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Modelling of Peripheral Wood Milling Power Using Design of Experiment Approach

Modeliranje snage obodnoga glodanja drva primjenom pristupa dizajna eksperimenta

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ABSTRACT • *For efficient production planning, it is necessary to know the power consumption of a particular woodworking operation in advance. In the past, many power measurement tests have been carried out based on a large number of different combinations of technological parameters. However, in this paper, the effects of technological parameters and wood properties on the power magnitude of peripheral milling are analysed using experimental design methods, where the effects of the different factors can be tested with a much smaller number of combinations. Therefore, a central composite experimental design was used to plan the experiments. Three different tree species with different densities were milled with three different numbers of cutting knives and three depths of cut at constant feeding speed and rotational velocity. For each milling combination, the power was measured continuously and then the average power was calculated. Based on the measurements, a suitable model was determined that allowed the magnitude of the cutting power to be determined for each combination of technological parameters and wood species tested. The model proved to be suitable, as the deviations between the measured and modelled power values are minimal.*

KEYWORDS: *wood cutting; milling; power consumption; response surface methodology; central composite design*

SAŽETAK • *Za učinkovito planiranje proizvodnje potrebno je unaprijed znati potrošnju energije za pojedine operacije u obradi drva. U prošlosti su mnoga istraživanja snage mehaničke obrade drva provedena na temelju velikog broja različitih kombinacija tehnoloških parametara. Međutim, u ovom se radu analiziraju utjecaji tehnoloških parametara i svojstava drva na vrijednosti snage obodnoga glodanja primjenom metoda dizajniranja eksperimenta kojima se utjecaji različitih parametara mogu ispitati s mnogo manjim brojem kombinacija tih parametara. Stoga je za planiranje eksperimenta primijenjen centralni kompozitni dizajn eksperimenta. Tri različite vrste drva različitih gustoća obrađivane su s tri različita broja oštrica i tri dubine glodanja pri konstantnoj posmičnoj brzini i frekvenciji vrtnje alata. Za svaku kombinaciju parametara glodanja kontinuirano je mjerena snaga, a zatim je izračunan prosjek te snage. Na temelju mjerenja izrađen je odgovarajući model koji omogućuje određivanje snage rezanja za svaku ispitivanu kombinaciju tehnoloških parametara i vrstu drva. Model se pokazao prikladnim jer su odstupanja između izmjerene i modelirane snage bila minimalna.*

KLJUČNE RIJEČI: *rezanje drva; glodanje; potrošnja energije; metoda odzivne površine; centralni kompozitni dizajn*

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1 INTRODUCTION
1. UVOD

Nowadays, energy consumption is a very important factor in the production process, where it is desirable to minimise energy consumption as much as possible. Reducing energy consumption has an important impact on greenhouse gas emissions and the economic efficiency of the product. In addition to these factors, energy consumption also has an impact on the capacity of the production process. In woodworking, for example, where a specific machine with limited capacity is available, the maximum load on the machine can be calculated so as not to exceed the available capacity of the machine.

The average power required for milling or cutting wood is influenced by a number of factors, which can be divided into technological factors and factors related to material properties (Kollmann and Côte, 1975). Technological factors include the feeding speed, rotational velocity and diameter of the tool, number of cutting blades, rake angle of the blades, coefficient of friction between the blade and the chip, sharpness of the blade, depth of cut, cutting direction, *etc.* (Ettelt, 2004; Kivimaa, 1952). Among the properties of the working material, the mechanical properties, such as the strength of the material and fracture toughness have the greatest influence on the cutting performance and vary with the type of wood or wood density, direction of loading and moisture content of wood (Ettelt, 2004; Kivimaa, 1952).

Depending on the factors described, there are many ways to calculate the cutting force or power. The first is modelling based on the mechanical properties of wood, where both the stress-strain conditions must be considered and compared with the properties of wood, such as wood strength and fracture toughness. In the author's opinion, this method is not very suitable for an industrial user who wants to quickly calculate the cutting power and thus predict the energy consumption for a specific type of wood and specific cutting conditions as the user would need to know all the mechanical properties of the wood being cut. Imagine that a company must cut hundreds of cubic metres of wood, for which there is little information about mechanical properties of wood, and the company's technologist has only a limited amount of time to calculate the energy. This approach makes it impossible to acquire all information needed to calculate in a short time.

This method has been studied by many authors who have analysed more or less complex models taking into account different parameters (Aboussafy and Guilbault, 2021; Hlásková *et al.*, 2021; Kubík *et al.*, 2023; Liao and Axinte, 2016; Merhar and Bucar, 2012; Minagawa *et al.*, 2018; Orlowski *et al.*, 2022; Radmanovic *et al.*, 2018; Yang *et al.*, 2023), while others studied the influence of various woodworking tools on power consumption (Kopecký *et al.*, 2022; Svoreň *et al.*, 2022). However, since wood is an anisotropic material that can be described as orthotropic under certain conditions, the models must consider different mechanical properties for each tissue orientation. In addition, the tensile strength of wood is higher than the compressive strength, which must also be taken into account as both tensile and compressive failure of the fabric occurs when wood is cut. Thus, despite the many models for cutting wood that have already been developed and contain different variables, there is still no universal model that can calculate the cutting forces for different combinations of technological parameters and different tree species.

In the other way of calculating the cutting force, the mechanistic approach, the force is calculated using specific coefficients that are determined by the user for each operation (Axelsson *et al.*, 1993; Cristóvão *et al.*, 2012; Ettelt, 2004; Goli *et al.*, 2010; Kivimaa, 1952; Li *et al.*, 2022; Mandic *et al.*, 2015; Pałubicki, 2021; Porankiewicz *et al.*, 2007; Wang *et al.*, 2023). Thus, the specific coefficient should be determined as a function of wood density, cutting direction, angle between the tissue orientation and the blade velocity vector, coefficient for a given rake angle of the blade, moisture content of wood and sharpness of the blade. The value of these coefficients is also based on the mechanical properties of wood described above and can be determined based on these mechanical properties. The first way to calculate these coefficients can be by using the models described in the previous paragraph, which are complex and still unsatisfactory. The second way to determine these coefficients is through experiments in which the coefficients are calculated from measurements of the forces at different combinations of technological parameters and wood properties. Of course, these coefficients are only applicable within the range of values of the variables in which the experiment was carried out. For the above case, this method of calculating force or power offers the technologist in industry the possibility of calculating the cutting force or power required for a particular woodworking operation quickly and relatively accurately. From the technological side, the user only needs the technological parameters that must be known for the specific case and only the wood density in terms of wood properties.

To calculate the cutting power in the mechanistic model, the mean force for one chip F_m is calculated first (Ettelt, 2004),

$$F_m = k_s \cdot b \cdot h_m \tag{1}$$

where k_s is the specific cutting force in N/mm^2, b is the cutting width in mm and h_m is the mean thickness of the chip in mm (Figure 1), calculated as

$$h_m = f_z \cdot \sqrt{\frac{a}{d}} \tag{2}$$

where a is the depth of cut in mm, d is the diameter of the milling head in mm and f_z is the feed per tooth in mm calculated as

$$f_z = \frac{v_f}{n \cdot z} \tag{3}$$

v_f is the feeding speed in mm/min, n is the tool rotational velocity in rpm in and z is the number of cutting edges on the circumference of the blade. The above equations show that the average thickness of the chip is influenced by the feed per tooth f_z , which in turn depends on the feeding speed v_f, rotational velocity n and the number of cutting edges z on the circumference of the cutting head. This means that the feed per tooth f_z and therefore the average chip thickness h_m can be the same for different workpiece feeding speeds and tool rotational velocities, provided that the relationship between the parameters in equation 3 is constant.

The specific cutting force k_s in Eq. 1 is therefore influenced by various technological parameters and the properties of the material to be cut (Ettelt, 2004; Kivimaa, 1952). In addition to the strength properties of the material, which are related to the density of the material, the specific cutting force k_s is also influenced by the cutting direction or the angle between the current cutting direction v_c and the tissue orientation as shown in Figure 1. For example, the angle between the wood tissue and the cutting direction v_c is 0 when the blade starts to cut (Figure 1). As the tool rotates, the angle j increases until the blade leaves the workpiece where the angle is φ_{out}. At this point, the specific cutting force is also the greatest, as for example in Figure 1, where the blade cuts almost perpendicular to the grain. The total force is therefore greatest at the angle φ_{out}, which is the consequence of the maximum specific cutting force k_s and the maximum thickness of the chip h_{max}. An exact calculation of the cutting force would therefore require an integral that takes into account both the changing specific cutting force due to the increasing angle between the cutting vector and the orientation of the wood tissue and the increasing thickness of the chip. However, as this is impractical for industrial applications, the calculation can also be simplified by taking into account the mean thickness of the chip h_m and the specific cutting force k_s at the mean cutting angle φ_m (Figure 1).

The magnitude of the specific cutting force k_s is also influenced by the rake angle of the blade, where the specific cutting force increases with decreasing rake angle (Ettelt, 2004). Thus, for the calculation of the mean angle φ_m, the following equations can be used

$$\varphi_m = \frac{\varphi_{out}}{2} \tag{4}$$

$$\varphi_{out} = \arccos\left(\frac{r-a}{r}\right) \tag{5}$$

where r is the radius of the milling head in *mm*. If the angular function (cos) is developed into a Taylor series, it can also be written

$$\varphi_{out} = 2 \cdot \sqrt{\frac{a}{d}} \tag{6}$$

where d is the diameter of the milling head in mm. The latter equation shows that the exit angle φ_{out} depends on

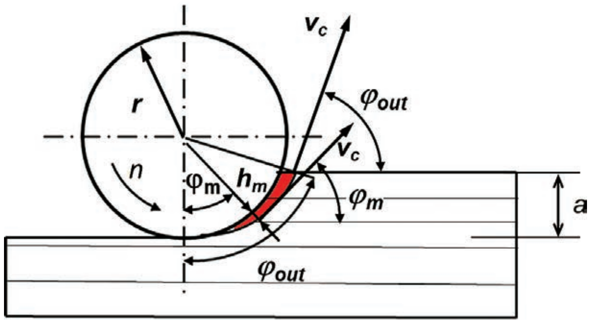

Figure 1 Schematic of cutting principle; v_c – cutting direction, a – depth of cut, r – cutting tool radius, n – rotational velocity, φ_{out} – tool exit angle, φ_m – mean cutting angle, h_m – mean chip thickness
Slika 1. Shema načela rezanja; v_c – smjer rezanja, a – dubina rezanja, r – radijus alata, n – frekvencija vrtnje alata, φ_{out} – izlazni kut alata, φ_m – srednji kut rezanja, h_m – srednja debljina strugotine

both the depth of cut a and the diameter of the blade d. Thus, for smaller blade diameters, the exit angle φ_{out} is larger, and hence the mean angle φ_m as well as specific cutting force k_s.

Once the mean force per cut F_m has been determined (Eq. 1), it is necessary to calculate the average or effective number of blades cutting in the process

$$z_{ef} = \frac{z \cdot \hat{\varphi}_{out}}{2\pi} \tag{7}$$

where $\hat{\varphi}_{out}$ out is the exit angle in radians. If equation 5 is also taken into account, it can be written as

$$z_{ef} = \frac{z \cdot \hat{\varphi}_{out}}{2\pi} = \frac{z \cdot 2 \cdot \sqrt{\frac{a}{d}}}{2\pi} = \frac{z}{\pi}\sqrt{\frac{a}{d}} \tag{8}$$

Thus, from the mean force for one chip F_m and the effective number of teeth z_{ef}, the mean force of the operation is calculated

$$F_{op} = F_m \cdot z_{ef} \tag{9}$$

and further, the cutting moment and cutting power

$$M_c = F_{op} \cdot \frac{d}{2} \tag{10}$$

$$P_c = M_c \cdot \omega \tag{11}$$

where ω is angular velocity in rad/s. Putting all together the final theoretical equation for power calculation is

$$P_c = k_s \cdot b \cdot h_m \cdot z_{ef} \cdot \frac{d}{2} \cdot \omega \tag{12}$$

However, with the advent of computers and Design of Experiments (DOE) methods, it is possible to improve the power calculation using functions determined according to the DOE principle. This method has been used by a number of researchers to vary certain cutting parameters and measure cutting forces and cutting power (Mandic *et al.*, 2015; Porankiewicz *et al.*, 2021; Xu *et al.*, 2022; Zhu *et al.*, 2022).

The disadvantage of these studies is that the relationships obtained are only useful for a limited range of cutting conditions and cannot be used in other conditions. Moreover, the models are usually obtained from linear cutting experiments (Axelsson *et al.*, 1993; Cristóvão *et al.*, 2012), so in the case of a circular cut, the mean thickness of the chip h_m must be calculated, and the mean angle φ_m between the tooth velocity vector and the direction of the wood tissue varies, which in turn requires additional calculations. In other cases, the authors have developed very complex models that include, in addition to linear relationships, power relationships and higher degree polynomials with dozens of coefficients, that, although they describe the measured forces very accurately, are too complicated and therefore impractical for the industrial end user (Mandic *et al.*, 2015; Porankiewicz *et al.*, 2007). Furthermore, the question arises whether such precise models are useful at all, especially when considering the general variability of the mechanical properties of wood and the resulting variability of cutting forces.

The aim of this research is therefore to develop a simple model that can be used to calculate the average cutting power required in peripheral milling of wood. The model will take into account the most important technological parameters in the case of peripheral milling, the input parameters being technological variables that are known to the operator. At the same time, the model will take into account the fact that some conditions change during circular cutting, such as the specific cutting force due to the increasing angle between the cutting direction vector and the wood tissue, as well as the increasing chip thickness.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

14 samples measuring 650 mm × 45 mm × 25 mm (Figure 2) were milled longitudinally on a table milling machine with a milling width of 45 mm. 4 samples of linden (*Tilia platyphyllos*) with the average density of 390 kg/m^3 and standard deviation of 8.9 kg/m^3, 4 samples of ash (*Fraxinus excelsior*) with the density of 640 kg/m^3 and standard deviation of 10.5 kg/m^3 and 6 samples of hornbeam (*Carpinus betulus*) with the average density of 790 kg/m^3 and standard deviation of 11.1 kg/m^3 were used, where all samples had a moisture content of (12±0.5) %. Samples of the same tree species were made from a single board. The feeding speed was 23 m/min, the diameter of the milling cutter 125 mm and the rotational velocity 5900 rpm. Three different cutters were used, each with 4, 6 and 8 cutting edges (Figure 2), consisting of new and sharp carbide inserts with a wedge angle of 60° and rake angle of 20°. The milling depths a (Figure 1) were 2.5, 4.5 and 7 mm. The milling head had an inclination of the cutting edge of 15° where the cutting edge was segmented. The two facts have no influence on the cutting force and power, as shown in Appendix A and B.

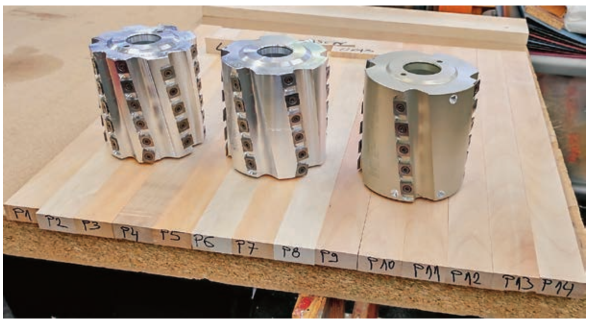

Figure 2 Wood samples together with milling heads
Slika 2. Uzorci drva i alati za glodanje

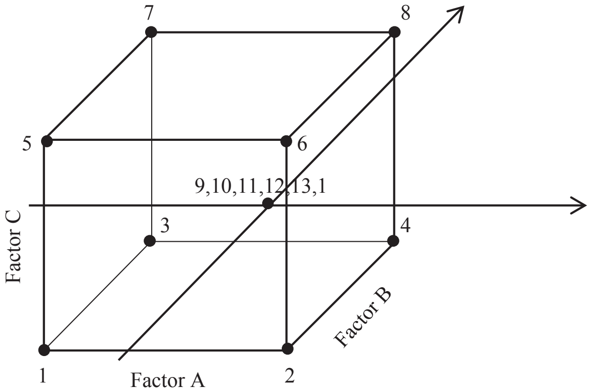

Figure 3 Graphical representation of central composite design (CCD)
Slika 3. Grafički prikaz centralnoga kompozitnog dizajna (CCD)

To plan the experiment, an experimental design was developed using the Design-Expert software (V10, Stat-Ease, Inc., Minneapolis, USA). A conventional two-stage factorial experimental design with three unknowns and 6 central points was used, as shown in Figure 3.

As already mentioned, the density of the wood ρ, the number of knives z and the depth of the cut a varied in the experiment. From these variables, the feed per tooth f_z can be calculated according to Eq. 3, which is different for each number of knives. However, the feed per tooth can also change with different feeding speeds v_f or rotational speed n, but since they were constant in the experiment, the feed per tooth was included as an input parameter in the power equation. Similarly, the depth of cut a influences the mean angle φ_m (Eq. 4) between the vector of blade speed v_c and tissue orientation (Figure 1), which influences the specific cutting force k_s. However, the mean angle φ_m can also be changed if the cutting depth a is constant but the tool diameter d changes. Since different parameters can be influenced by different process factors, the material density ρ, the mean cutting angle φ_m and the feed per tooth f_z were selected as input parameters for the cutting power model. For all input parameters, the values have been converted to base units, i.e. density in kg/m^3, φ_m in radians and feed per tooth f_z in metres, as shown in Table 2, using Eqs. 2-5, to

Table 1 Real value parameters used in experiment
Tablica 1. Stvarne vrijednosti parametara obuhvaćenih eksperimentom

Cutting depth – a *Dubina rezanja – a,* mm	2.5	4.5	7
Corresponding medium cutting angle – φ_m, rad *Odgovarajući srednji kut rezanja –* φ_m, rad	0.141	0.190	0.237
Number of cutting edges – z *Broj oštrica – z*	4	6	8
Corresponding feed per tooth – f_z, m *Odgovarajući posmak po zubu –* f_z, m	0.000975	0.00065	0.000487

Table 2 Parameters used in DOE cutting model
Tablica 2. Parametri korišteni u DOE modelu rezanja

	Encoded values *Kodirane vrijednosti*		
	-1	0	1
Factor A – ρ, kg/m^3	390	640	790
Factor B – φ_m, rad	0.141	0.190	0.237
Factor C – f_z, m	0.000487	0.00065	0.000975

avoid confusion when obtaining the power equation. At the end, the units of the basic variables are converted back to the commonly used units.

The cutting power was measured for different combinations of technological parameters and material properties. First, the idle power of the machine was measured and then the total power during milling under different conditions, from which the idle power was then subtracted. The power was calculated by measuring the voltage (U) and current (I) in all three phases of the electric motor that drives the table cutter. An electrical voltage transformer was used to convert the electrical voltage from the -400 to +400 V range to the -10 to +10 V range, and an electrical current transformer was used to generate a voltage proportional to the current, also in the -10 to +10 V range. All voltages were acquired using a National Instruments NI-USB 6351(Austin, Teksas, USA) acquisition board with a sampling frequency of 2500 Hz and then converted to the real value of the voltage and current. National Instruments LabVIEW (Austin, Teksas, USA) software was used for the acquisition and calculation. The power for each phase was calculated 10 times per second, where for each calculation 250 samples of U and I were used (2500/10) and the total power was the sum of the power of all three phases.

The cutting power was therefore determined as an average value over the entire length of the workpiece. The cutting power was used to calculate the cutting forces, which were further normalised (F_{mb}) to a cutting width of 1 m, dividing by the cutting width b of 0.045 m. An ANOVA analysis was then carried out using the Design-Expert software and significant factors for the model were determined.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Figure 4 shows the measured power when milling with 4 cutting edges with a cutting depth of 2.5 mm, which corresponds to an average angle φ_m of 0.19 rad and a feed per tooth f_z of 0.974 mm. The increase in power from an initial value of 959 W to 1726 W is due to the transition from idling to cutting, where a slight fluctuation in power can be observed due to the variability of wood properties.

Table 3 shows the parameter combinations at which the measurements were carried out, together with the measured cutting powers $P_{c\text{-eksp}}$ and the normalised cutting forces per 1 m chip width (F_{mb}) calculated from the power. The values used in the DOE analysis are highlighted in grey. In addition to the input parameters for the analysis (ρ, φ_m, f_z, F_{mb}), the parameters a and z, from which the values of the input parameters were obtained, are also given.

Table 4 shows the results of the ANOVA analysis. All main factors and their correlations are significant for the model (p = 0.05), except for the combination AB, i.e. ρ* φ_m, while the combination AC has only a slightly increased p-value and was therefore also included in the model. The R^2 for the model is 0.9556, while the adjusted R^2 and the predicted R^2 are 0.9279 and 0.8067, respectively, and are therefore in reasonable agreement. The Adequate Precision, which measures the ratio of signal to noise as 20.8, is also well above the desirable value of 4.

The model in terms of coded and actual factors is shown in Table 5. The model in coded factors shows that all factors have approximately equal values and thus all have equal significant influence on the determination of the cutting force.

The distribution of the residuals is shown in Figure 5. The residuals are normally distributed, as there are no major deviations from the ideal distribution.

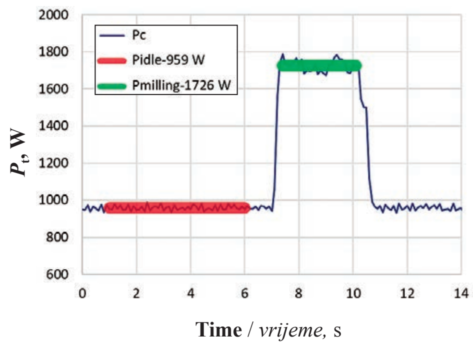

Figure 4 Variation of power during specimen milling
Slika 4. Varijacije snage tijekom glodanja uzorka

Table 3 Combinations of analysis parameters
Tablica 3. Kombinacije analiziranih parametara

Run	ρ, kg/m³	φ_m, rad	f_z, m	a, mm	z	$P_{c\text{-eksp}}$, kW	F_m, N	F_{mb}, N/m
1	390	0.237	0.000975	7	4	2.79	239.8	5328.77
2	640	0.190	0.000650	4.5	6	1.81	129.3	2874.44
3	640	0.190	0.000650	4.5	6	2.02	144.4	3207.94
4	640	0.190	0.000650	4.5	6	2.01	143.6	3192.05
5	790	0.141	0.000975	2.5	4	1.15	165.4	3675.36
6	790	0.237	0.000975	7	4	3.44	295.7	6570.24
7	390	0.141	0.000975	2.5	4	0.76	109.3	2428.93
8	640	0.190	0.000650	4.5	6	1.9	135.8	3017.36
9	390	0.141	0.000487	2.5	8	1.5	107.9	2396.97
10	390	0.237	0.000487	7	8	3.15	135.4	3008.18
11	790	0.237	0.000487	7	8	3.58	153.8	3418.82
12	640	0.190	0.000650	4.5	6	1.86	132.9	2953.84
13	640	0.190	0.000650	4.5	6	1.97	140.8	3128.53
14	790	0.141	0.000487	2.5	8	1.71	123.0	2732.55

Table 4 Result of ANOVA analysis
Tablica 4. Rezultati ANOVA analize

Source *Izvor*	Sum of squares *Zbroj kvadrata*	df	Mean square *Srednji kvadrat*	*F*-value *F-vrijednost*	*p*-value *p-vrijednost*
Model	16400000	6	2733000	25.130	0.000
$A-\rho$	1056000	1	1056000	9.710	0.017
$B-\varphi_m$	6250000	1	6250000	57.450	0.000
$C-f_z$	6445000	1	6445000	59.250	0.000
AB	523.34	1	523.34	0.005	0.947
AC	434900	1	434900	4.000	0.086
BC	2536000	1	2536000	23.310	0.002

There are also no significant deviations between the calculated and measured values (Figure 5). The significance of the parameters can be clearly seen in Figure 6.

The resulting model with actual factors must then be multiplied by the cutting width b to get the F_m,

$$Fm=\left(5105.-8426276f_z-16866\varphi_m+4.84\times10^7 f_z\varphi_m-\right.$$
$$\left.-1.694\rho+4771f_z\rho\right)b \tag{13}$$

In this model (Eq. 13), f_z and b are the feed per tooth and the cutting width still in metres, respectively, is the mean angle in radians, and ρ is the wood density in kg/m³.

Table 5 Model for calculating cutting forces in terms of coded and actual factors
Tablica 5. Model za proračun sila rezanja u smislu kodiranih i stvarnih čimbenika

Coded factors *Kodirani čimbenici*		Actual factors *Stvarni čimbenici*	
F_{mb}	=	F_{mb}	=
+3530.52		+5105.04	
+358.66	*A	-1.69	* ρ
+928.17	*B	-16866	*φ_m
+877.85	*C	-8.42E+06	*f_z
+232.85	*AC	+4771.50	* ρ * φ_m
+591.31	*BC	+4.84E+07	*φ_m * f_z

However, since f_z and φ_m are not basic technological parameters but, as already mentioned, depend on the basic technological parameters, they must be replaced by equations 3 to 5. Multiplying the resulting equation by z_{ef} (Eq. 7) gives the force of the operation F_{op}, which is further multiplied by the cutting radius to obtain the torque, and then by the angular velocity to obtain the final equation for the cutting power. Changing the units of the input parameters, b and a back to mm, the final model that takes into account the relevant technological parameters for the power calculation will be

$$Pc=b\left(a\left(0.807v_f-0.000281nz\right)+\sqrt{\frac{a}{d}}d\left(\left(-0.14+0.0000795\rho\right)v_f\right.\right.$$
$$\left.\left.+n\left(0.0000850-2.82\times10^{-8}\rho\right)z\right)\right) \tag{14}$$

Where v_f is the feeding speed in m/min, n is the rotational speed of the tool in rpm, z is the number of cutting edges on the circumference of the tool, a is the cutting depth in mm, d is the diameter of the tool in mm and ρ is the density of the material in kg/m³.

The measured and calculated cutting powers from Eq. 14 are shown in Table 6 together with their ratios. The latter show that the average deviation of the calculated values from the measured values is 6.6 %, which represents a good agreement between the measured and calculated values.

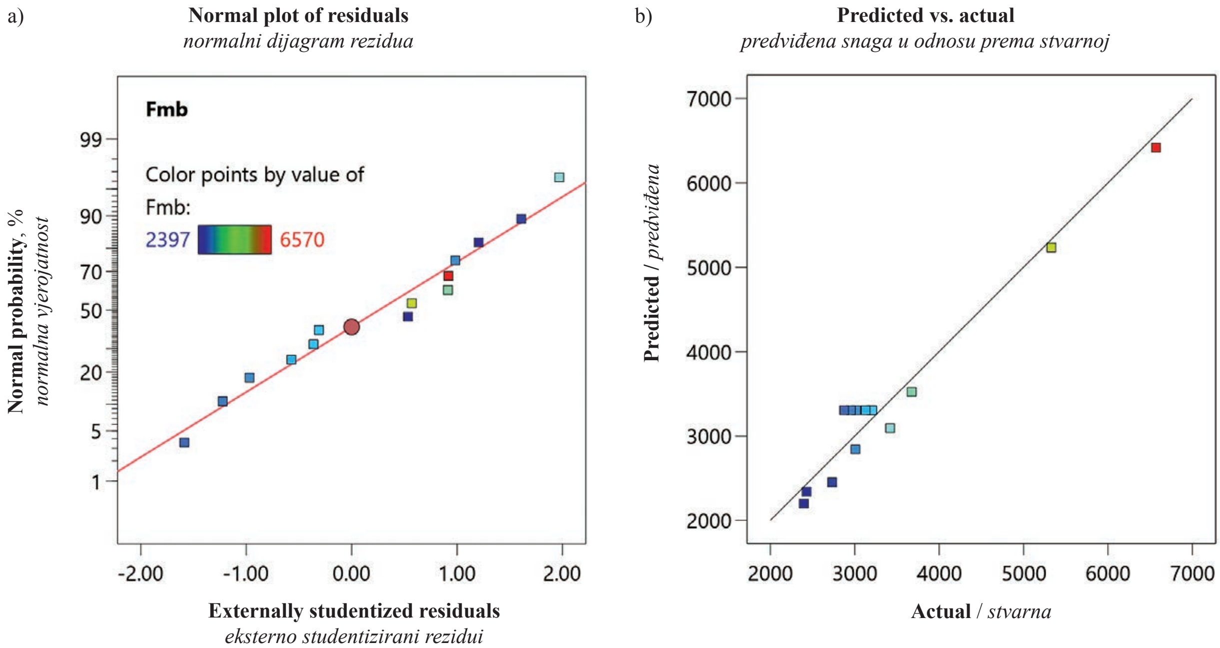

Figure 5 Distribution of residuals (a) and predicted vs. actual cutting forces for DOE model (b)
Slika 5. Distribucija rezidua (a) i predviđene sile rezanja u odnosu prema stvarnima za DOE model (b)

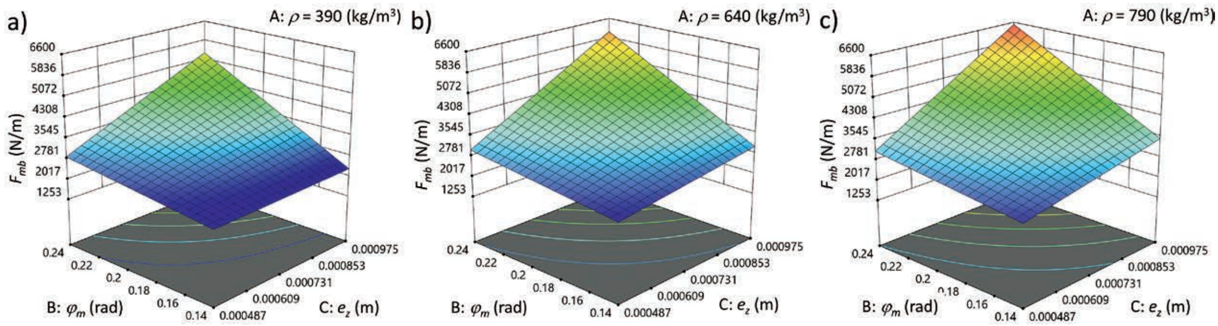

Figure 6 3D plot of cutting model with various factors
Slika 6. 3D dijagram modela rezanja pri različitim čimbenicima

Table 6 Measured and calculated cutting power values (ρ – density, *a* – depth of cut, *z* – number of cutting knives, P_{c-eksp} – measured cutting power, P_{c-cal} – calculated cutting power)
Tablica 6. Izmjerene i izračunane vrijednosti snage rezanja (ρ – gustoća, *a* – dubina rezanja, *z* – broj oštrica, P_{c-eksp} – izmjerena snaga rezanja, P_{c-cal} – proračunana snaga rezanja)

Run	ρ, kg/m³	*a*, mm	z	P_{c-eksp}, kW	P_{c-cal}, kW	P_{c-eksp}/P_{c-cal}
1	390	7	4	2.79	2.74	1.02
2	640	4.5	6	1.81	2.08	0.87
3	640	4.5	6	2.02	2.08	0.97
4	640	4.5	6	2.01	2.08	0.97
5	790	2.5	4	1.15	1.10	1.04
6	790	7	4	3.44	3.36	1.02
7	390	2.5	4	0.76	0.73	1.04
8	640	4.5	6	1.9	2.08	0.91
9	390	2.5	8	1.5	1.38	1.09
10	390	7	8	3.15	2.98	1.06
11	790	7	8	3.58	3.24	1.10
12	640	4.5	6	1.86	2.08	0.89
13	640	4.5	6	1.97	2.08	0.95
14	790	2.5	8	1.71	1.53	1.11

4 CONCLUSIONS
4. ZAKLJUČAK

From the results presented in this research, it can be concluded that:

The resulting model can be used to predict the average cutting power during peripheral milling of tested wood species in the machining conditions similar to the ones used in the experiment with an accuracy of 6.6 % as a function of tool diameter, tool rotational speed, number of cutting blades, feed rate, depth of cut and wood density.

With modern methods of experimental design, it is possible to obtain reliable and accurate models with a relatively small number of measurements.

The resulting model can also be used to calculate the cutting power for other tree species with densities in the range of 390 to 790 kg/m^3, as it is known that the mechanical properties and thus the cutting power vary with the density of the wood.

Using the same procedure, it is possible to develop a model for calculating the cutting power in other cutting directions.

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APPENDIX A
DODATAK A

Inclination of the cutting edge
Nagib oštrice

The milling head had an inclination angle of 15°, which can have two effects. First, the inclination increases the effective rake angle and secondly, the time course of the forces is not the same as without inclination, as the cutting edge does not begin to cut all at once, but gradually.

The effect of the inclination on the effective rake angle is shown in Figure A1.

In the case of an inclination for an angle λ, for a blade with a nominal rake angle γ_{eff}, the following can be written

$$\tan \gamma_{\mathrm{eff}} = \frac{AC}{AD} \tag{A1}$$

$$\tan \gamma_{\mathrm{nom}} = \frac{AB}{AD} \rightarrow AD = \frac{AB}{\tan \gamma_{\mathrm{nom}}} \tag{A2}$$

and also

$$\cos \lambda = \frac{AB}{AC} \rightarrow AC = \frac{AB}{\cos \lambda}. \tag{A3}$$

Combining AC and AD from Eqs. A2 and A3 and inserting into Eq. A1 gives the following expression for the effective rake angle

$$\tan \gamma_{\mathrm{eff}} = \frac{\frac{AB}{\cos \lambda}}{\frac{AB}{\tan \gamma_{\mathrm{nom}}}} = \frac{\tan \gamma_{\mathrm{nom}}}{\cos \lambda} \tag{A4}$$

$$\gamma_{\mathrm{eff}} = \mathrm{atan} \frac{\tan \gamma_{\mathrm{nom}}}{\cos \lambda} \tag{A5}$$

If the nominal rake angle is 20° and the inclination angle is 15°, the effective rake angle is 20.6°, which practically corresponds to the nominal rake angle and, in our case, the influence of the inclination on the effective rake angle can be neglected.

Another factor that influences the inclination is the progression of the force over time, because the cutting edge does not start to cut all at once, but penetrates into the wood gradually. The effect of the inclination on the total cutting force can be analysed as follows.

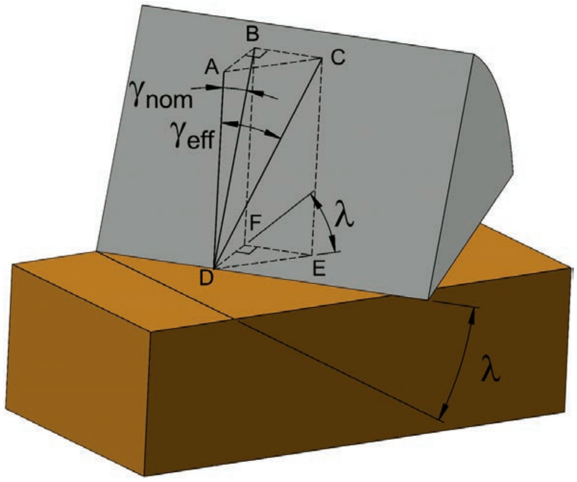

Figure A1 Inclined cutting
Slika A1. Rezanje pod kutom

If the cutting edge is divided into infinitesimal lengths Δb, the average force for each Δb to create a chip can be calculated as follows

$$\Delta F_{\mathrm{m}} = k_{\mathrm{s}} \cdot \Delta b \cdot h_{\mathrm{m}}. \tag{A6}$$

For each Δb, the ΔF_{op} can then be calculated

$$\Delta F_{\mathrm{op}} = \Delta F_{\mathrm{m}} \cdot z_{\mathrm{ef}} \tag{A7}$$

and further ΔM_c and ΔP_c

$$\Delta M_{\mathrm{c}} = \Delta F_{\mathrm{op}} \cdot \frac{d}{2} \tag{A8}$$

$$\Delta P_{\mathrm{c}} = \Delta M_{\mathrm{c}} \cdot \omega \tag{A9}$$

Since ΔP_c for the individual Δb can be added together, the total power is equal to

$$P_{\mathrm{c}} = \sum \Delta P_{\mathrm{c}} = \sum (\Delta M_{\mathrm{c}} \cdot \omega) = \sum (\Delta F_{\mathrm{op}} \cdot \frac{d}{2} \cdot \omega) = \sum (\Delta F_{\mathrm{m}} \cdot z_{\mathrm{ef}} \cdot \frac{d}{2} \cdot \omega)$$
$$= \sum \left(k_{\mathrm{s}} \cdot \Delta b \cdot h_{\mathrm{m}} \cdot z_{\mathrm{ef}} \cdot \frac{d}{2} \cdot \omega \right) = k_{\mathrm{s}} \cdot h_{\mathrm{m}} \cdot z_{\mathrm{ef}} \cdot \frac{d}{2} \cdot \omega \cdot \sum \Delta b \tag{A10}$$

Considering further

$$\sum \Delta b = b \tag{A11}$$

The final equation for calculating the cutting power of inclined cutting edge is

$$P_{\mathrm{c}} = k_{\mathrm{s}} \cdot h_{\mathrm{m}} \cdot z_{\mathrm{ef}} \cdot \frac{d}{2} \cdot \omega \cdot b \tag{A12}$$

which is the same as Eq. 12, meaning that the overall cutting force is unaffected by the inclination in terms of the temporal distribution of forces.

APPENDIX B
DODATAK B

Segmented cutting edge
Segmentirana oštrica

As the cutting edge is segmented, the resulting chip does not have a uniform cross-section across the entire width of the workpiece, as the wood between the two cutting edges remains in the running cut and is only removed by the next cutting edge. This means that the thickness of the chip varies across the width of the workpiece.

The milling head has a segmented cutting edge where the length of the insert is 15 mm and the distance between the inserts is 9 mm (Figure 2). If a crosscut is made through the workpiece at the point where the chip has an average thickness as shown in Figure B1, the cross-section can be seen in Figure B2.

The cross-section of a single cut is represented by the same colour and a number. If any position is taken and the next following cut is marked with the number 1, blue cross-section chips with the number 1 are made. Then comes the next cutting edge with the number 2, which produces red cross-section chips with the number 2. This is followed by 3, 4... As the cutting edge is segmented, the thickness of the chip varies. At the point where the cutting inserts overlap, each cutting edge cuts a chip with an average chip thickness of h_{m1}, and at the point where they do not overlap, every second cutting edge cuts a chip with an average thickness of h_{m2}. The force of a segmented cutting edge (Equation 1) can therefore be described as follows

$$F_m = k_s \cdot \frac{6}{24} b \cdot h_{m1} + k_s \cdot \frac{9}{24} b \cdot h_{m2} \tag{B1}$$

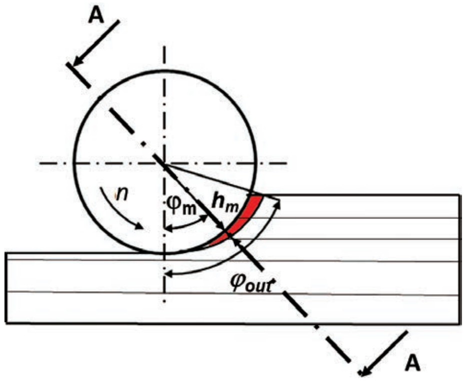

Figure B1 Schematic of cutting principle
Slika B1. Shema načela rezanja

Considering Eqs. 2 and 3, the mean thickness of the chip h_{m1} is

$$h_{m1} = \frac{v_f}{n \cdot z} \cdot \sqrt{\frac{a}{d}} \tag{B2}$$

and h_{m2}

$$h_{m2} = \frac{v_f}{n \cdot \frac{z}{2}} \cdot \sqrt{\frac{a}{d}} = 2 \frac{v_f}{n \cdot z} \cdot \sqrt{\frac{a}{d}} = 2 \cdot h_{m1} \tag{B3}$$

Inserting Eq. B3 into B1, the following relationship can be written

$$\begin{aligned} F_m &= k_s \cdot \frac{6}{24} b \cdot h_{m1} + k_s \cdot \frac{9}{24} b \cdot 2h_{m1} \\ &= k_s \cdot \frac{6}{24} b \cdot h_{m1} + k_s \cdot \frac{18}{24} b \cdot h_{m1} = k_s \cdot b \cdot h_{m1} \end{aligned} \tag{B4}$$

Considering that $h_m = h_{m1}$, it follows that the mean force per cut with a segmented cutting edge is equal to the mean force per cut with a non-segmented cutting edge, which proves that a segmented cutting edge has no influence on the magnitude of the total cutting force.

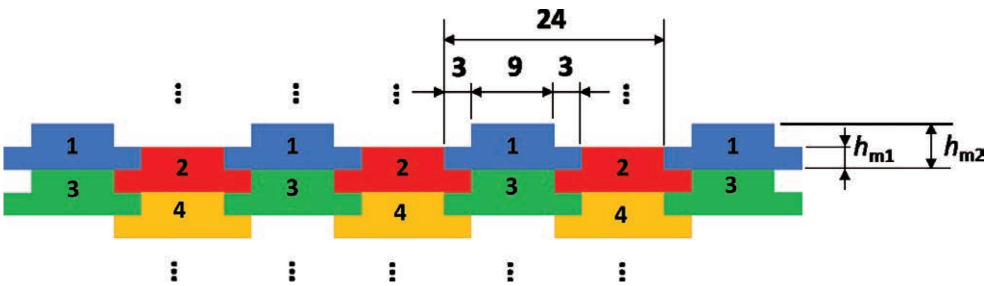

Figure B2 Cross section A – A from Figure B1. The numbers show the order of cutting edges (h_{m1} – mean thickness of the chip where the cutting inserts overlap, and each cutting edge cuts a chip; h_{m2} – mean thickness of the chip where consecutive cutting edges do not overlap, and every second cutting edge cuts a chip)
Slika B2. Presjek A – A na slici B1. Brojevi pokazuju redoslijed reznih rubova (h_{m1} – srednja debljina strugotine gdje se rezne pločice preklapaju i svaka oštrica reže strugotinu; h_{m2} – srednja debljina strugotine gdje se uzastopne oštrice ne preklapaju i svaki drugi rezni brid reže strugotinu).

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