SAWING PATTERNS FOR THE BREAKDOWN OF *Pinus caribaea* var. *caribaea* WOOD ON PORTABLE SAWMILLS

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Resumo

Modelos de corte para o desdobro da madeira de Pinus caribaea var. caribaea *em serraria portátil.* O objetivo foi avaliar o efeito de modelos de corte no rendimento, consumo energético e qualidade de superfície da madeira serrada de *Pinus caribaea* var. *caribaea* em serraria portátil. Foram avaliadas toras com diâmetro médio de 29 cm, comprimento de 3 m e idade de 46 anos. Utilizou-se um modelo de corte específico para a produção de blocos e tábuas e outro para semiblocos, com a necessidade da operação de refilo. Após a mensuração do volume das toras e tábuas, pela relação dessas variáveis calculou-se o rendimento em madeira serrada (RMS). O consumo energético no desdobro foi mensurado pela corrente elétrica e tempo de execução dos cortes. A qualidade de superfície foi avaliada pelo método de microesferas de vidro, seguindo norma técnica. O RMS variou de 48 a 53%, sendo considerado satisfatório. O RMS e consumo energético foram inferiores no modelo de corte para blocos, enquanto a qualidade de superfície das tábuas foi independente dos modelos, sendo classificada como de textura fina a muita fina. O consumo energético e a qualidade de superfície das tábuas não variaram com a posição do diâmetro das toras em que foram realizados os cortes. Embora o modelo de corte para blocos apresente menor RMS, o menor consumo de energia associado a ausência de operações em máquinas refiladeiras, pode torná-lo mais atrativo para o pequeno produtor de madeira serrada. Mas, essa decisão deve ser tomada juntamente com uma análise econômica e ponderando o valor de mercado da madeira a ser processada.
Palavras-chave: serrarias, métodos de desdobro, serra de fita horizontal, rendimento, consumo energético, microesferas de vidro.

Abstract

The aim was to assess the effect of sawing patterns on lumber yield, energy consumption, and surface quality of *Pinus caribaea var. caribaea* wood sawn on a portable sawmill. The logs had an average diameter of 29 cm, length of 3 m, and age of 46 years. A specific sawing pattern was used for the production of cants and boards and another for two-sided cants, obtained after a subsequent edging operation. Log and board volumes were determined, and the ratio of these variables was used to calculate the lumber yield. The amount of energy used during breakdown was determined by measuring the electric current applied and time of execution of the process. Surface quality was assessed by the glass microsphere method, according to technical standards. Lumber yield ranged from 48 to 53%, considered satisfactory. Lumber yield and energy consumption were lower with the cant sawing pattern. Board surface quality was not influenced by sawing pattern, with all boards having fine to very fine surface textures. Energy consumption and board surface quality were not influenced by cutting position. Although the cant sawing pattern provided a lower lumber yield, the energy savings associated with the absence of edging operations may make it attractive for small lumber producers. However, this decision should be based on an economic analysis and take into account the market value of the wood to be processed.
Keywords: sawmills, breakdown methods, horizontal band saw, yield, energy consumption, glass microspheres.

INTRODUCTION

At sawmills, log breakdown is the first industrial processing operation for the manufacture of solid wood products as well as the first value-adding step. However, log processing is a complex activity affected by the heterogeneity and anisotropic characteristics of the raw material (MELO *et al*., 2016), which in turn influence process energy consumption and product quality.

The amount of energy used during wood processing may vary according to wood type, technology level, and geographical location of enterprises. Fossil fuels, electricity, and wood residues are the most common energy sources, whereas solar and wind energy systems are not widely used. Energy consumption and sources used by the wood industry have a direct impact on production costs (MONTEIRO *et al.*, 2017). Despite the importance of this topic, few studies have sought to optimize mechanical processes while taking into account energy balance and final product quality (THIBAUT *et al.*, 2016).

Surface homogeneity and textural characteristics are determinants of product quality and market value. Surface quality assessment methods typically involve determining the optimum feed per tooth on cutting tools or visual analysis after drying and planing (ANDRADE *et al*., 2016; SILVA *et al*., 2016; ANDRADE *et al*., 2018). However, the surface quality of wood obtained after log breakdown, popularly known as rough-sawn lumber, is a little-studied but important characteristic, as some lumber yards sell recently sawn lumber without finishing. Another fact that adds to the importance of lumber surface quality is the possibility to reduce losses in nominal dimensions and minimize the time and resources consumed in subsequent planing and sanding operations. In this scenario, glass microsphere-based methods may be of great value for measuring surface macrotexture in rough lumber.

Logs are traditionally processed on fixed-site sawmills, which require that logs be transported to factory facilities for breakdown. Stationary sawmills have several disadvantages: high acquisition and maintenance costs, raw material transportation costs, large structures, assembly particularities, and high energy consumption. Such characteristics might make it impossible for small-scale lumber producers to acquire fixed-site mills or perform breakdown operations.

Portable sawmills appear as an interesting alternative. Given their portability, these machines allow the breakdown of raw materials close to the logging site, reducing transportation costs (LOIOLA *et al.*, 2019). Additional advantages include easy assembly, easy maintenance, and low installation costs (JUIZO *et al*., 2014). It is also noteworthy that portable sawmills can be adapted to the most affordable energy source of each region, are easy to operate, and can execute different sawing patterns. The major challenge to their implementation is the lack of information on operational performance (e.g., lumber yield and efficiency), energy consumption, process parameters, and product quality (FITZGERALD; BAILLERES, 2014; JUIZO *et al*., 2014), as well as the need for ergonomic design interventions (MILÉO *et al*., 2019). Furthermore, there is limited information on the influence of different sawing patterns on operational performance, lumber yield, workability, and sawn wood quality. Starting from the hypothesis that an adequate sawing pattern can improve the yield and quality of sawmill products, this study aimed to investigate the effects of two sawing patterns on the lumber yield, energy consumption, and surface quality of pine wood sawn on a portable sawmill.

MATERIAL AND METHODS

Sampling procedures and log breakdown

This study used a load of logs from *Pinus caribaea* Morelet var. *caribaea* trees aged about 46 years harvested from the arboretum of the Federal University of Espírito Santo in Alegre, Espírito Santo State, Brazil (20°47′09″S 41°31′28″W). The site has no history of forest farming; tree cutting is performed exclusively for security and safety reasons related to surrounding buildings. Six representative logs were selected from the load. The average diameter was 29 cm and the average length 3.40 m. A 20 cm long section was trimmed from the ends of each log with a chainsaw to eliminate defects and excessively dry parts, obtaining pieces with a standard length of 3.00 m. Logs were scaled by the Smalian method to obtain the under-bark log volume (V_u), which was used in the calculation of lumber yield.

Breakdown was performed on a portable sawmill (model EF-8012, Ecoserra Cooperative) equipped with a horizontal band saw, an electric motor, a 508 mm band wheel, a saw blade (4000 × 32 × 1.1 mm, 182 teeth, 22 mm tooth pitch), and a support frame with a total length of 6000 mm and maximum cutting width of 700 mm. The cutting speed of the machine is 25.76 m s^{-1}.

Sawing patterns

A tangential cutting system was used, with two sawing patterns and three logs per pattern. Six boards (average dimensions of 30 × 180 × 3000 mm) were produced from each log. In the first sawing pattern (named cant sawing pattern, Figure 1A), the logs were positioned at the base of the portable sawmill and rotated counterclockwise three times for the removal of four outer edges, producing a cant that was subsequently cut into boards. In the second sawing pattern (hereafter referred to as two-sided cant sawing pattern, Figure 1B), the logs were rotated twice clockwise for the removal of three outer edges, affording a two-sided cant that was subjected to successive cuts. This sawing pattern produced boards with an untrimmed round edge (wane). Edging was performed using a circular table saw (model SCI-25, Invicta) with a maximum cutting height of 65 mm.

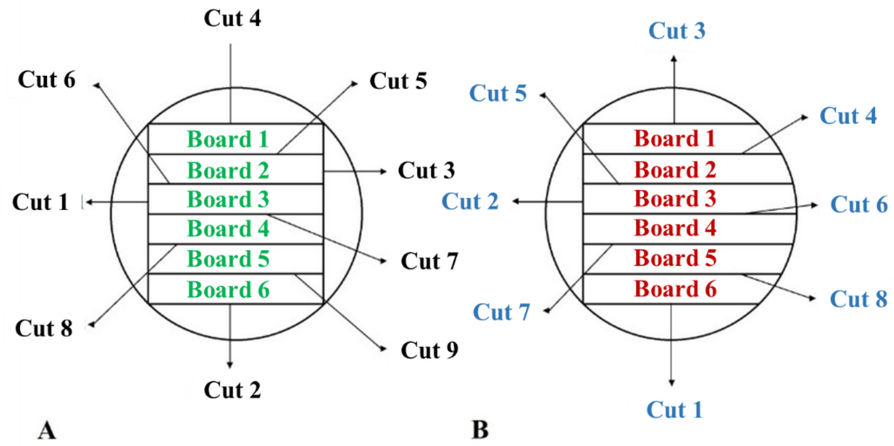

Figure 1. Breakdown of *Pinus caribaea* var. *caribaea* logs on a portable sawmill. Cutting sequences and board positions of (A) cant and (B) two-sided cant sawing patterns.

Figura 1. Desdobro das toras de *Pinus caribaea* var. *caribaea* em serraria portátil. Sequência de cortes e posição das tábuas no diâmetro das toras para os modelos de corte para (A) blocos e (B) semiblocos.

Energy consumption during breakdown

To estimate the amount of energy used for each sawing pattern, we measured the total cutting time (Figure 1A and B) using a digital stopwatch and the electric current using ammeter pliers connected to a distribution board. Energy consumption was calculated from Equation 1.

$$P = \frac{V \times I \times t}{3600} \quad (1)$$

where P is the electric power (Wh), V is the voltage (V), I is the current (A), t is the time of operation (s), and 3600 represents the conversion of seconds to hours.

The total energy consumed for each sawing pattern was then converted to 1 m^3 of log. Sawing was performed by a single operator to minimize variations in feed speed.

Lumber yield

After scaling, logs were broken down and each board was identified with numbers corresponding to the cutting position and log sample (Figure 1). Board dimensions were determined using a tape measure and used for the calculation of individual board volumes. The sum of the volume of all boards produced afforded the volume of sawn lumber per log, which was used in yield calculation, as shown in Equation 2.

$$Y = \left(\frac{V_s}{V_u}\right) \times 100 \quad (2)$$

where Y is the lumber yield (%), V_s is the volume of sawn lumber (m^3), and V_u the under-bark log volume (m^3).

Surface quality analysis

The surface quality of sawn lumber was assessed by the glass microsphere method. The test was performed on two points of each lumber. Points were located on the same face, 1500 mm apart from each other, as shown in Figure 2A. The results of the glass microsphere test were used to classify surface macrotexture according to the American Society for Testing and Materials (ASTM) E965-15 standard (ASTM, 2019). It is important to note that macrotexture is an indicator of wood surface quality.

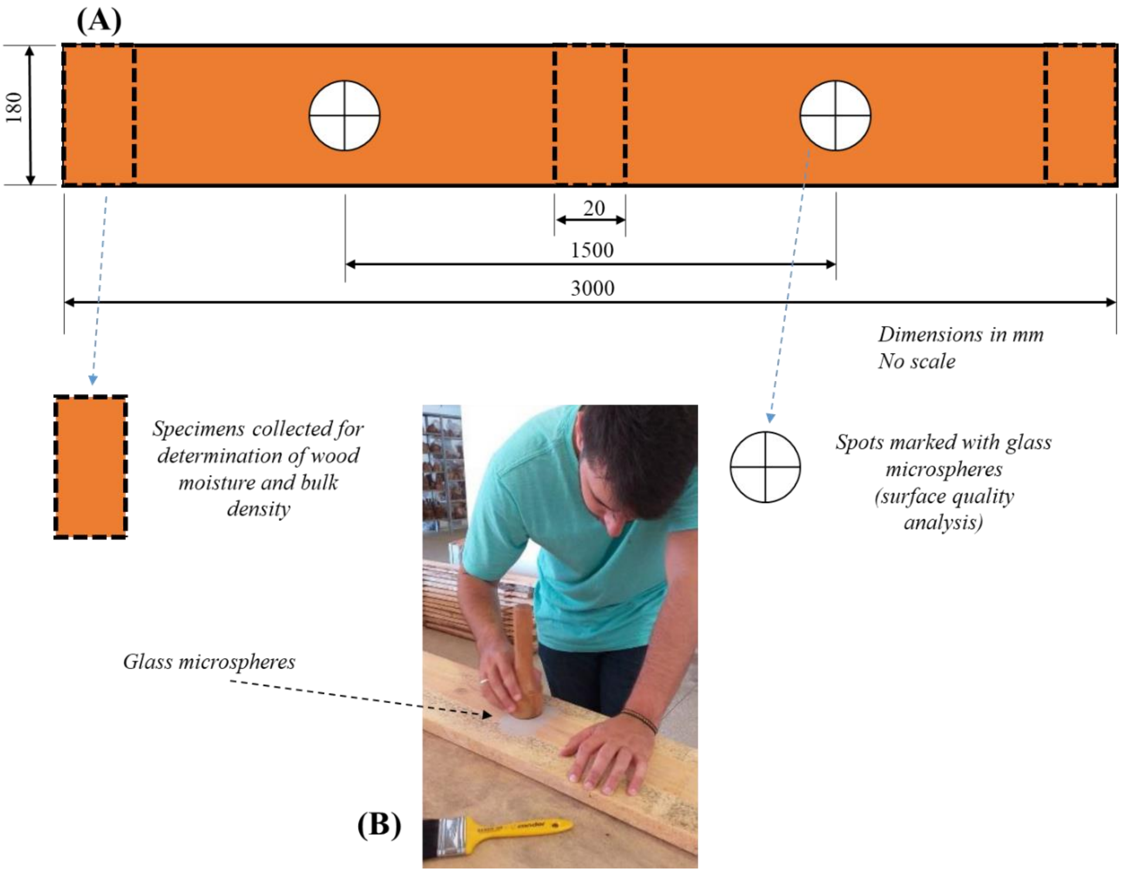

Figure 2. (A) Points used for surface quality assessment and specimen collection for determination of bulk density and moisture in boards of *Pinus caribaea* var. *caribaea* and (B) application of glass microspheres to the board surface.

Figura 2. (A) Posições de avaliação da qualidade de superfície e de retirada de corpos de prova para determinação da densidade aparente e umidade da madeira nas tábuas de *Pinus caribaea* var. *caribaea* e (B) espalhamento das microesferas de vidro na superfície das tábuas.

The method described by E965-15 (ASTM, 2019) was adopted, and the following materials were used:
(i) a brush for cleaning the board surface;
(ii) glass microspheres with a standardized particle size (90% was sieved through a 60-mesh sieve and retained in an 80-mesh sieve) and a sphericity degree of 90%;
(iii) a wooden tool with a round base (64 mm diameter) coated with rubber (1.5 mm thickness); and
(iv) a millimetric ruler for measuring the diameter of glass microsphere markings;

Briefly, the board surface was cleaned, and glass microspheres (3000 mm^3) were spread onto the surface in circular motions with the aid of the wooden tool (Figure 2B). The diameter of circular markings was measured, and Equations 3 and 4 were used to calculate the spot height.

$$A = \frac{\pi}{4}\left(\frac{D_1 + D_2}{2}\right)^2 \quad (3)$$

$$h = \frac{V}{A} \quad (4)$$

where A is the area of the circular spot marked with glass microspheres (mm^2), D_1 is the largest diameter of the circular marking (mm), D_2 is the diameter perpendicular to D_1 (mm), h is the spot height (mm), and V is the glass microsphere volume (mm^3).

Determination of wood bulk density and moisture content

The bulk density and moisture content of wood were determined to investigate their possible effects on energy consumption during sawing. For this purpose, samples sized 30 × 180 × 20 mm in thickness, width, and height, respectively, were taken from the end and middle sections of boards (Figure 2). Analyses were performed according to the NBR 7190 method (Brazilian Association of Technical Standards, ABNT, 1997).

Data analysis

Lumber yield, energy consumption, and marking height data were compared between sawing patterns using the analysis of variance (ANOVA) *F*-test test. ANOVA assumptions of data normality and variance homoscedasticity were previously confirmed by Shapiro–Wilk and Cochran tests, respectively. Differences in energy consumption and spot height between board positions along the log diameter were analyzed by the *F*-test. When significant, data were subjected to the Scott–Knott test for comparison of group means. The functional relationship of wood moisture and bulk density with energy consumption during breakdown was assessed by Pearson’s correlation analysis. The level of significance was set at 5% for all tests. Statistical analyses were performed using Sisvar software version 5.6.

RESULTS

Lumber yield, total energy consumption, and board surface quality according to sawing pattern

The two-sided cant sawing pattern afforded a higher lumber yield than the cant sawing pattern (Figure 3). However, no significant differences in total energy consumption or surface quality, as assessed by the spot height of glass microspheres, were observed between sawing patterns.

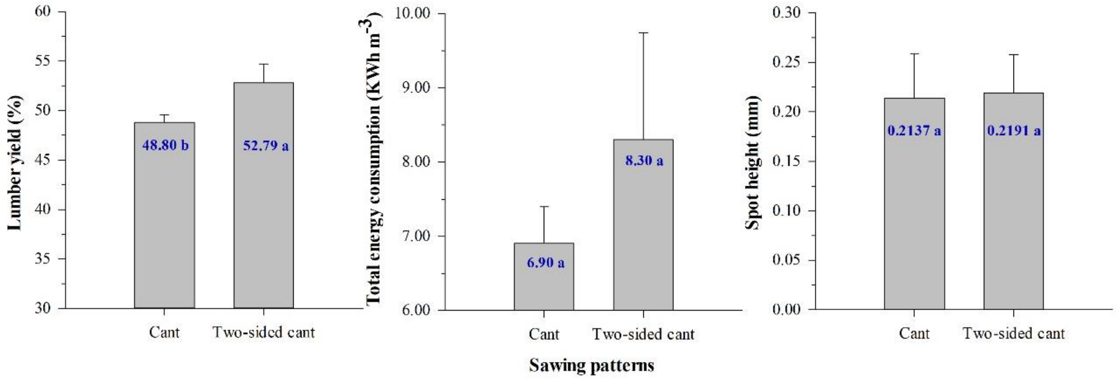

Figure 3. Lumber yield, total energy consumption, and spot height of glass microspheres on *Pinus caribaea* var. *caribaea* boards obtained using different sawing patterns on a portable sawmill.

Figura 3. Valores médios de rendimento em madeira serrada, consumo energético total da serraria portátil e altura da mancha de microesferas de vidro nas tábuas de *Pinus caribaea* var. *caribaea* por modelo de corte.

Energy consumption of each cutting operation

The mean energy consumption of the portable sawmill during each cutting operation (Figure 1) was similar between sawing pattens (Table 1). That is, regardless of whether *P. caribaea* var. *caribaea* logs were cut in the central or peripheral region, no significant differences in energy consumption were observed.

Table 1. Energy consumed by a portable sawmill during the breakdown of *Pinus caribaea* var. *caribaea* logs using different sawing patterns.

Tabela 1. Consumo energético pela serraria portátil na sequência de cortes em diferentes posições do diâmetro das toras de *Pinus caribaea* var. *caribaea* em cada modelo de corte.

Cutting operation	Energy consumption (kWh)	
	Cant sawing pattern	Two-sided cant sawing pattern
1	0.0993 ± 0.022 a	0.1148 ± 0.011 a
2	0.0856 ± 0.012 a	0.1102 ± 0.015 a
3	0.0842 ± 0.006 a	0.0780 ± 0.020 a
4	0.0796 ± 0.006 a	0.0791 ± 0.014 a
5	0.0887 ± 0.013 a	0.1000 ± 0.027 a
6	0.0797 ± 0.003 a	0.1128 ± 0.027 a
7	0.0838 ± 0.003 a	0.1093 ± 0.022 a
8	0.0846 ± 0.005 a	0.1108 ± 0.044 a
9	0.0916 ± 0.008 a	-

Values are presented as mean ± standard deviation. Means within a column followed by the same letter do not differ by the Scott–Knott test ($p > 0.05$).

Figure 4 shows the scatter plot of *P. caribaea* var. *caribaea* lumber moisture and bulk density against sawmill energy consumption. There was no significant relationship between moisture and energy consumption during breakdown, and the correlation coefficient was low. However, it was observed that the higher the bulk density, the higher the energy consumption, as indicated by the weak but significant correlation.

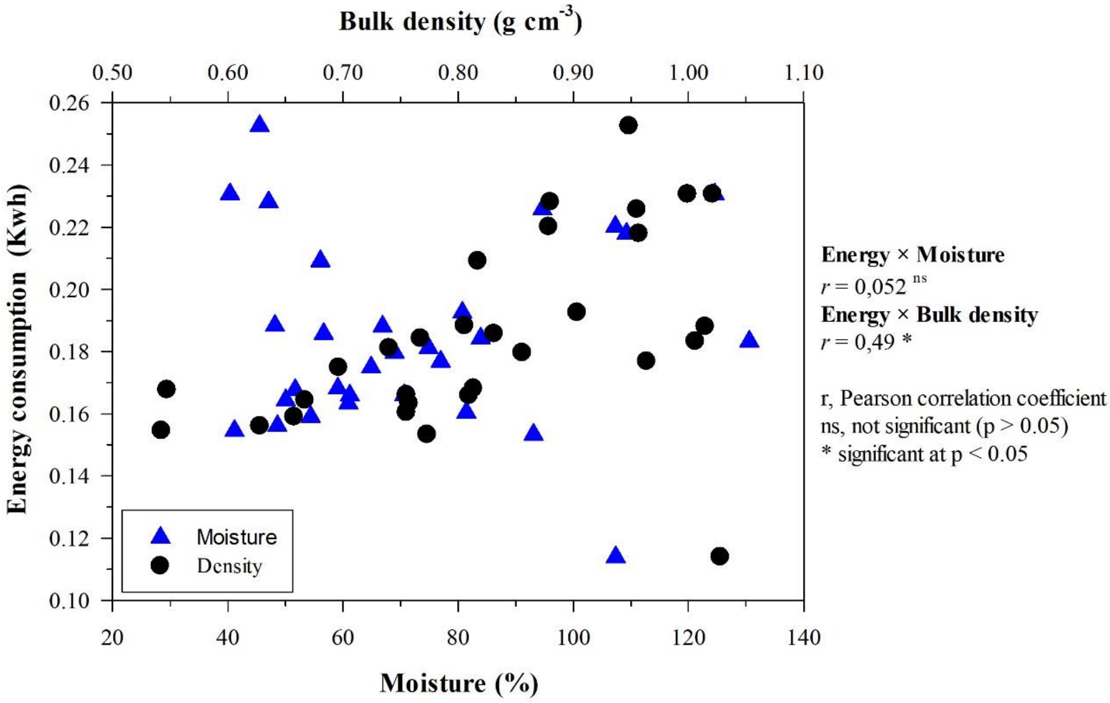

Figure 4. Scatterplot of portable sawmill energy consumption and the moisture and bulk density of *Pinus caribaea var. caribaea* lumber.

Figura 4. Dispersão dos valores de consumo energético durante o desdobro em serraria portátil e a umidade e densidade aparente da madeira de *Pinus caribaea var. caribaea*.

Lumber surface quality

The height of glass microsphere spots allows analyzing the surface quality of sawn lumber obtained by each cutting operation (Table 2). Regardless of the position of the cut along the log, no differences were observed between microsphere spot height, indicating that the surface quality of *P. caribaea* var. *caribaea* lumber was homogeneous.

Table 2. Mean values of glass microsphere spot height on *Pinus caribaea* var. *caribaea* boards obtained using different cutting operations and sawing patterns.

Tabela 2. Valores médios da altura das manchas de microesferas de vidro nas tábuas de *Pinus caribaea* var. *caribaea* provenientes de diferentes posições do diâmetro das toras em cada modelo de corte.

Cutting position	Glass microsphere spot height (mm)	
	Cant sawing pattern	Two-sided cant sawing pattern
1	0.2115 ± 0.05 a	0.2592 ± 0.05 a
2	0.2086 ± 0.07 a	0.2284 ± 0.06 a
3	0.2014 ± 0.03a	0.2165 ± 0.04 a
4	0.2053 ± 0.02 a	0.1992 ± 0.03 a
5	0.1980 ± 0.02 a	0.2031 ± 0.02 a
6	0.2572 ± 0.06 a	0.2078 ± 0.02 a

Values are presented as mean ± standard deviation. Means within a column followed by the same letter do not differ by the Scott–Knott test ($p > 0.05$).

DISCUSSION

Lumber yield, total energy consumption, and board surface quality according to sawing pattern

The effect of sawing pattern on *P. caribaea* var. *caribaea* lumber yield can be explained by the secondary log breakdown process used in the two-sided cant sawing pattern, namely edging. This procedure allows obtaining boards with a greater width, making better use of the optimal log volume for lumber production. In the cant sawing pattern, the decisions made by the operator to cut the four outer edges had a direct influence on the optimal lumber volume and, consequently, on the width of the boards produced. Edging did not negatively influence yield, as it basically consists in removing the external edges of sawn lumber.

It is possible to observe that, in addition to log quality and machinery characteristics, such as stability during cutting, thickness, and blade sharpness, the decisions made by the operator during log breakdown on a portable sawmill have a great influence on lumber yield. A significant influence of operator decision-making on sawn lumber production was also observed with the use of a stationary sawmill (MANHIÇA *et al.*, 2013) and chainsaw (BATISTA *et al.*, 2013).

The lumber yields of *P. caribaea* var. *caribaea* logs afforded by both sawing patterns were lower than the range considered normal for coniferous wood processed on a stationary sawmill (55–65%) (VITAL, 2008) but similar to yields normally obtained with small stationary sawmills. The yields observed in the current study were considered satisfactory for a portable sawmill, in view of the raw material used, lumber products obtained, and operational variables. Manhiça *et al.* (2012) processed *Pinus elliottii* logs of four diameter classes (24–33 cm) using a stationary sawmill and obtained a mean yield of 49.01–52.14%, similar to the values recorded in the present study. In both studies, the mean log diameter was approximately 29 cm.

A slightly higher yield (53.60%) was achieved in the breakdown of *Pinus taeda* logs of 18 to 44 cm in diameter (MURARA JÚNIOR *et al.*, 2013). Dobner Júnior *et al.* (2012) also obtained a higher yield (59.42%) in the breakdown of *P. taeda* logs of 20–57 cm in diameter. Such high yields can be attributed to the machinery used, operator skills, and log quality. Log diameter is an important factor, as logs with a larger diameter provide a greater volume of sawn wood per log, that is, a higher yield. Large-diameter logs have a large volume and a low outer edge height, resulting in a high useful volume.

Although not significant, the two-sided cant sawing pattern resulted in higher energy consumption (Figure 3). It should be noted that the energy consumed by the circular table saw was not considered. The increase in energy consumption may be associated with the cutting of outer edges with bark. Because of the thickness and density of the bark, combined with those of the wood, a greater cutting effort was required to breakdown wood fibers during processing. The lack of significant differences between sawing patterns can be attributed to the high variation in energy consumption afforded by the two-sided cant pattern, as evidenced by the high standard deviation values.

Monteiro *et al.* (2017) observed a higher energy use in the breakdown of 30 cm diameter *Eucalyptus grandis* logs on a vertical stationary band sawmill. Such a difference may be associated with wood density or the method used to estimate energy consumption. In stationary sawmills, the energy required to saw 1 m^3 of log also includes non-productive time, associated with pneumatic carriage movement, dimensioning, and guide regulation, operations that do not occur when using a portable sawmill. Log diameter can also markedly increase energy consumption during log processing. An increase of only one centimeter in log diameter led to an increase of 0.305 kWh in the amount of energy used by a sawmill (MONTEIRO *et al.*, 2017).

Sawing patterns did not significantly influence board surface quality. Surface quality was satisfactory: the macrotexture was classified as fine to very fine, according to the ASTM E965-15 standard (ASTM, 2019). The high quality of cuttings made by serrated blades of portable sawmills can result in a reduction in wood loss and planing and sanding requirements.

Portable sawmills are a more affordable alternative for small-scale lumber producers, as investments in stationary sawmills can be unfeasible in the case of low log volume, uneven supply, and limited workforce availability and skill level. Currently, this is the reality of African mahogany producers in Brazil, who process logs at a thinning age on portable sawmills, either due to the absence of stationary sawmills or the cost/benefit ratio of using a portable sawmill, given its workability and practicality, limited number of logs obtained by thinning, and lower workforce requirements.

Energy consumption during each cutting operation

Wood density and moisture directly influence energy consumption during sawing (MORADPOUR *et al.*, 2013). It is noteworthy that the density of wood increases from the pith to the bark in species such as *P. taeda* (MELO *et al*., 2015), *P. caribaea* (ADENAIYA; OGUNSANWO, 2016), and *P. patula* (RIOS *et al*., 2018). Despite the variability of physical properties with diameter, energy consumption was not altered by cutting along the pith–bark direction of *P. caribaea* logs. Other properties, such as grain angle, vessel/fiber ratio, and mechanical strength may also influence energy consumption.

The energy source used to breakdown pine logs was electricity. Apparent power was used to quantify energy expenditure, calculated as the sum of active and reactive power, to account for the total energy needed by the system. The main advantage of portable sawmills is the possibility of being transported and installed near the felling site. This allows for the use of other energy sources, such as fossil fuels, waste, and hydraulic and solar energy. The choice of energy source depends on technology level, product type, and location of log processing systems (MONTEIRO *et al.*, 2017). Studies are needed on the operational performance and energy consumption of portable sawmills run on different energy sources. Most studies investigating energy consumption during wood processing are focused on the machining of dried lumber (MELO *et al.*, 2015; 2016; NASCIMENTO *et al.*, 2017; MELO *et al.*, 2019). Few studies have been conducted to evaluate the energy consumption of portable sawmills.

Although previous research identified a relationship between wood moisture, density, and energy consumption during sawing (MORADPOUR *et al.*, 2013), in the present study, only density influenced energy expenditure (Figure 5), an effect also observed by Melo *et al.* (2016). The increase in energy consumption with wood density may be associated with a higher proportion of dense latewood near the bark, requiring a higher torque from the portable sawmill motor, thereby increasing energy consumption (MELO *et al.*, 2006). A greater force is required to cut through the fibers of dense wood because of the high cell wall thickness. In contrast to that observed for pine logs, Nascimento *et al.* (2017) found that moisture reduction (from 75 to 12%) in *Eucalyptus* and *Corymbia* wood afforded a 75% reduction in energy consumption.

Board surface quality

The surface macrotexture of lumber is classified as very thin when the height of glass microsphere spots is lower than 0.200 mm and thin when between 0.200 and 0.400 mm, according to ASTM E965-15 (ASTM, 2019). The surface quality of *P. caribaea* var. *caribaea* boards obtained by using a portable sawmill was acceptable, as 41.66% of the boards were classified as having a very thin macrotexture and 58.34% were classified as having a thin macrotexture.

Factors such as tree species, cutting pattern, and machinery have a significant impact on the surface quality of sawn lumber. However, the hypothesis that log cutting position has an effect on lumber surface quality in *P. caribaea* var. *caribaea* was not confirmed. The dimensions of xylem components vary during tree growth, particularly those of earlywood and latewood, which form growth rings, and juvenile and mature wood along the pith–bark direction (PANSHIN; de ZEEUW, 1980). Despite these anatomical differences, the surface quality of sawn lumber did not differ with cutting position.

The surface quality of machined dry wood is commonly assessed by a variety of texture evaluation methods, such as roughness and drag tests, visual evaluation according to ASTM D1666-11 (2011), feed per tooth, and, more recently, the Sunset laser technique, used to compare machined surfaces (ANDRADE *et al.*, 2016). Dry machined wood generally has a higher quality surface than rough sawn lumber; thus, these evaluation methods do not perform well for sawn lumber, and new techniques are needed. Application of glass microspheres to assess surface quality is a practical and inexpensive method that does not require additional equipment, such as a rough gauge. The method can be used in the field by small producers and joiners to evaluate lumber quality.

CONCLUSIONS

- Sawing models influenced lumber yield but had no effect on the total energy consumption of portable sawmills and the surface quality of *P. caribaea* var. *caribaea* boards.
- Wood heterogeneity along the pith–bark direction did not influence board surface quality or energy consumption, but a direct relationship was observed between bulk density and energy consumption.
- The cant sawing pattern is a potential alternative for small lumber producers who use portable sawmills, obviating the need for edging lumber on other machines. Nevertheless, the choice of sawing pattern must be made considering economic factors and the market value of logs.

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