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SPECIFIC CUTTING ENERGY CONSUMPTION IN A CIRCULAR SAW FOR EUCALYPTUS STANDS VM01 AND MN463

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ABSTRACT: Modern technologies for continuous carbonization of *Eucalyptus* sp. require special care in wood cutting procedures. Choosing the right tool, cutting speeds and feed rates is important to manage time and energy consumption, both of which being critical factors in optimizing production. The objective of this work is to examine the influence of machining parameters on the specific cutting energy consumption of *Eucalyptus* sp. stands MN 463 and VM 01, owned by V&M Florestal. Tests were performed at the Wood Machining Laboratory of the Federal University of Lavras (DCF/UFLA). Moist logs 1.70m in length were used. The experiment was set up using a 3 x 3 x 4 x 2 factorial design (cutting speed x feed rate x number of teeth x tree stand). Results were subjected to analysis of variance and means were compared by the Tukey test at the 5% significance level. Greater cutting speeds, lower feed rates and the 40 teeth circular saw consumed more specific energy. Stand MN 463 consumed more specific energy. The combination of cutting speed 46 m.s⁻¹, feed rate 17 m.min⁻¹ and 24 teeth circular saw produced better specific energy consumption results for stand MN 463. As for stand VM 01, the combination of cutting speed 46 m.s⁻¹, feed rate 17 m.min⁻¹ and 20 teeth circular saw resulted in lower specific energy consumption.

Key words: *Eucalyptus* sp., specific energy, transverse cutting, circular saw, machining.

ENERGIA ESPECÍFICA DE CORTE EM SERRA CIRCULAR PARA OS CLONES DE *EUCALYPTUS* VM01 E MN463

RESUMO: Novas tecnologias de carbonização contínua do *Eucalyptus* sp. requerem cuidados no corte da madeira. A escolha da ferramenta e das velocidades de corte e de avanço influenciam no tempo e no consumo de energia, fatores importantes para otimizar a produção. Objetivou-se, com o presente estudo, verificar a influência dos parâmetros de usinagem no consumo de energia específica de corte da madeira dos clones de *Eucalyptus* sp., MN 463 e VM 01, da Empresa V&M Florestal. Os ensaios foram desenvolvidos no Laboratório de Usinagem da Madeira (DCF/UFLA). Foram utilizadas toras úmidas de 1,70 m de comprimento. O delineamento experimental utilizado foi fatorial 3 x 3 x 4 x 2 (velocidade de corte x velocidade de avanço x número de dentes x clone). Os resultados obtidos foram submetidos à análise de variância e as médias comparadas pelo teste de Tukey a 5% de significância. Maiores velocidades de corte, menores velocidades de avanço e serra circular de 40 dentes consumiram mais energia específica de corte. O clone MN 463 consumiu maior quantidade de energia específica. A interação entre a velocidade de corte de 46 m.s⁻¹, a velocidade de avanço de 17 m.min⁻¹ e a serra circular com 24 dentes apresentou melhores resultados de consumo de energia específica de corte para o clone MN 463. Para o clone VM 01, a interação entre a velocidade de corte de 46 m.s⁻¹, a velocidade de avanço de 17 m.min⁻¹ e a serra circular com 20 dentes apresentou menor consumo de energia específica de corte.

Palavras-chave: *Eucalyptus* sp., energia específica, corte transversal, serra circular, usinagem.

1 INTRODUCTION

Nonnative origin wood charcoal plays an important part in Brazilian economy, in particular the economy of

Minas Gerais state, the main producing and consuming state in Brazil. Most *Eucalyptus* stands there are intended for charcoal production for use in metallurgy. According to Minas Gerais Silviculture Association-AMS (2009),

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in 2008 the total area covered by *Eucalyptus* stands in the state intended for pig iron production was 65,587 ha, and the total consumption of wood charcoal by the steel industry was 20.9 million meters. Other than the steel industry, charcoal is also a substitute for fuel oil in boilers and combustion furnaces in the cement and other primary material industry (TRUGILHO et al., 2001).

Where charcoal is produced in traditional ovens, wood is cut to approximately 3.60 m in length and tools include chainsaws or other forest equipment. Where continuous carbonization is used, log pieces are approximately 30cm in length and sections are processed using circular saws. Wood processing operations should be done so as to spare equipment of excessive wear and tear, damage or destruction, ultimately seeking to reduce maintenance and replacement costs (BROWN; BETHEL, 1975).

Néri et al. (1999) argued that cutting force requirements have considerable importance in the design of cutting tool geometry and also in the power demanded from equipment. Cutting forces may vary depending on the sharpness and type of tool being used, on the species and also on grain orientation and cut direction.

Specific cutting energy consumption is defined as the relationship between net cutting energy consumption and volume of removed material. Meyer (1926), as cited by Kollmann and Cotê Júnior (1968), found that higher cutting speeds are associated with reduced cutting energy efficiency. Specific energy along with specific force allows comparison and assessment of cutting tool efficiency (LUBKIN, 1957, as cited by KOLLMANN; COTÊ JÚNIOR, 1968).

Ersoy and Atici (2004) argued that from specific cutting energy data one can estimate the power required, noting however that motor efficiency as well as friction and inertia effects are also factors to be considered.

Given the need to boost production and reduce costs, the charcoal industry is proposing to use variable frequency drives, operated at different speeds (SIMÃO; ALMEIDA NETO, 2002). Campana et al. (2000) argued that variable frequency drives are effective tools to correct load indices, performance and power factors found lower than nominal, and to prevent unnecessary burden on electric motors, ultimately translating as reduced energy consumption. The use of variable frequency drives in irrigation has provided satisfactory results, helping reduce power consumption and allowing energy savings (HANSON et al., 1996).

Through combined efforts of UFLA, CIRAD/ France and V&M Florestal, the objective of this study is to optimize both production and quality of *Eucalyptus*

charcoal for the steel industry, by studying the influence of cutting speeds, feed rates, number and geometry of circular saw teeth on specific cutting energy consumption regarding *Eucalyptus* sp. stands MN 463 and VM 01.

2 MATERIAL AND METHODS

Logs 1.70m in length and 7 to 11 cm in diameter were used from stands MN 463 (a natural *Eucalyptus urophylla* hybrid) and VM 01 (*Eucalyptus camaldulensis* x *Eucalyptus urophylla*), at age 8 years, located in the municipality of Paraopeba/MG and owned by V&M Florestal. Newly felled logs were selected (unseasoned wood). The average basic wood density was 0.514 and 0.574 g.cm⁻³, for stands MN 463 and VM 01 respectively. Tests were performed at the Wood Machining Laboratory of the Department of Forest Sciences, Federal University of Lavras (DCF/UFLA).

Measurements were taken of feed rates and rotation frequency of the circular saw used by the production unit of V&M Florestal, and cutting speed was then calculated. With these data at hand, an automatic table motion system was devised for the moving circular saw, at the Wood Machining Laboratory (DCF/UFLA) (Figure 1), controlled by a variable frequency drive that stored electrical parameters. The variable frequency drive used was a CFW08 (WEG) model, equipped with a serial communication interface (KSD CFW08), SuperDrive® software.



Figure 1 – Feed rate and cutting speed controlled moving circular saw (DCF/UFLA). 1) circular saw, 2) log section, 3) pneumatic pistons, 4) feed motor, 5) variable frequency drive and 6) computer.

Figura 1 – Serra circular de carrinho (DCF/UFLA), com controle de velocidade de avanço e de corte. 1) serra circular, 2) tora, 3) pistões pneumáticos, 4) motor de avanço, 5) inversor de frequência e 6) computador.

Four parameters were acquired simultaneously during the cutting operation, namely: value proportional to rotation frequency ($\text{min}^{-1} = \text{RPM}$), motor output current (Amperes), motor output voltage (Volts) and motor torque (%). Parameter acquisition time was 250 milliseconds, according to the work of Oliveira et al. (2008). To determine specific energy, rotation frequency and torque were used.

Once data was collected by the software, log cutting intervals were identified by selecting abruptly ascending/descending torque values alternating with reduced, relatively constant torque ranges, the latter being discarded.

Machining parameters being assessed are described in Table 1. The teeth geometry used was alternate cutting edges. However, for the 40 teeth saw, which is similar to the saw used by V&M Florestal, two successive alternating teeth were used, one trapezoidal and one flat.

Table 1 – Levels and specifications of machining parameters used.

Tabela 1 – Níveis e especificações dos parâmetros de usinagem adotados.

Factors	Levels		Specifications		
Cutting speed (m.s^{-1})	3	46	58*	70	
Feed rate (m.min^{-1})	3	7	12*	17	
Number of teeth	4	20	24	40*	48
Tree stand	2	MN 463	VM 01		
Treatments total	72				

*Machining conditions at V&M Florestal

To calculate the specific energy consumption of each treatment, Equations 1, 2 and 3 were used.

$$Power = \frac{T \times n \times 0.0014 \times 736}{1000} \quad (1)$$

$Power$ = cutting power (kW);

T = torque (kgf.m);

n = rotation ($\text{min}^{-1} = \text{rpm}$).

$$E = \left(\frac{Power \times D}{Vf} \right) \times 60 \quad (2)$$

E = energy (kJ);

$Power$ = cutting power (kW);

D = log diameter (m);

Vf = feed rate (m.min^{-1}).

$$Es = \frac{4 \times E}{\pi \times D^2 \times k} \quad (3)$$

Es = specific energy (kJ.cm^{-3});

E = energy (kJ);

D = average log diameter (cm);

k = tooth thickness (cm).

The experiment was set up using a completely randomized design with a $3 \times 3 \times 4 \times 2$ factorial arrangement (cutting speed x feed rate x number of teeth x tree stand), with 20 replicates. Data were subjected to analysis of variance and means were compared by the Tukey test at the 5% significance level.

3 RESULTS AND DISCUSSION

Results showed that a cutting speed of 70 m.s^{-1} produced a higher overall mean ($4.84 \times 10^{-2} \text{ kJ.cm}^{-3}$) of specific energy consumption whereas a cutting speed of 58 m.s^{-1} produced a lower mean ($4.16 \times 10^{-2} \text{ kJ.cm}^{-3}$). In both stands there was a tendency for the specific cutting energy consumption to decrease with increasing feed rates. With increasing cutting speeds, on the other hand, there was a tendency for specific energy consumption to increase. High cutting speeds are associated with higher rotation frequency values, consequently increasing the cutting power requirements (Equations 1, 2 and 3). In a study on specific energy consumption at different cutting speeds for aluminum and steel, Rodrigues and Coelho (2007) found that specific energy consumption decreased with increasing cutting speeds. The authors reported that facilitated metal ductility and chip formation was due to the temperature rise during the cutting procedure. Owing to its insulating properties, wood does not favor substantial temperature rises.

A feed rate of 7 m.min^{-1} produced the highest average value of specific cutting energy consumption, whereas a feed rate of 17 m.min^{-1} produced the lowest (6.40 and $2.74 \times 10^{-2} \text{ kJ.cm}^{-3}$ respectively). A similar pattern was observed in steel machining, as described by Diniz et al. (2000). According to these authors, during the cutting process some of the removed material (chip fragment) is driven between the flank face of the tool and the machined surface (through the clearance angle), and this generates lateral chip flow. The slower the flow, the more friction is created between the cutting tool and the workpiece surface, consequently increasing energy consumption.

The analysis of variance (Table 2) showed that main effects and their relevant interactions were significant, and factors are interdependent. The breakdown of cutting speed at each level of feed rate, number of teeth and tree stand was done by multiple comparisons at the 5% significance level, by the Tukey test.

Table 2 – Analysis of variance summary for specific cutting energy consumption concerning *Eucalyptus* sp. stands MN 463 and VM 01, as a function of cutting speed, feed rate, number of teeth, stand and respective double, triple and quadruple interactions.

Tabela 2 – Resumo da análise de variância para o consumo da energia específica de corte da madeira dos clones de *Eucalyptus* sp. MN 463 e VM 01, em função das velocidades de corte, velocidade de avanço, número de dente, clone e suas respectivas interações duplas, triplas e quádruplas.

Source	Degree of Freedom	Mean Square
Cutting speed (Vc)	2	0.006320*
Feed rate (Vf)	2	0.163665*
Number of teeth (Z)	3	0.024844*
Tree stand	1	0.003921*
Vc x Vf	4	0.006710*
Vc x Z	6	0.004246*
Vc x Tree stand	2	0.016456*
Vf x Z	6	0.002986*
Vf x Tree stand	2	0.000153*
Z x Tree stand	3	0.006511*
Vc x Vf x Z	12	0.002190*
Vc x Vf x Tree stand	4	0.008087*
Vf x Z x Tree stand	6	0.001025*
Vc x Vf x Z x Tree stand	12	0.002823*
Error	1374	0.000038
Corrected Total	1799	

* – significant at the 5% significance level; overall mean = 0.044238; coefficient of variation = 13.98%.

There was a tendency for specific cutting energy consumption to increase as a function of increasing number of teeth, in both stands (Figures 2, 3 and 4). Overall, the 40 teeth and 48 teeth circular saws produced higher values of specific cutting energy consumption (5.11 and $5.16 \times 10^{-2} \text{ kJ.cm}^{-3}$ respectively), not differing statistically. On average, the 24 teeth circular saw produced lower values

of specific energy consumption ($3.57 \times 10^{-2} \text{ kJ.cm}^{-3}$). A larger number of teeth could infer wood scraping rather than cutting when interacting with the cutting speeds and feed rates being studied, consequently causing more energy consumption.

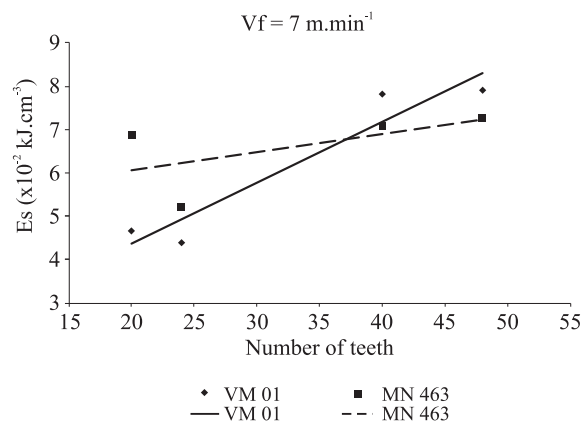


Figure 2 – Specific energy consumption tendency for *Eucalyptus* sp. stands MN 463 and VM 01 as a function of number of teeth, with a feed rate of 7 m.min^{-1} .

Figura 2 – Tendência do consumo de energia específica de corte para os clones de *Eucalyptus* sp. MN 463 e VM 01 em função do número de dentes para a velocidade de avanço de 7 m.min^{-1} .

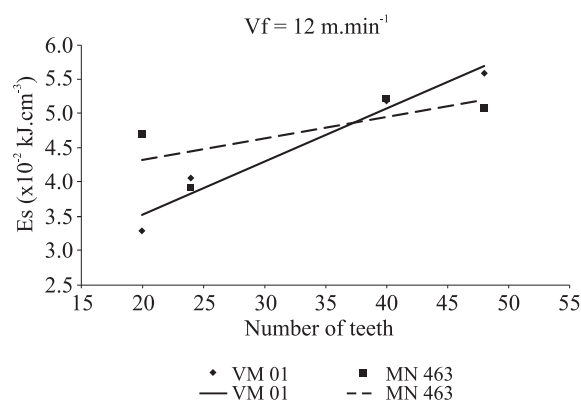


Figure 3 – Specific energy consumption tendency for *Eucalyptus* sp. stands MN 463 and VM 01 as a function of number of teeth, with a feed rate of 12 m.min^{-1} .

Figura 3 – Tendência do consumo de energia específica de corte para os clones de *Eucalyptus* sp. MN 463 e VM 01 em função do número de dentes para a velocidade de avanço de 12 m.min^{-1} .

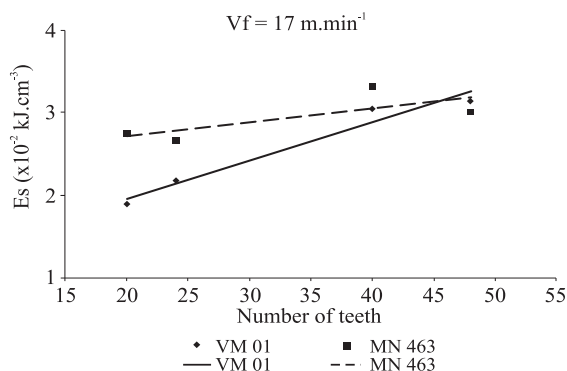


Figure 4 – Specific energy consumption tendency for *Eucalyptus* sp. stands MN 463 and VM 01 as a function of number of teeth, with a feed rate of 17 m.min⁻¹.

Figura 4 – Tendência do consumo de energia específica de corte para os clones de *Eucalyptus* sp. MN 463 e VM 01 em função do número de dentes para a velocidade de avanço de 17 m.min⁻¹.

When cutting the wood from stand MN 463, the 40 teeth and the 48 teeth circular saws produced overall higher mean values of specific energy consumption, 5.04 and 4.95 x 10⁻² kJ.cm⁻³ respectively, though these values did not differ statistically. The 24 alternate teeth circular saw produced the lowest mean value of specific cutting energy consumption, 3.76 x 10⁻² kJ.cm⁻³.

With wood from stand MN 463, using a feed rate of 7 m.min⁻¹, a 40 teeth circular saw (alternate flat and trapezoidal teeth) and a cutting speed of 70 m.s⁻¹ resulted in the highest value of specific cutting energy consumption, 9.02 x 10⁻² kJ.cm⁻³. The lowest value of specific energy consumption (1.88 x 10⁻² kJ.cm⁻³) was produced when using a feed rate of 17 m.min⁻¹, a 24 alternate teeth circular saw and a cutting speed of 46 m.s⁻¹.

With wood from stand VM 01, the 48 teeth saw produced a higher mean value of specific cutting energy consumption (5.38 x 10⁻¹ kJ.cm⁻³). The 20 alternate teeth saw produced a lower mean value of energy consumption (3.11 x 10⁻² kJ.cm⁻³).

The highest value of specific cutting energy consumption (11.52 x 10⁻² kJ.cm⁻³) for stand VM 01 was observed when using a feed rate of 7 m.min⁻¹, a 48 alternate teeth circular saw and a cutting speed of 58 m.s⁻¹. The use of a feed rate of 17 m.min⁻¹, a 20 alternate teeth saw and a speed of 46 m.s⁻¹ produced the lowest value of specific energy consumption, 1.10 x 10⁻² kJ.cm⁻³.

It was noted that, regardless of stand density, cutting speed and feed rate, there was an increase in specific cutting energy consumption with increasing number of teeth being used. Overall analysis of data (Figures 5, 6 and 7) revealed

that stand MN 463 (0.514 g.cm⁻³) showed more specific energy consumption in comparison to stand VM 01 (0.574 g.cm⁻³), with mean values of specific energy consumption at 4.59 and 4.26 x 10⁻² kJ.cm⁻³ respectively. The stand with higher numerical value of density showed less specific cutting energy consumption, disputing literature in general. However, analyses of variance of moisture (Table 3) and basic density (Table 4) of logs from stands MN 463 and VM 01 reveal statistical similarity for these variables, ruling out the possibility of inferring that the wood from stand VM 01 is denser.

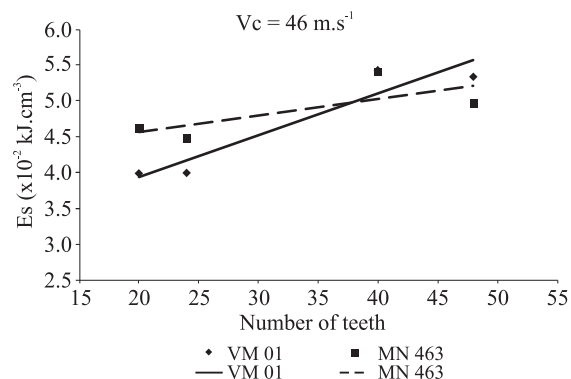


Figure 5 – Specific energy consumption tendency for *Eucalyptus* sp. stands MN 463 and VM 01 as a function of number of teeth, for a cutting speed of 46 m.s⁻¹.

Figura 5 – Tendência do consumo de energia específica de corte para os clones de *Eucalyptus* sp. MN 463 e VM 01 em função do número de dentes para a velocidade de corte de 46 m.s⁻¹.

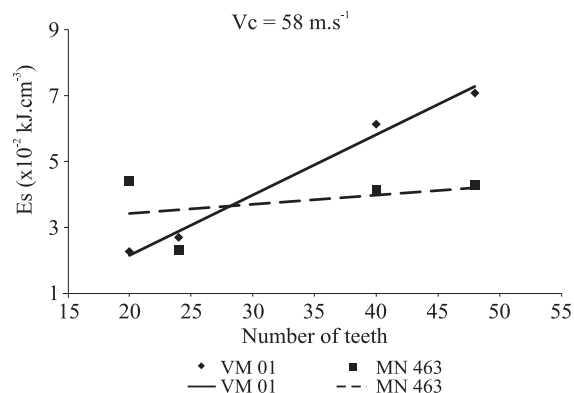


Figure 6 – Specific energy consumption tendency for *Eucalyptus* sp. stands MN 463 and VM 01 as a function of number of teeth, for a cutting speed of 58 m.s⁻¹.

Figura 6 – Tendência do consumo de energia específica de corte para os clones de *Eucalyptus* sp. MN 463 e VM 01 em função do número de dentes para a velocidade de corte de 58 m.s⁻¹.

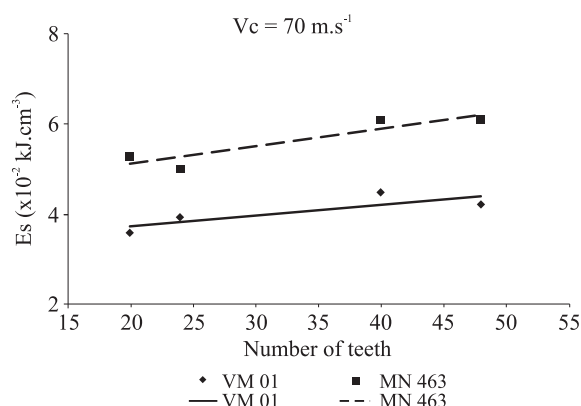


Figure 7 – Specific cutting energy consumption tendency for *Eucalyptus* sp. stands MN 463 and VM 01 as a function of number of teeth, for a cutting speed of 70 m.s⁻¹.

Figura 7 – Tendência do consumo de energia específica de corte para os clones de *Eucalyptus* sp. MN 463 e VM 01 em função do número de dentes para a velocidade de corte de 70 m.s⁻¹.

Table 3 – Analysis of variance summary for unseasoned woods from *Eucalyptus* sp. stands MN 463 and VM 01, as a function of moisture.

Tabela 3 – Resumo da análise de variância das madeiras denominadas verdes, para os clones de *Eucalyptus* sp. MN 463 e VM 01, em função da umidade.

Source	Degree of Freedom	Mean Square
Tree stands	1	229.336806 ^{ns}
Error	70	141.709853
Corrected Total	71	

Overall mean = 73.0930556; Coefficient of variation = 16.29%.
^{ns} – nonsignificant at the 5% significance level.

Table 4 – Analysis of variance summary for wood from *Eucalyptus* sp. stands MN 463 and VM 01, as a function of basic density.

Tabela 4 – Resumo da análise de variância da madeira dos clones de *Eucalyptus* sp. MN 463 e VM 01, em função da densidade básica.

Source	Degree of Freedom	Mean Square
Tree stands	1	0.375000 ^{ns}
Error	4	0.125000
Corrected Total	5	

Overall mean = 0.7500000; Coefficient of variation = 47.14%.
^{ns} – nonsignificant at the 5% significance level.

These values correspond to an average increase of 7.7% in energy consumption to cut wood from stand MN 463.

4 CONCLUSIONS

From analyses performed on stands MN 463 and VM 01, including cutting speeds, feed rates, number of teeth and teeth geometry of circular saws, the following conclusions were drawn:

- higher cutting speeds and lower feed rates demanded more specific cutting energy consumption;
- the 40 teeth circular saw with alternate trapezoidal and flat teeth demanded more specific cutting energy consumption, thus being unsuitable for the cut in question;
- the interaction of a cutting speed of 46 m.s⁻¹, a feed rate of 17 m.min⁻¹ and a 24 alternate teeth circular saw showed better results of specific cutting energy consumption for unseasoned wood from stand MN 463;
- the interaction of a cutting speed of 46 m.s⁻¹, a feed rate of 17 m.min⁻¹ and a 20 alternate teeth circular saw demanded less specific cutting energy consumption for unseasoned wood from stand VM 01;
- unseasoned wood from stand MN463 demanded more specific cutting energy in comparison to unseasoned wood from stand VM 01, despite them being statistically similar.

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