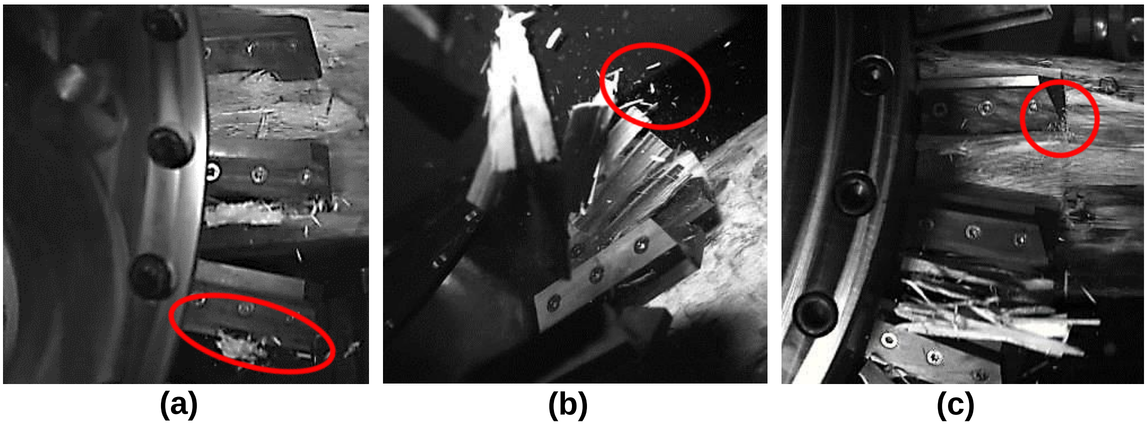

(a) (b) (c)

Fig. 6. Fines production: (a) cuts corresponding to the external parts of the log, (b) at strand width formation, and (c) at the scoring edge of the knife

The covariates knots, MC, and cutting volume also had significant effects on the production of fines and pin chips, while SG only significantly affected the amount of pin chips (Table 3). Wood zones with grain deviations around the knots were prone to produce higher fines and pin chip volumes. The effect of moisture content on fines and pin chip proportions depended on wood condition. Higher MCs will increase the ice volume inside the wood under frozen conditions, making it more brittle, producing more small particles. Wood with higher SG represents more material. Therefore it was more resistant to failure and resulted in fewer small particles. The experiment’s cutting volume was associated with the variation in log diameter within and among logs as the cutting width was kept constant at 20 mm. Higher cutting volumes corresponded thus to higher cutting heights. As a result, larger strand sheets had more possibilities to make strands instead of small particles.

Strand Width

Means of the strand width were below 20 mm for all stranding conditions. The ANCOVA showed that the strand width was significantly affected by WT, CKA, CKD, and the interaction between CKD and CKA (Table 5). The wood temperature on strand width was the most important factor observed from the F and eta squared values. The eta squared indicated that 55% of the variation in strand width was accounted for by wood temperature, followed by the counter-knife angle, which contributed to about 25% of the variation in strand width. The interaction between CKD and CKA on strand width was relatively small, contributing to only 3.3%.

Table 5. F-values and Eta Squared Obtained from the ANOVAs for Strand Width

Source of Variation	F Values	Eta Squared
MC	5.2*	0.003
SG	11.2***	0.006
CV	78.3***	0.043
CKA	116.2***	0.254
CKD	7.3***	0.008
WT	1014.5***	0.551
CKD x CKA	7.7***	0.033
CKD x WT	1.4^{ns}	0.001

***statistically significant at 0.001 probability level; **statistically significant at 0.01 probability level; *statistically significant at 0.05 probability level; ns not statistically significant

As indicated before, the effect of temperature can be explained by the nature of wood when exposed to freezing conditions. The strand width was 9.4 mm for frozen wood and 15.7 mm for unfrozen wood (nine stranding conditions pooled). Frozen wood becomes more brittle and stiffer and, as a consequence, prone to fracture when being cut, which generates narrower strands (Gaete-Martinez *et al*. 2008). The increase in brittleness is predominantly due to the reinforcing effect of the ice formation in the wood cell, the stiffening of the wood cell itself, and the increase of cohesive force caused by thermal contraction (Koran 1979; Green *et al*. 1999; Jiang *et al*. 2014). The covariable moisture content, especially above the fiber saturation point (FSP), also played an important role in strand formation under frozen conditions (Table 5). Higher MC generates greater reinforcement of frozen wood (Hernández *et al*. 2014), producing narrower strands. Conversely, unfrozen green wood becomes softer and more pliable as temperature increases (Xing *et al*. 2017). This means that when the strand-sheet is passing through the counter-knife, it tends to support more bending stresses before fracturing, which results in wider strands.

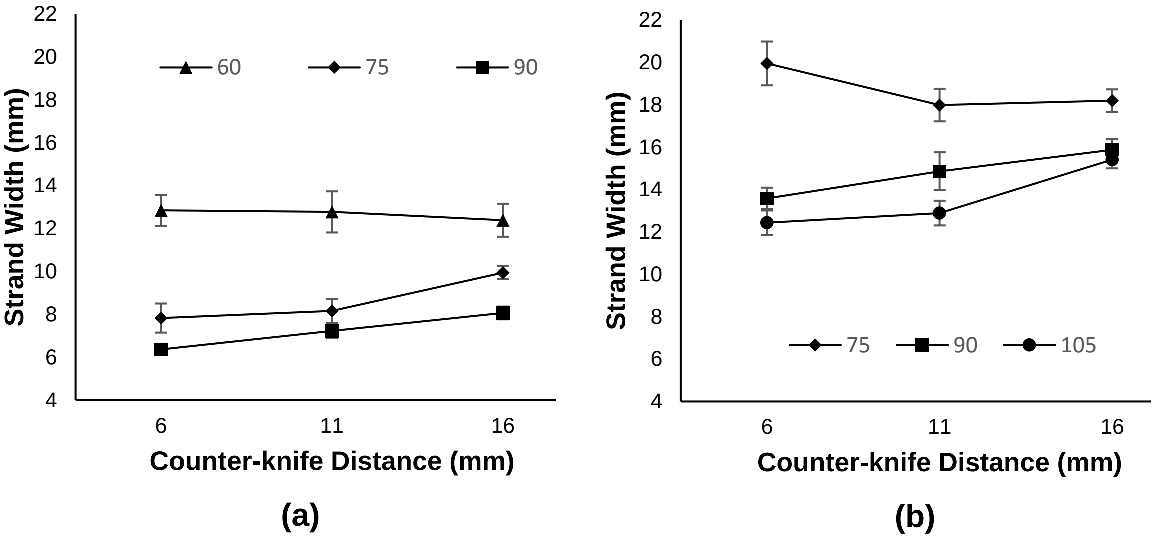


Fig. 7. Strand width (mm) as a function of counter-knife angle and counter knife distance for (a) frozen wood and (b) unfrozen wood. Each point represents a mean of 15 replicates of logs (a total of 1500 strands)

The main role of counter-knife is to further bend the strand-sheet, which will cause new fractures and complete those already initiated by the knife edge. As the counter-knife angle increased, transverse bending of the strand-sheet increased, and the frequency of fractures increased, which reduced the mean strand width (Fig. 7). The multiple comparisons tests showed that CKAs of 60° and 75° led to the largest strands for the frozen and unfrozen wood, respectively. At these values of CKA, the effect of distance between the knife edge and the counter-knife edge was not statistically significant (Table 4). Therefore, the mean values of the three distances studied for each CKA were pooled. The resulting average widths of strands were 12.7 mm for frozen wood (60° CKA) and 18.7 mm for unfrozen wood (75° CKA). As mentioned before, the practical width strand requirements of the OSB mills ranges between 13 and 25 mm (Geimer and Price 1978; Van *et al*. 2019). Therefore, mean values of width obtained were virtually within the practical range required by the OSB mills. However, the dimensions of strands in the present work were obtained directly after stranding. Strands width at the source can be further reduced during the subsequent steps of OSB manufacturing (kiln drying, transport, gluing, pressing, *etc*.). For this, wider strands should be aimed for as a means to compensate for refragmentation due to handling during subsequent panel fabrication steps. Results from Fig. 7 suggest that lower CKAs than those studied should lead to wider strands. Further experiments considering these parameters should be conducted to better optimize the CKA with respect to the strand width.

The ANCOVA also showed that the specific gravity and cutting volume had an effect on the strand width. Denser logs have more material, which makes the wood more resistant to fracture by transverse bending. Higher cutting volumes were due to higher cutting heights. This resulted in larger strand sheets with more possibilities to make strands instead of small particles.

Strand Length and Thickness

The nominal length of strands, given by the feed per knife of the strander-canter, was 102 mm. The mean lengths obtained ranged between 88 and 101 mm, depending on the stranding conditions. Strands produced from frozen wood were shorter (overall mean of 94 mm) than unfrozen wood (overall mean of 99 mm). This decrease in length resulted from the production of fines and pin chips during fragmentation of the strand sheet. Therefore, as fines and pin chips increased, the strand length was negatively affected by the increase of fractures, particularly those produced by the scoring tip of the knives (Fig. 6c). As a result, length was better maintained for the selected CKAs, with 97 mm for frozen wood (means of three conditions at 60° CKA pooled) and 100 mm for unfrozen wood (means of three conditions at 75° CKA pooled).

On the other hand, the nominal thickness of strands was set using the radial offset between two consecutive knife edges, which corresponded to 0.9 mm. Thus, the counter-knife did not directly affect strand thickness. Strands produced from frozen wood were slightly thinner (overall mean of 0.96 mm) than unfrozen wood (overall mean of 0.99 mm). Differences between the nominal and the actual strand thicknesses can be explained by the stress relaxing during cutting, in which both the workpiece and chip experience spring-back to some extent (Hoadley 2000; Thibaut *et al*. 2016). It is known that frozen wood has less elastic recovery or spring-back, as it is more rigid and brittle (Meulenberg *et al*. 2021). Because of these different behaviors, lower side clearances on circular saws are suggested during winter periods (Lunstrum 1985; Meulenberg *et al*. 2021). The less elastic recovery or spring-back for frozen wood could explain their thinner strands than those produced from unfrozen wood.

Vibrations during cutting could also play a role in length and thickness variations. The higher cutting energy required for frozen wood should provoke more vibration during stranding. Length and thickness were measured in 100 strands per replicate (15 replicates per stranding condition). Thus, the coefficients of variation (CoV) of these replicates for strand length and thickness were greater for frozen wood (average CoV = 15% and 28%, respectively) than for unfrozen wood (average CoV=9% and 13%, respectively). The stranding was, therefore, more homogeneous with unfrozen logs. Nevertheless, this variation in thickness and length between strands in each cut, particularly for unfrozen wood, was under the same range as reported by other studies (Nishimura *et al*. 2004; Han *et al*. 2006; Beck *et al*. 2009; Xing *et al*. 2017). This also indicates that the cutterhead of the strander-canter had a good performance in controlling strand length and thickness.

Finally, the prototype of cutterhead tested for primary log breakdown showed good behavior for strand production. Thus, its utilization can be a solution for the problem of pulp chips' overproduction in the Canadian sawmills. In line with that, strands produced can be used as an alternative by-product that will contribute to the sawmill's revenue.

CONCLUSIONS

1. A prototype of cutterhead used for primary log breakdown showed good feasibility for strand production. The design of the counter-knife was in particular studied for stranding Jack pine logs.
2. The results showed that the counter-knife angle and wood temperature affected the proportion of strands, fines, and pin chips, as well as the width of strands. The setting of the machine controlled the length and thickness of strands relatively well. The low variation observed was directly related to the production of fines and pin chips. The wood temperature was the main factor that affected the proportion of strands, fines, pin chips, and the strand width, followed by the counter-knife angle. The effect of the distance between the edge knife and edge counter-knife was only significant when the angle of the counter-knife was too high and not appropriate.
3. The best performance of the prototype was obtained with a counter-knife angle of 60° for frozen wood (-13.4 °C) and 75° for unfrozen wood (18.6 °C). These angles produced the highest strand proportions, the lowest volumes of small particles, and the wider strands.

ACKNOWLEDGMENTS

Funding for this project was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by DK-SPEC Inc. The authors are grateful for the support of Rentry Augusti Nurbaity, Jacob Bédard, Pierre-Olivier Gélinas, Remi Vande-Weghe, Jonathan Guérard-Poirier, Philippe Riel, Henri Lecrosnier, Renaud Drissen-Robert, and Gabriel Poulin during the laboratory experiments. The authors also thank Marius Sirbu, Daniel Bourgault, Félix Pedneault, Paul Desaulniers, Luc Germain, and Jean Ouellet for their technical assistance.

REFERENCES CITED

Aitchison, J. (1982). "The statistical-analysis of compositional data," *J. Royal Stat. Soc. Ser. B-Met.* 44(2), 139-177. DOI: 10.1111/j.2517-6161.1982.tb01195.x

Banerjee, S., Hooda, U., and Conners, T. E. (2007). "Temperature effects on fines generation during wood flaking," *Appita J.* 60(6), 482-484.

Barnes, D. (2000). "An integrated model of the effect of processing parameters on the strength properties of oriented strand wood products," *Forest Prod. J.* 50(11), 33-42.

Beck, K., Cloutier, A., Salenikovich, A., and Beauregard, R. (2009). "Effect of strand geometry and wood species on strandboard mechanical properties," *Wood Fiber Sci.*

41(3), 267-278.

Cáceres, C. B., Hernández, R. E., and Koubaa A. (2015). "Effects of 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. DOI: 10.1007/s00107-015-0894-0

Cáceres, C. B., Hernández, R. E., and Koubaa A. (2016). "Effects of log position in the stem and cutting width on size distribution of black spruce chips produced by a chipper-canter," *Wood Fiber Sci.* 48(1), 25-42.

Cafferata, A. (2003). *The Effect of Fines on Oriented Strandboard Bending Properties*, Master's Thesis, The University of British Columbia, Vancouver, BC, Canada.

Chen, S., Du, C., and Wellwood, R. (2008). "Analysis of strand characteristics and alignment of commercial OSB panels," *Forest Prod. J.* 58(6), 94-98.

Dai, C., Yu, C., and Zhou, X. (2005). "Heat and mass transfer in wood composite panels during hot pressing. Part II. Modeling void formation and mat permeability," *Wood Fiber Sci.* 37(2), 242-257.

Dai, C., Yu, C., and Zhou, C. (2007). "Theoretical modeling of bonding characteristics and performance of wood composites. Part I. Inter-element contact," *Wood Fiber Sci.* 39(1), 48-55.

Dai, C., Yu, C., and Jin, J. (2008). "Theoretical modeling of bonding characteristics and performance of wood composites. Part IV. Internal bond strength," *Wood Fiber Sci.* 40(2), 146-160.

Fakhri, H. (2005). *Measurement and Modeling of the Effect of Fines Content on the Transverse Permeability of Oriented Strand Board (OSB)*, Master's Thesis, The University of British Columbia, Vancouver, BC, Canada. DOI: 10.14288/1.0075068

Fakhri, H. R., Semple, K. E., and Smith, G. D. (2006). "Permeability of OSB. Part 1. The influence of core fines content and mat density on transverse permeability," *Wood Fiber Sci.* 38(3), 450-462.

Feng, M. W., and Knudson, R. M. (2007). "Effect of log rehydration on quality of OSB strands manufactured from beetle-killed lodgepole pine," *Forest Prod. J.* 57(1-2), 35-42.

Food and Agriculture Organization of the United Nations (FAO) (1976). *Wood Chips-Production, Handling, Transport* (2nd ed.), FAO, Rome, Italy, pp. 1-136.

Gaete-Martinez, V., Shaler, S. M., Edgar, R., and Hill, J. (2008). "Effect of strand geometrical distribution (SGD) in oriented strand composite (OSC) formation quality," in: *Proceedings of the 51st International Convention of Society of Wood Science and Technology*, Concepción, Chile, paper WS-62, pp. 1-10.

Gardner Pinfold Consultants (2019). *Economic Impacts of Northern Pulp Nova Scotia* (2019 Report), Gardner Pinfold Consultants Inc., Sackville, NB, Canada.

Geimer, R. L., and Price, E. W. (1978). *Construction Variables Considered in Fabrication of a Structural Flakeboard* (Report WO-5), U.S. Department of Agriculture, Forest Products Laboratory, Madison, WI, USA.

Ghafghazi, S., Lochhead, K., Mathey, A., Forsell, N., Leduc, S., Mabee, W., and Bull, G. (2017). "Estimating mill residue surplus in Canada: A spatial forest fiber cascade modeling approach," *Forest Prod. J.* 67(3-4), 205-218. DOI: 10.13073/FPJ-D-16-00031

Gouvernement du Québec. (2016). *Competitiveness in the Québec Forest Industry*, (Budget Report 2016-2017), Quebec City, Quebec, Canada.

Green, D. W., Evans, J. W., Logan, J. D., and Nelson, W. J. (1999). "Adjusting modulus of elasticity of lumber for changes in temperature," *Forest Prod. J.* 49(10), 82-94.

Han, G., Wu, Q., and Lu, J. Z. (2006). "Selected properties of wood strand and oriented strandboard from small-diameter southern pine trees," *Wood Fiber Sci*. 38(4), 621-632.

Han, G., Wu, Q., and Lu, J. Z. (2007). "The influence of fines content and panel density on properties of mixed hardwood oriented strandboard," *Wood Fiber Sci*. 39(1), 2-15.

Hernández, R. E., and Boulanger, J. (1997). "Effect 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, R. E., and Lessard, J. (1997). "Effect of 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, R. E., and Quirion, B. (1995). "Effect 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.

Hernández, R. E., Passarini, L., and Koubaa, A. (2014). "Effects of temperature and moisture content on selected wood mechanical properties involved in the chipping process," *Wood Sci. Technol.* 48(6), 1281-1301. DOI: 10.1007/s00226-014-0673-9

Hoadley, R. B. (2000). *Understanding Wood: A Craftsman's Guide to Wood Technology*, Taunton Press, Newtown, CT, USA.

Iswanto, A. H., Febrianto, F., Wahyudi, I., Hwang, W., Lee, S. H., Kwon, J. H., Kwon, S., Kim, N., and Kondo, T. (2010). "Effect of pre-treatment techniques on physical, mechanical, and durability properties of oriented strand board made from sentang wood (*Melia excelsa* Jack)," *J. Fac. Agr.* 55(2), 371-377. DOI: 10.5109/18854

Jessome, A. P. (2000). *Strength and Related Properties of Woods Grown in Canada*, Forintek Canada Corp, Québec, Canada.

Jiang, J., Lu, J., Zhou, Y., Zhao, Y., and Zhao, L. (2014). "Compression strength and modulus of elasticity parallel to the grain of oak wood at ultra-low and high temperature," *BioResources* 9(2), 3571-3579. DOI: 10.15376/biores.9.2.3571-3579

Jin, J., Chen, S., and Wellwood, R. (2016). "Oriented strand board: Opportunities and potential products in China," *BioResources* 11(4), 10585-10603. DOI: 10.15376/biores.11.4.Jin

Koran, Z. (1979). "Tensile properties of spruce under different conditions," *Wood and Fiber* 11(1), 38-49.

Kruse, K., Dai, C., and Pielash, A. (2000). "An analysis of strand and horizontal density distributions in oriented strand board (OSB)," *Holz als Roh- und Werkstoff* 58(4), 270-277. DOI: 10.1007/s001070050424

Lau, K., MacDonald, R., Loth, R., Marshall, K., Woodbridge, P., and Lam, F. (2007). *Conversion of MPB Sawmill Residuals to Flakes for OSB* (Report MDP-07-041), University of British Columbia-Ainsworth, Vancouver, BC, Canada.

Leney, L. (1960). *Mechanism of Veneer Formation at Cellular Level* (Research Bulletin 744), University of Missouri, Columbia, MO, USA.

Liu, C., Ruel, J., Groot, A., and Zhang, S. Y. (2009). "Model development for lumber volume recovery of natural balsam fir trees in Quebec, Canada," *The Forestry Chronicle* 85(6), 870-877. DOI: 10.5558/tfc85870-6

Lunstrum, S. J. (1985). *Balanced saw performance* (Report No. 12), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI, USA.

Malanit, P., Kyokong, B., and Laemsak, N. (2005). "Oriented strand lumber from rubberwood residues," *Walailak J. Sci. Tech.* 2(2), 115-125.

Meulenberg, V., Ekevad, M., and Svensson, M. (2021). "Thin kerf cutting forces of frozen and non-frozen Norway spruce and Scots pine wood," *Wood Mat. Sci. Eng.* DOI: 10.1080/17480272.2021.1925964

Mirski, R., Derkowski, A., and Dziurka, D. (2019). "Influence of strand size, board density, and adhesive type on characteristics of oriented strand lumber boards manufactured from pine strands," *BioResources* 14(3), 6686-6696. DOI:

10.15376/biores.14.3.6686-6696

Nagubadi, V., and Zhang, D. (2006). "Production structure and input substitution in Canadian sawmill and wood preservation industry," *Can. J. Forest. Res.* 36(11), 3007-3014. DOI: 10.1139/x06-187

Natural Resources Canada (NRCAN) (2019). "How does the forest sector contribute to Canada's economy? Indicator: Production of forest products," (https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/state-canadas-forests-report/how-does-forest-sector-contribut/indicator-production/16410), Accessed 24 December 2020.

Natural Resources Canada (NRCAN). (2020). "State of Canada's forests report," (https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/state-canadas-forests-report/16496), Accessed 22 January 2021.

Nishimura, T., Amin, J., and Ansell, M. P. (2004). "Image analysis and bending properties of model OSB panels as a function of strand distribution, shape and size," *Wood Sci. Technol.* 38(4), 297-309. DOI: 10.1007/s00226-003-0219-z

Price, E. W., and Lehmann, W. F. (1979). "Flakeboard properties as affected by flake cutting techniques," *Forest Prod. J.* 29(3), 29-33.

Salmon, D. (2018). *Ressources et Industries Forestières du Québec: Portrait Statistique.* (Ed. 2017) [*Forest Resources and Industries of Quebec: Statistical Portrait*], Ministère des Forêts, de la Faune et des Parcs, Québec, Canada.

Spelter, H., and Alderman, M. (2005). *Profile 2005: Softwood Sawmills in the United States and Canada* (FPL-RP-630), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI, USA. DOI: 10.2737/FPL-RP-630

Spelter, H., McKeever, D., and Alderman, M. (2006). *Status and Trends: Profile of Structural Panels in the United States and Canada* (FPL-RP-636), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI, USA. DOI: 10.2737/FPL-RP-636

Spelter, H., Wang, R., and Ince, P. (1996). *Economics Feasibility of Products from Inland West Small-diameter Timber* (FPL-GLTR-92), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI, USA. DOI: 10.2737/FPL-GTR-92

Stiglbauer, P., Conners, T., and Banerjee, S. (2006). "Influence of knife angle and ambient temperature on fines generation from flakers," *Forest Prod. J.* 56(10), 86-89.

Tabachnick BG, Fidell LS. (2006). *Using Multivariate Statistics.* Allyn and Bacon, Boston, USA.

Thibaut, B., Denaud, L., Collet, R., Marchal, R., Beauchêne, J., Mothe, F., Méausoone, P., Martin, P., Larricq, P., and Eyma, F. (2016). "Wood machining with a focus on French research in the last 50 years," *Ann. For. Sci.* 73(1), 163-184. DOI: 10.1007/s13595-015-0460-2

United Nations Economic Commission for Europe/Food and Agriculture Organization of the United Nations (UNECE/FAO) (2010). *Forest Product Conversion Factors for the UNECE Region* (ECE/TIM/DP49), UNECE/FAO, Geneva, Switzerland.

Van, T. P., Schöpper, C., Klüppel, A., and Mai, C. (2019). "Effect of wood and panel density on the properties of lightweight strand boards," *Wood Mat. Sci. Eng.* 16(4), 237-245. DOI: 10.1080/17480272.2019.1705906

Wan-Mohd-Nazri, W., Kasim, J., Sudin, R., Yuziah, M. N., and Abdul-Hamid, H. (2011). "Strand properties of *Leucaena leucocephala* (Lam.) de wit wood," *Afr. J. Agr. Res.* 6(22), 5181-5191. DOI: 10.5897/AJAR11.514

Xing, C., Matuana, L. M., and Dawson-Andoh, B. E. (2017). "Effect of processing parameters on the quality of red oak flakes," *Int. Wood Prod. J.* 8(3), 139-143. DOI: 10.1080/20426445.2017.1331537

Zhang, D., and Nagubadi, V. (2006). "Total factor productivity growth in the sawmill and wood preservation industry in the United States and Canada: A comparative study," *Forest Sci*. 52(5), 511-521. DOI: 10.1093/forestscience/52.5.511

Zhang, S. Y. T., and Koubaa, A. (2008). *Softwoods in Eastern Canada: Their Silvics, Characteristics, Manufacturing and End-uses* (SP-526E), FPInnovations, Quebec, Canada.

Article submitted: October 1, 2021; Peer review completed: November 20, 2021; Revised version received and accepted: March 17, 2022; Published: March 22, 2022.
DOI: 10.15376/biores.17.2.2632-2651