Specific cutting energy of *Eucalyptus* wood with different densities

Energia específica de corte da madeira de *Eucalyptus* com diferentes densidades

Energía específica de corte de madera de *Eucalyptus* con diferentes densidades

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Abstract
The aim of the study was to evaluate how the specific cutting energy is influenced by the variation of the wood basic density in *Eucalyptus* spp. clones. Five clones, 10 years old, were used in the study: three hybrids of *Eucalyptus grandis* x *Eucalyptus urophylla*, one of *Eucalyptus grandis* and one of *Eucalyptus urophylla*. From each clone, five trees were cut down and divided into 2.0 m long logs. In two axial regions of the trunk (from 2.5 to 4.5 m and from 4.5 m to 6.5 m) the logs were cut into boards and reduced to specimens with dimensions of 660 x 110 x 21 mm. The basic density was determined by the hydrostatic method in two opposite wedges obtained from discs removed at 2.5, 4.5 and 6.5 m from the total height of the tree. To analyze the specific cutting energy, 10 specimens were selected for each axial region and clone. A frequency inverter was used to monitor the cutting process. Analysis of variance was applied to evaluate the specific cutting energy and the wood basic density. The results obtained appointed a significant difference between the woods of the clones for basic density and specific cutting energy. For the wood in the different axial regions, only the specific cutting energy was significant. Clone 1 required less specific cutting energy, as it was influenced by the lower basic density. In the 2.5 to 4.5 m axial region, a higher specific cutting energy was observed even with lower basic density.
Keywords: Mechanical processing; Lumber; Production engineering.

Resumo
O objetivo do estudo foi avaliar a influência da variação da densidade básica da madeira de clones de *Eucalyptus* na energia específica de corte. Utilizou-se cinco clones sendo três híbridos de *Eucalyptus grandis* x *Eucalyptus urophylla*, um de *Eucalyptus grandis* e um de *Eucalyptus urophylla*, com 10 anos. De cada clone foram derrubadas cinco árvores e traçadas em toras de 2,0 metros, em duas regiões axiais do tronco (2,5 a 4,5 m e 4,5 m a 6,5 m) que foram desdobradas em tábuas e depois reduzidas a corpos de prova com dimensões de 660 x 110 x 21 mm. A densidade básica foi determinada pelo método hidrostático em duas cunhas opostas obtidas nos discos retirados a 2,5; 4,5 e 6,5 m da altura total da árvore. Para a análise da energia específica de corte foram selecionados 10 corpos de prova para as regiões axiais e clones. O monitoramento dos cortes feito pelo inversor de frequência CW 08 (WEG). Foi feita a análise de variância para a energia específica de corte e para a densidade básica das madeiras. Os resultados obtidos apontaram diferenças significativas, a 5%, entre as madeiras dos clones para as densidades básicas e energia espefícia de corte. Para as madeiras nas diferentes regiões axiais, apenas a energia específica de corte se mostrou

significativa. O clone 1 exigiu menor energia específica de corte sendo influenciado pela menor densidade básica. Na região de 2,5 a 4,5 m, observou maior energia específica de corte mesmo apresentando menor densidade básica.
Palavras-chave: Processamento mecânico; Madeira serrada; Engenharia da produção.

Resumen
El objetivo del estudio fue evaluar la influencia de la variación de la densidad básica de la madera del clon *Eucalyptus* sobre la energía específica de corte. Se utilizaron cinco clones, tres híbridos de Eucalyptus grandis x Eucalyptus urophylla, uno de Eucalyptus grandis y uno de Eucalyptus urophylla, de 10 años de edad. De cada clon, se talaron cinco árboles y se trazaron sobre troncos de 2,0 metros, en dos regiones axiales del tronco (2,5 a 4,5 m y 4,5 m a 6,5 m), los cuales se partieron en tablas y luego se redujeron a especímenes con dimensiones de 660 x 110 x 21 mm. La densidad básica se determinó por el método hidrostático en dos cuñas opuestas obtenidas de los discos removidos a 2.5; 4,5 y 6,5 m de la altura total del árbol. Para el análisis de la energía específica de corte se seleccionaron 10 especímenes para las regiones axiales y clones. El monitoreo de los cortes realizados por el convertidor de frecuencia CW 08 (WEG). Se realizó análisis de varianza para la energía específica de corte y para la densidad básica de las maderas. Los resultados obtenidos mostraron diferencias significativas, al 5%, entre las maderas de los clones para las densidades básicas y energía específica de corte. Para las maderas en las diferentes regiones axiales, solo la energía específica de corte fue significativa. El clon 1 requirió menor energía específica de corte, siendo influenciado por la menor densidad básica. En la región de 2,5 a 4,5 m, se observó mayor energía específica de corte aún con menor densidad básica.
Palabras clave: Procesamiento mecánico; Tablas de madera; Ingeniería de producción.

1. Introduction

Knowledge the technological properties of a certain wood species is essential to obtain products with characteristics suitable for the intended use and to predict the wood behavior during its processing, as a way of guarantee the control of the entire process (Melo et al., 2016; Taques & Arruda, 2016).

The factors that influence the wood mechanical processing are related to both biological material and processing. Wood properties such as the presence of abrasive mineral deposits inside the cells, resin content, porosity, fiber dimensions, grain orientation, presence of knots, moisture content and density act as influencing factors on the energy expenditure during the material cutting process (Koch, 1964; Axelsson et al., 1993; Porankiewicz et al., 2008; Goli et al., 2009; Cristóvão et al., 2012; Chuchala et al., 2013; Delatorre et al., 2020). In addition to the factors inherent to the wood, cutting speed, feed speed and number of tooth in the tool can also influence the energy required for cutting (Gorczyca, 1987; Rodrigues & Coelho, 2007).

Beside the wood properties and the variables obtained in machinery and equipment, wood processing operations must be carried out in order to reduce tool wear, avoid damage or excessive destruction (Eyma et al., 2004; Carvalho et al., 2010; Souza et al., 2011; Andrade et al., 2019; Csanády et al., 2019; Paul et al., 2019). The purpose of these actions is to reduce maintenance costs and even frequency of replacement of the machines (Brown & Bethel, 1975). To avoid excessive wear of the machines, frequency inverters should be used, in order to control the variation in the rotation of electric motors and to avoid electrical instability of the motor, allowing the increase of torque at low speeds (WEG, 2008).

The specific cutting energy, is the energy required when cutting the wood, and must be evaluated to ensure that the machines are efficient in the mechanical processing, without energy waste. In addition, it avoids overloads that cause production interruption due to exceedance of the request limits of electromotive motors (Andrade et al., 2018; Guedes et al., 2020). The specific cutting energy required may vary according to the process parameters, such as cutting and feed speed, and also with the characteristics related to the raw material, which is of great interest when working with wood (Guedes et al., 2020). The required cutting forces are of great importance to project the cutting tool geometry and determine the power required by the machines that compound the mechanical processing units, such as a sawmill. These cutting forces vary according to the wood species, fibers direction and cutting direction, sharpening of the cutting tool, among other variables related to both the raw material and the cutting tool (Néri et al., 2000).

Due to the increase in environmental pressure caused by the felling of native species, the furniture market is replacing the use of wood from native forests with wood from planted forests, such as Eucalyptus. As a result, industries and processing companies are constantly adjusting their equipment and process parameters to suit the new species used in the timber market.

Due to the difficulty of processing and frequent presence of defects in *Eucalyptus* sawn wood, such as cracks and warping, genetic improvement has been used as an alternative to remedy these irregularities and further spread the use of this species. However, the desired objectives for the generation of improved material are not always achieved, and further studies are necessary to adapt the processing variables to the correct use of that species.

Thus, the specific energy of cutting appears as a possibility for the improvement of the mechanical processing of the wood of the genus Eucalyptus, contributing to an optimization of the process, reduction of production costs, and products with superior quality.

Considering the above, the study aimed to evaluate the influence of the basic density on the specific cutting energy required by the wood of five clones of Eucalyptus spp., which will be used for the production of furniture.

2. Methodology

The five clones used were developed by the company Arborgen Tecnologia Florestal and were located at an experimental planting in the city of Mogi Guaçu, State of São Paulo, on the premises of the company International Paper.

The collection of the material took into account the phytosanitary aspects of the trees, diameter at 1.30 m above the ground ($D_{1.30m}$) and shape of the trunk. Three hybrid clones of *Eucalytptus grandis* x *Eucalyptus urophylla* (clones 1, 3 and 5), one clone of *Eucalyptus urophylla* (clone 2) and one clone of *Eucalyptus grandis* (clone 4) were used. At the time of harvesting, all trees were 10 years old. Five trees were felled for each clone and the trunks were segmented into 2.0 m long logs. The segments used in this study were located at 2.5 m to 4.5 m (axial region 1) and at 4.5 m to 6.5 m (axial region 2), for each clone. During the felling of the trees, disks were removed at 2.5, 4.5 and 6.5 m in height, to determine the wood basic density, using the hydrostatic balance method, according to the NBR 11941 standard (Brazilian Association of Technical Standards 2003).

After the felling, the logs were split into boards, which were sent to the Federal University of Paraná (UFPR) in the city of Curitiba, where they were air-dried up to 20% moisture content. Thereafter, the boards were reduced to 660 mm in length and placed to dry in a Pilot Drying Chamber in the Wood Drying Laboratory at UFPR, until reaching a moisture content of 10%. After the drying, ten specimens from each axial region of each clone were selected, totaling 20 specimens per clone, and sent to the Federal University of Lavras (UFLA), in order to determine the specific cutting energy.

The mechanical processing of the wood was carried out on a planer with a head diameter of 105 mm, three new knives (without wear) and rotation of the tool holder axis fixed at 3500 min^{-1}. The planer also had a local exhaust ventilation system that favors the chip exit, allowing the effective measurement of the wood cutting process. The specimens, with dimensions of 660 x 110 x 21 mm (length, width, and thickness, respectively), were planed with a feed speed of 30 $m.min^{-1}$, with the help of a mechanical feeder system coupled to the planer. The standardization of the parameters aimed to ensure that the process variables did not represent a source of variation in the specific cutting energy data, the variation being relate only to the genetic material.

The cutting monitoring was performed by the frequency inverter (CFW-08), connected to the trigger motor of the tool holder axis of the planer. The data acquired by the frequency inverter were exported to a Microsoft Office Excel spreadsheet, for better adjustment of the data. In addition, the data capture using the parameterization software was carried out without interruption over time, with four readings per second. The analysis of the specific cutting energy was performed according to the methodology of Souza et al. (2011) through Equations 1, 2 and 3.

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$$P = \frac{T_{mec} \times n \times 0{,}0014 \times 736}{1000} \tag{1}$$

In which:

P = cutting power (kw);

Tmec = mechanical torque of the engine (kgf.m);

n = rotation (min^{-1}).

$$E = \left(\frac{P \times C}{V_f}\right) \times 60 \tag{2}$$

In which:

E = energy (J);

P = cutting power (kw);

C = cutting length (m);

V(f) = feed speed ($m.min^{-1}$)

$$Es = \frac{E}{c \times e \times K} \tag{3}$$

In which:

Es = Specific cutting energy ($J.cm^{-3}$);

E = energy (J);

c = specimen length (cm);

e = specimen thickness (cm);

K = tooth thickness of the cutting tool (cm).

The statistical software Statgraphics Centurion XVI.I was used to analyze the data obtained by means of the analysis of variance (ANOVA), considering the factors specific cutting energy and basic density. For this, a completely randomized design was applied, with a 2 x 5 factorial arrangement (axial region x clone). Due to the significance of the F value, the data obtained for the specific cutting energy and basic density were submitted to a procedure of comparison of means, using the Tukey test at 95% probability.

3. Results and Discussion

Table 1 presents the summary of the analysis of variance for basic density, and specific cutting energy, as well as for their interaction.

Table 1. Summary of the analysis of variance for basic density and specific cutting energy obtained for the wood of five clones of *Eucalyptus* spp.

	Variable	Significance
Basic density	(A) Clone	*
	(B) Axial region	ns
	(A x B) Interaction	ns
Specific cutting energy	(A) Clone	*
	(B) Axial region	*
	(A x B) Interaction	ns

* = Significant ($0.01 \leq p < 0.05$); ns = Not significant ($p \geq 0.05$), at 95% probability.

Source: Authors.

In the case of the variable Clone, it can be highlighted that the result was significant for both basic density and specific cutting energy. This fact is probably a result of the five clones presenting different matrices. There are also two pure clones (*E. urophylla* and *E. grandis*) and three hybrid clones (*E. grandis* x *E. urophylla*), which provide different behaviors for each genetic material.

The variable axial region was significant for specific cutting energy and not significant for basic density. The statistical equality verified for basic density is probably the result of the proximity between the two logs used, with reduced variation in the axial structural composition. However, the statistical differences observed for specific cutting energy may be due to the various factors that affect this variable (Gorczyca, 1987; Rodrigues & Coelho, 2007).

Table 2 shows the mean values for the basic density of the five clones. Considering all the values obtained, the variation from 0.423 to 0.619 $g.cm^{-3}$ stands out for clones 1 and 2, respectively, with a coefficient of variation of 8.53%. Batista et al. (2010), when determining the basic density of five 11-year-old clones of the species *Eucalyptus saligna*, *Eucalyptus grandis* and *Eucalyptus dunnii*, obtained similar mean values, corroborating with the data obtained for the five clones. Evangelista et al. (2010) found for a 6.3-year-old *E. urophylla* a lower basic density (0.450 $g.cm^{-3}$) when compared to clone 2 (*E. urophylla*), probably due to the age difference between the clones in the two studies.

Table 2. Basic density for the variables clone and axial region for the wood of five clones of *Eucalyptus* spp.

Clone	Species	Axial Region		Mean ($g.cm^{-3}$)
		1	2	
1	*E. grandis* x *E. urophylla*	0.475	0.482	0.479 a
2	*E. urophylla*	0.596	0.585	0.590 d
3	*E. grandis* x *E. urophylla*	0.484	0.510	0.497 ab
4	*E. grandis*	0.533	0.538	0.536 c
5	*E. grandis* x *E. urophylla*	0.507	0.516	0.511 bc
	Mean ($g.cm^{-3}$)	0.519 A	0.526 A	

Means followed by the same lowercase letter in the column or uppercase letter in the row do not differ statistically by the Tukey test, at 95% probability. Source: Authors.

It was observed for the variable clone that the five genetic materials showed statistical differences between them, with clones 1, 3 and 5 presenting the lowest mean values. The difference can probably be explained by the fact that clones 1, 3 and 5 are hybrids of *E. grandis* x *E. urophylla*, unlike clones 2 and 4, which are pure *E. grandis* and *E. urophylla*, respectively.

Of the five clones analyzed, clone 2 (*E. urophylla*) was the one with the highest density, indicating the possibility of greater mechanical strength and better surface finishing, but with greater dimensional variation and greater specific cutting energy consumption, unlike clone 1, with lower basic density. However, it is worth mentioning that the density alone is not the limiting factor for the amount of energy that the wood will require during the cutting process. Andrade et al. (2022) evaluating the specific cutting energy required during the peripheral milling of woods with different densities, observed that the wood that required greater specific cutting energy was not among the woods with the highest densities.

For the variable axial region, it was not observed statistical differences between the two logs, probably due to the short distance at which they were obtained. Lopes et al. (2011) also found no variation when evaluating the basic density in three axial positions along the trunk for the wood of *E. grandis*, *E. dunnii* and *E. urophylla* (18 years old). Melo et al. (2013) observed longitudinal variation in the basic density of *Pinus elliottii* only above 35% of the commercial height of the trunk.

As for the specific cutting energy, the mean values for clones and positions are shown in Table 3. In the general analysis of the data, it was observed that the highest specific cutting energy value was presented by clone 2 in the axial region of 4.5 to 6.5 m, requiring 407 $J.cm^{-3}$ for the planing. It was observed that the clone 4 in the axial region of 4.5 to 6.5 m was the one that required less energy during the cutting process (98 $J.cm^{-3}$). The coefficient of variation for the values of specific cutting energy in relation to the two axial regions and the five clones was 21.4%.

Table 3. Specific cutting energy required by the wood of five clones of *Eucalyptus* spp. during the planing process, for the variables clone and axial position.

Clone	**Species**	**Axial Region**		**Mean ($J.cm^{-3}$)**
		2.5 to 4.5 m	**4.5 a 6.5 m**	
1	*E. grandis* x *E. urophylla*	233	226	229 a
2	*E. urophylla*	264	252	258 b
3	*E. grandis* x *E. urophylla*	241	243	242 ab
4	*E. grandis*	272	247	260 b
5	*E. grandis* x *E. urophylla*	267	257	262b
	Mean ($J.cm^{-3}$)	255 B	245 A	

Means followed by the same lowercase letter in the column or uppercase letter in the row do not differ statistically by the Tukey test, at 95% probability. Source: Authors.

Regarding the variable clone, statistical differences were observed between the genetic materials, ranging from 229 to 262 $J.cm^{-3}$ (Table 3). Andrade et al. (2022) during milling with CNC of *E. grandis*, with basic density of 0.495 $g.cm^{-3}$, obtained specific cutting energy of 845 $J.cm^{-3}$, and for *E. saligna* with basic density of 0.598 $g.cm^{-3}$, specific cutting energy of 855 $J.cm^{-3}$.

Clone 1 stood out with the lowest specific cutting energy requirement for wood planing, being statistically superior to the clones 2, 4 and 5. This difference can be explained by the lower wood density of clone 1 when compared to the other clones, consequently requiring less energy for planing.

A statistical difference was also observed between the two axial regions evaluated, in which the wood present between 2.5 and 4.5 m in height required greater specific cutting energy for planing. However, this result was not expected, once this position presented a lower basic density (Table 2). Andrade et al. (2022) found similar results for some species, and the author pointed out that in addition to density, the type of grain, fiber, vessels and parenchyma cells layout also have influence over the values obtained for the specific cutting energy. In this case, the age of formation of the growth rings may have been a factor for the log between 2.5 and 4.5 m to have demanded more energy during its cutting process, because in this part of the tree there are rings that were formed earlier during the tree formation.

4. Conclusions

The axial region between 2.5 and 4.5 m presented the lowest basic density, but the highest specific cutting energy. Clone 1 showed the lowest basic density and, consequently, the lowest specific energy consumption during the planing. The basic density influenced the specific cutting energy value only for the variable Clone.

As a suggestion for future work, it is recommended to evaluate the influence of other variables on the specific energy of wood cutting, since, as observed in this study, a single variable may not exert an influence on a certain species. In addition, it is also recommended to evaluate the specific cutting energy of other species commonly used by the furniture industry, to better understand the behavior of these woods during their processing and thus optimize the production process.

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