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Artificial Neural Network-Based Optimization of CO_2 Laser Cutting Parameters for Beech Plywood and HDF: A Kerf Geometry Perspective

Optimizacija parametara rezanja bukove furnirske ploče i HDF-a CO_2 laserom, uz primjenu umjetne neuronske mreže: geometrija reza

ORIGINAL SCIENTIFIC PAPER
Izvorni znanstveni rad
Received – prispjelo: 31. 7. 2025.
Accepted – prihvaćeno: 13. 10. 2025.
UDK: 674.05
https://doi.org/10.5552/drvind.2026.0284

ABSTRACT • *This study presents the results of Artificial Neural Networks (ANN) predictions with the aim of optimizing the process of beech plywood and HDF laser cutting. A survey is given of the results of predictions of cutting kerf parameters made by Artificial Neural Networks to cover a wide spread of CO_2 laser parameters, as well as the results of experimental cutting with maximum laser power ($\underline{P}$) equal to 135 W and maximum feed rate ($\underline{v}$) equal to 20 mm/s. Validity of the best neural network was checked versus overfitting of the best neural networks, confirmed according to $\underline{r}$ value of the model (minimum 0.971), MAPE (%) (maximum 6.21 %) and compared with the results of other authors. The article also presents the effect of energy density values $\underline{E}$ on values of cutting kerf parameters and their variance. The results show that the optimal value of laser power ($\underline{P}$) and feed rate ($\underline{v}$) for beech plywood are (200-300 W; 10-15 mm/s), while for more dense and more homogenous high-density fibreboard (HDF) they are (300-500 W; 5-10 mm/s). Optimal energy densities ($\underline{E}$) are then 133 MJ/m^2 for beech plywood and 433 MJ/m^2 for HDF. Similar as for other wooden materials, it follows that more dense species of wood should be cut with higher values of energy densities. The results can be applied to reduce the material and energy demands by optimizing the quality of cut with minimum symmetrical kerf widths.*

KEYWORDS: *artificial neural networks; laser cutting; cutting kerf; wood composite materials; optimization*

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SAŽETAK • *Studija predstavlja primjenu umjetnih neuronskih mreža (ANN) za optimizaciju procesa laserskog rezanja bukove furnirske ploče i HDF-a. Prikazani su rezultati predviđanja parametara geometrije reza primjenom umjetnih neuronskih mreža kako bi se pokrio širok raspon parametara* CO_2 *lasera te su izneseni rezultati eksperimentalnog rezanja laserom najveće snage (*$\underline{P}$*) od 135 W i najvećom brzinom pomaka (*$\underline{v}$*) od 20 mm/s. Validacija najbolje neuronske mreže provjerena je s obzirom na pretjerano prilagođivanje najboljih neuronskih mreža i potvrđena je prema* $\underline{r}$ *vrijednosti modela (najmanje 0,971), vrijednosti MAPE (%) (najviše 6,21 %) te je uspoređena s rezultatima drugih autora. Studija prikazuje i utjecaj vrijednosti gustoće energije* $\underline{E}$ *na parametre geometrije reza i njihovu varijancu. Iz prikazanih rezultata proizlazi da su optimalne vrijednosti snage lasera (*$\underline{P}$*) i brzine pomaka (*$\underline{v}$*) za bukovu furnirsku ploču 200 – 300 W i 10 – 15 mm/s, dok su optimalne vrijednosti za gušću i homogeniju tvrdu ploču vlaknaticu (HDF) 300 – 500 W i 5 – 10 mm/s. Optimalne gustoće energije (*$\underline{E}$*) pritom su bile 133 MJ/m*^{2} *za bukovu furnirsku ploču i 433 MJ/m*^{2} *za HDF. Slično kao i za druge drvne materijala, proizlazi da je vrste drva veće gustoće bolje rezati uz veću gustoću energije. Rezultati se mogu primijeniti za smanjenje potreba za materijalom i energijom optimiziranjem kvalitete reza s minimalnom simetričnom širinom reza.*

KLJUČNE RIJEČI: *umjetna neuronska mreža; rezanje laserom; geometrija reza; kompozitni drvni materijali; optimizacija*

1 INTRODUCTION
1. UVOD

Laser cutting is considered one of the advanced and promising methods for processing wood materials. Its main advantages include improved cutting quality compared to conventional sawing, reduced heat-affected zones, and contactless operation. Several studies have investigated the use of CO_2 laser cutting for wood processing (Ready *et al*., 2001; Zhou and Mahdavian, 2004; Barcikowski *et al*., 2004; Aniszewska *et al*., 2020; Nath *et al*., 2020; Barcikowski *et al*., 2006; Eltawahni *et al*., 2011; Martínez-Conde *et al*., 2017).

Prior research has examined the impact of laser parameters on the cutting characteristics of medium-density fibreboard and plywood materials, but only on a limited scale of laser beam parameters or using different types of lasers. Optimization of laser cutting processes for wood-based agglomerates has been carried out primarily on materials such as plywood and medium-density fibreboard (MDF). For plywood, the influence of laser parameters on cut quality has been investigated by Pikuma *et al*. (2019) and Yung *et al*. (2021), focusing on factors such as laser power, feed rate, and beam type. In the case of MDF, Eltawahni *et al*. (2013) and Lum *et al*. (2000) optimized laser cutting by analyzing the effects of laser power and feed rate on kerf characteristics. These investigations highlight the importance of selecting appropriate laser parameters to achieve minimum thermal damage, improved edge quality, and efficient material removal during the cutting of engineered wood products.

Although laser cutting offers numerous advantages such as high precision, non-contact processing, and flexibility in cutting complex geometries across a wide range of materials including thermoplastics and composites, it also presents certain drawbacks. The most notable are the high initial investment costs for CO_2 laser systems, the need of material parameters optimization as well as energy consumption required to ensure cut quality of materials like polyethylene (PE), polypropylene (PP), and acrylonitrile-styrene-acrylate (ASA), which are thermally heterogeneous (Basar and Der, 2025; Der *et al.*, 2024). Additionally, achieving desirable surface quality and minimizing heat-affected zones in 3D-printed parts – particularly those produced by fused filament fabrication (FFF) using carbon fibre-reinforced polylactic acid (PLA) or acrylonitrile-styrene-acrylate (ASA) – requires extensive experimental calibration due to the inherent anisotropy and layer-dependent thermal response of such materials, further complicating the standardization and scalability of the process in industrial applications (Der, 2025; Basar *et al.,* 2025).

These challenges can be effectively addressed through prediction models either by non-linear mathematic fitting procedures or by artificial neural networks (ANN). Both approaches serve to decrease the number of experimental tests required for full-scale optimization of cutting processes thus reducing energy and material demands. However, ANN has been more extensively adopted as a regression mathematical model. Due to its higher versatility, ANN improved statistical prediction accuracy and reduced computational time owing to its AI-based architecture (Ružiak *et al.,* 2022; Ružiak *et al.,* 2024; Ružiak *et al.,* 2025).

The ANN methodology has also been successfully applied for the optimization of wood processing technologies. Bedelean *et al*. (2023) employed this method in combination with Response Surface Methodology (RSM) to optimize the plywood drilling process, achieving improvements in surface quality and tool performance. Similarly, Ozsahin *et al*. (2019) utilized ANN to minimize energy consumption during the milling of both heat-treated and untreated wood. These studies demonstrate the adaptability of ANN models in predicting complex relationships between processing parameters and output responses in wood-based manufacturing. As a result, ANN serves as a powerful tool for enhancing process efficiency and reducing material or energy waste.

During CO_2 laser cutting of wood, the quality of the cut is typically evaluated by measuring the kerf widths and the extent of the heat-affected zones (HAZ) on both the upper and lower surfaces of the material. The kerf widths on the upper and lower surfaces, where the laser beam initially interacts with the material and exits, are denoted as WKU (upper kerf width) and WKL (lower kerf width), respectively, as illustrated in Figure 1. Similarly, the widths of the heat-affected zones on the upper and lower surfaces are represented by WHAZU and WHAZL, indicating the thermal influence of the laser on both sides of the workpiece. These parameters are crucial indicators of cutting quality, affecting dimensional accuracy and surface integrity. Process of kerf creation on former irradiated surface (upper) and on opposite surface (lower) depends on laser processing parameters, cutting direction, density of material and many other parameters. Upper surface kerf width depends mainly on processing parameters, while lower surface kerf width also depends on heat transfer rate to HAZ, which leads to differences between WKU and WKL, resulting in asymmetric kerf. Finding values of laser processing parameters that lead to symmetric kerf is important for technological processing of samples.

Optimization of CO_2 laser cutting, focusing on the kerf width ratio ($WKR = \frac{WKL}{WKU}$), has been conducted utilizing ANN for spruce wood in studies (Ružiak *et al.,* 2022; Ružiak *et al.,* 2024) and for spruce, beech and oak wood in studies (Ružiak *et al.,* 2025). These investigations analyzed the influence of laser parameters – power (P), feed rate (v) – and cutting orientation relative to the fibre direction and perpendicular to the fibres.

ANN was also successfully applied for the modelling of wood surface roughness and power consumption after CO_2 laser cutting in the studies conducted by Tiryaki *et al*. (2014, 2016, and 2017). These studies demonstrated that ANN models could accurately predict surface quality and energy requirements based on laser cutting parameters. By capturing the nonlinear relationships between input variables and output responses, ANN provided a reliable framework for performance evaluation and process optimization. This approach enables researchers and manufacturers to improve cut quality and energy efficiency without extensive trial-and-error experimentation.

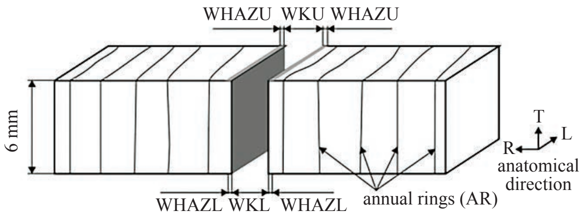


Figure 1 CO_2 laser cutting scheme of wood sample (Ružiak *et al.,* 2022)

Slika 1. Shema rezanja uzorka drva CO_2 laserom (Ružiak i sur., 2022.)

In this article the focus is on optimizing CO_2 laser cutting of beech plywood and high-density fiberboard (HDF) using ANN to model the relationship between laser power P, feed rate v, d as beam diameter in contact with upper surface, and energy density $E = \frac{P}{v{\cdot}d}$. The objective of the research is to identify the optimal P, v and E values (at which WKR value is closest to 1 and WKU, WKL are minimal), for each material individually within the complete range of P, with v applicable for these types of materials. Such routine lowers material and energy demands needed for inspection of cutting kerf parameters mentioned above. The objective of the research, therefore, is not only to determine the optimal laser parameter values for achieving ideal cuts, but also to compare these results regarding different microstructures of the material.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Experimental measurements were conducted on tangential sections of beech plywood and high-density fiberboard (HDF) samples, each with dimensions of 6 mm (thickness) × 70 mm (width) × 500 mm (length) acclimatized at $T = (20\pm1)$ °C and at relative air humidity of 65 %. These conditions were selected to ensure consistency and represent typical material states encountered in industrial applications. Density of HDF samples used was 850 kg/m^3, with a density of 5-ply beech plywood of 750 kg/m^3.

The samples were cut using a CO_2 laser beam with maximum laser power of 135 W and maximum feed rate of 20 mm/s. The beam diameter was $d = 0.15$ mm and wavelength 10.6 µm. Maximum power of laser intensity I on upper surface, computed as power divided by area of spot, was 7643 W/m^2. The specified parameters P and v served as the experimental input data. For each P, v pair, the average values of parameters WKU and WKL were obtained experimentally from 30 measurements.

The WKU and WKL values were determined using the VHX-H5M software, which is integrated with the Keyence VHX-7000 digital microscope (Keyence

Table 1 Experimental and predicted values of delivered energy density *E* for agglomerated materials
Tablica 1. Eksperimentalne i predviđene vrijednosti gustoće isporučene energije *E* za drvne materijale

v, mm/s / *P*, W	54	81	108	135	200	300	400	500
5	72	108	144	180	267	400	533	667
10	36	54	72	90	133	200	267	333
15	24	36	48	60	89	133	178	222
20	18	27	36	45	67	100	133	167
30	12	18	24	30	44	67	89	111
40	9	14	18	23	33	50	67	83
50	7	11	14	18	27	40	53	67

Corporation, Osaka, Japan). The effects of other laser parameters were not studied, as they were kept constant throughout the experiments. The predicted values of the WKU, WKL, and WKR parameters were obtained outside the measured values of *P* and *v* for all combinations of *P* values (200, 300, 400, 500) W and *v* values (5, 10, 15, 20, 30, 40 and 50) mm/s. The values of the delivered energy density *E* are also shown in Table 1. Experimental values are highlighted in red, and predicted values are in black. First row corresponds to values of *P* and first column values of *v* in selected units. Numerical values outside the 1st row or column correspond to energy density values in MJ/m^2.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In this section, we present the results of the ANN predictions, the effect of energy density value (E) on WKU, WKL, and WKR, and, in the final part, the full-scale optimization of WKR parameters with respect to laser power (*P*), feed rate (*v*), and energy density (*E*) for each material individually. All results are compared with reference values. This comprehensive analysis allows for a better understanding of how each parameter influences cutting quality across different material types.

Prediction validity depends on statistical parameters of the best neural networks. Therefore, the values of the above-mentioned statistical indicators for the best-performing network are first presented separately for beech plywood, and HDF, in Tables 2 to 3. The measured data are divided into training, validation, and testing datasets by a ratio of 60 % : 20 % : 20 %.

According to the above-mentioned statistical parameters of the best ANN, it is possible to predict how the values of WKL, WKU, and WKR parameters will be changed by laser parameters.

For the prediction of WKU, WKL and WKR values at non-measured values of *P*, *v* best neural networks must fulfil the condition of no overfitting of the training group. This condition was checked individually for beech plywood training and HDF training, through mean squared error (MSE). MSE for training, testing and validation group for beech plywood – HDF were equal to (3000-3150-3060; 450-480-469) (μm)^2. These results clearly show that the change of input data does not lead to change of best networks error, meaning that best neural networks are not overfitted. In the following sections, the predictions obtained, results of statistical tests, and optimized values of the observed parameters will be presented.

3.1 ANN prediction for beech plywood
3.1. Predviđanje ANN-a za bukovu furnirsku ploču

This section presents the results of the prediction for beech plywood in Figures 2 a, b, and c.

Figures 2a – c show:

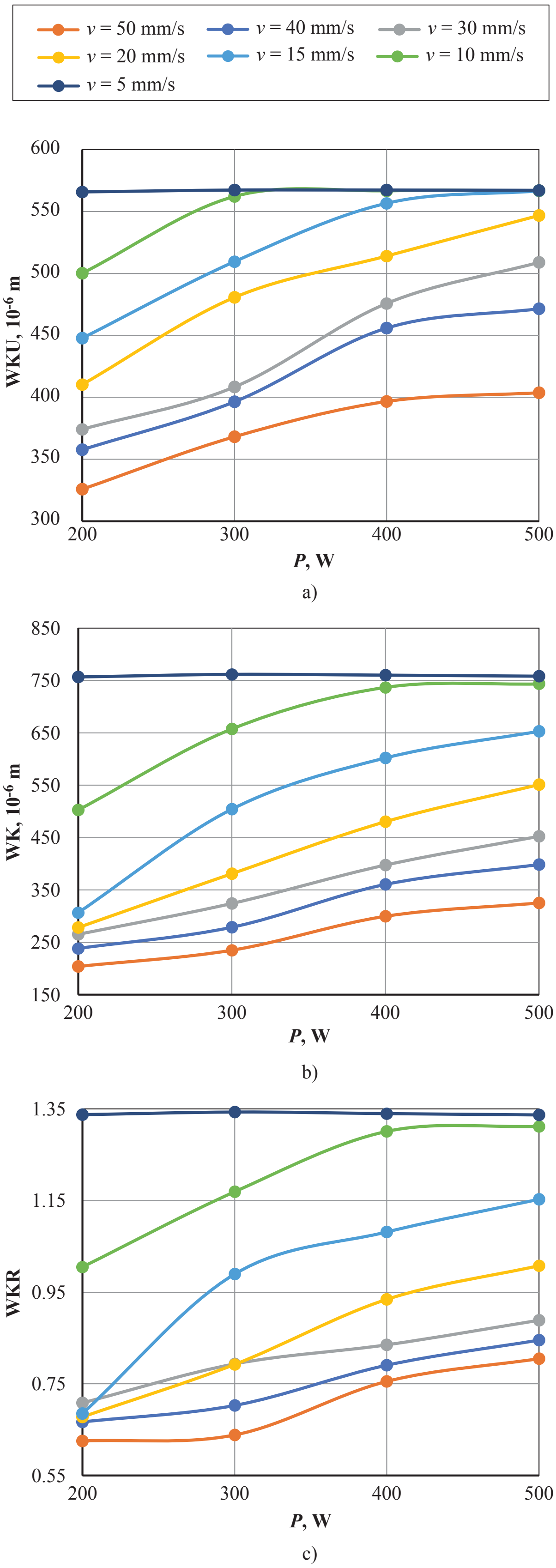
- The parameters WKU and WKL decrease nonlinearly with *v*, especially for feed rates above 15 mm/s. This results from the fact that the change in the delivered energy density *E* depending on the feed rate *v* is inversely proportional. The inverse effect of *v* on widths of cutting kerfs WKU and WKL was recorded by many other authors dealing with wood composites (Eltawahni *et al.*, 2011; Barnekov *et al.,* 1989; Lazov *et al.,* 2017; Eltawahni *et al.,* 2013; Lum *et al.,* 2000; Lum *et al.,* 2000; Pikuma *et al.,* 2019; Yung *et al.,* 2021), and wood materials (Barnekov *et al.,* 1986; Corleto *et al.,* 2024; Hérnandez-Castaneda *et al.,* 2011; Keles and Oner, 2010; Nukman *et al.,* 2008; Xu *et al.,* 2017; Ružiak *et al.,* 2022; Ružiak *et al.,* 2024; Ružiak *et al.,* 2025).

Table 2 Statistical parameters for predicting WKU, WKL, and WKR for beech plywood
Tablica 2. Statistički parametri za predviđanje vrijednosti WKU, WKL i WKR za bukovu furnirsku ploču

Parameter *Parametar*	*r*	**MAPE, %**	**Designation** *Oznaka*	**Activation functions** *Aktivacijske funkcije*
WKU (10^{-6}m)	0.979	2.80	MLP 2-7-3	Logistic, Exponential
WKL (10^{-6}m)	0.986	6.21		
WKR (-)	0.976	5.73		

Table 3 Statistical parameters for predicting WKU, WKL, and WKR for HDF
Tablica 3. Statistički parametri za predviđanje vrijednosti WKU, WKL i WKR za HDF

Parameter *Parametar*	*r*	**MAPE, %**	**Designation** *Oznaka*	**Activation functions** *Aktivacijske funkcije*
WKU (10^{-6}m)	0.971	2.15	MLP 2-6-3	Exponential, Tanh
WKL (10^{-6}m)	0.988	3.70		
WKR (-)	0.986	3.86		



a)

b)

c)

Figure 2 WKU (a), WKL (b), and WKR (c) versus *P*, *v* for beech plywood
Slika 2. WKU (a), WKL (b) i WKR (c) u odnosu prema *P*, *v* za bukovu furnirsku ploču

- The parameters *WKU* and *WKL* stabilize with increasing power, which is a typical trend reported by many authors (Eltawahni *et al.,* 2011; Nukman *et al.,* 2008; Xu *et al.,* 2017; Eltawahni *et al.,* 2013; Lum *et al.,* 2000; Lum *et al.,* 2000; Pikuma *et al.,* 2019; Yung *et al.,* 2021; Ružiak *et al.,* 2022; Ružiak *et al.,* 2024; Ružiak *et al.,* 2025).
- Given the definition of the parameter WKR, this parameter also stabilizes with increasing power.
- The width of the cutting kerf on both sides evens out at feed rate *v* of approximately 15 mm/s and at laser power *P* of 300 W.
- The parameter WKR shows a value close to 1 even at a feed rate *v* = 10 mm/s and laser power *P* of 200 W; nevertheless, both *P*, *v* combinations lead to the same value of the optimal energy density *E*, equal to 133 MJ/m^2.
- For feed rate *v* = 10 mm/s and lower, the ratio WKR values are significantly higher than 1, meaning that the WKU is significantly smaller than WKL.
- On the other hand, as the feed rate increases above 15 mm/s, the value of WKR decreases significantly below 1, meaning that the width of the cutting kerf on the lower surface WKL is significantly smaller than on the upper surface. This is caused by lowering value of WKL due to thermal losses to HAZ.

3.2 ANN prediction for HDF

3.2. Predviđanje ANN-a za HDF

Results of the prediction for HDF are presented in Figures 3 a-c.

From Figures 3a – c, the following can be concluded:

- The parameters WKL, WKU decrease nonlinearly with the feed rate v.
- For HDF material, the parameters WKU and WKL do not stabilize within the power range of up to 500 W. This is consistent with the fact that HDF has the highest density, and thus the optimal Energy density E is also maximum.
- The optimal value of WKR close to 1 is only achieved for minimum feed rates, up to 10 mm·s-1, which is because the HDF, as the densest wood species, requires the highest value of E for an optimal cut.
- For every higher feed rate, the value of WKU is greater than WKL, meaning that higher feed rates lead to increase in WHAZL thus lowering WKL value.

3.3 The study of *E* effect on WKU, WKL and WKR

3.3. Proučavanje utjecaja gustoće energije (*E*) na WKU, WKL i WKR

In this section, we will compare the results of WKU, WKL and WKR values for different energy densities. The results are extrapolated from the prediction graphs presented.

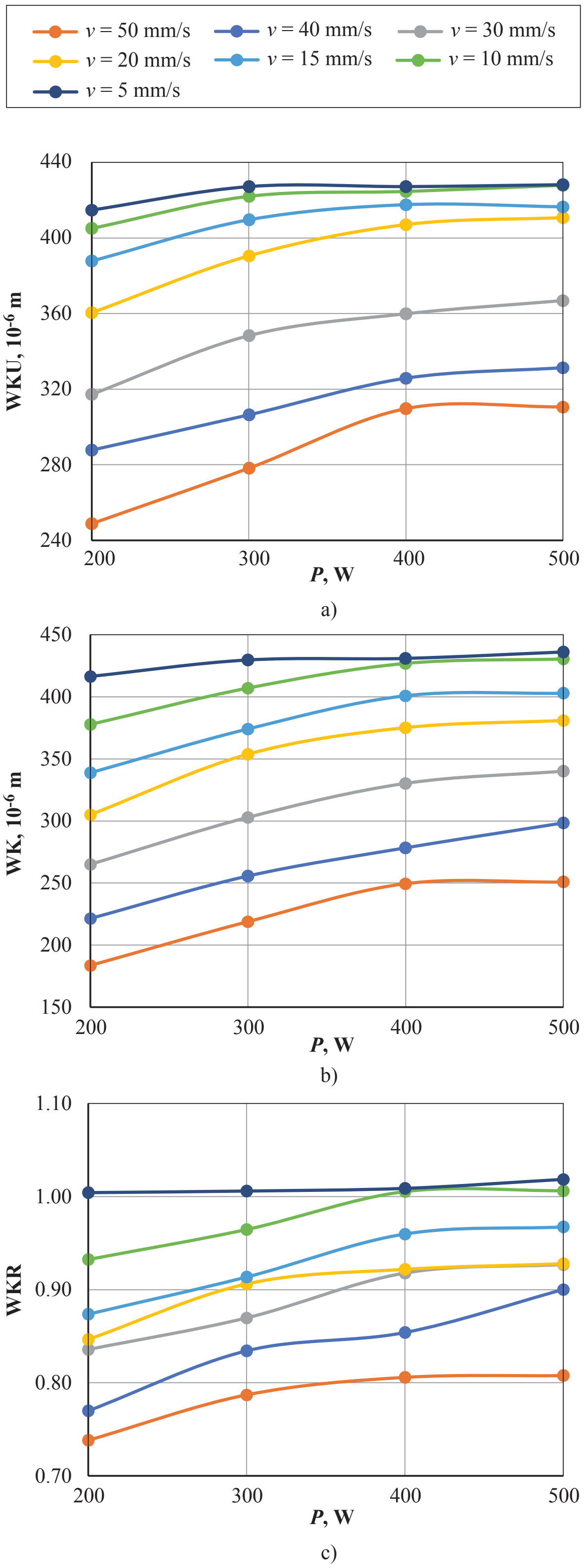


Figure 3 WKU (a), WKL (b), and WKR (c) versus P, v for HDF

Slika 3. WKU (a), WKL (b) i WKR (c) s obzirom na P, v za HDF

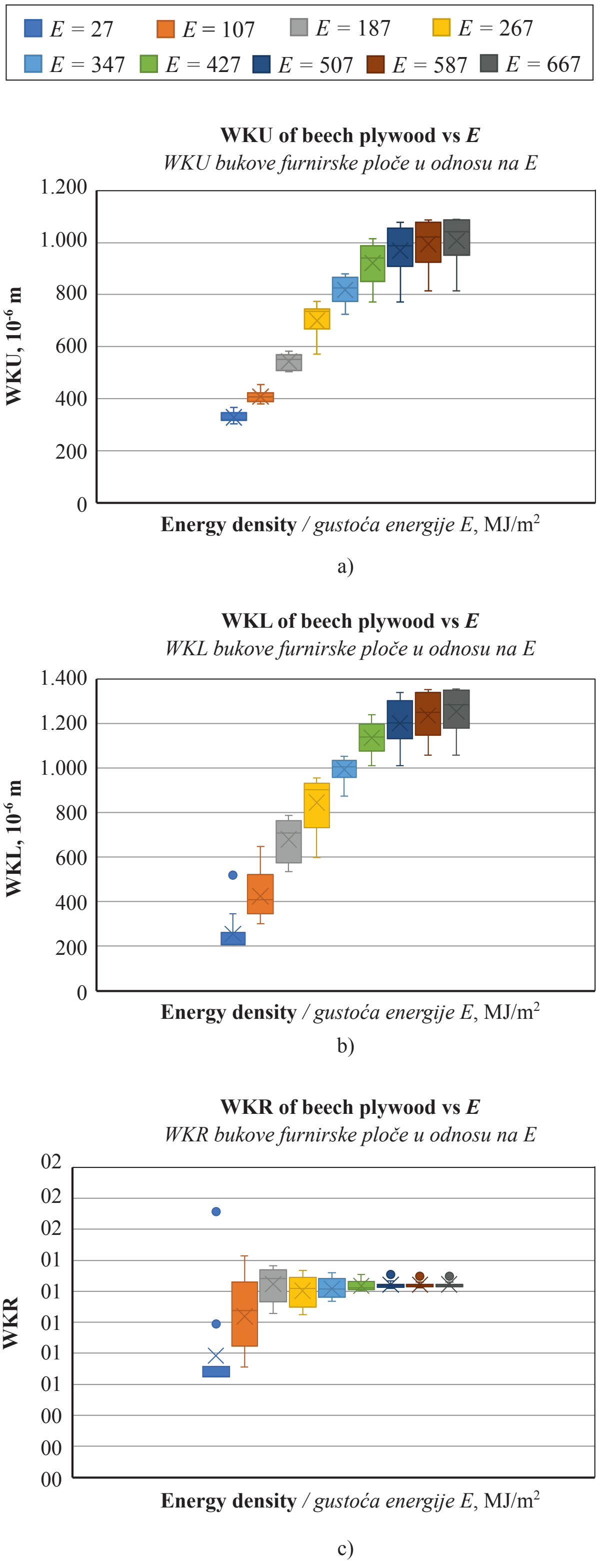


Figure 4 Effect of energy density E values on parameters of cutting kerf for beech plywood: WKU (a), WKL (b), and WKR (c)

Slika 4. Utjecaj gustoće energije E na parametre geometrije reza bukove furnirske ploče: WKU (a), WKL (b) i WKR (c)

The results are divided according to values of E = [27, 107, 187, 267, 347, 427, 507, 587, 667] MJ/m^2 in the form of box whisker plots for WKL, WKU and WKR in Figures 4 a, b, c for beech plywood. Similarly, for HDF the values are shown in Figures 5.

From the results presented in Figure 4, the following can be concluded:

- WKU variance increases with increased value of E. This occurs since the most significant amount of energy density is found on the upper board. Lower value of feed rate causes longer heat generation in cutting kerf, which raises together with the value of cutting kerf, with variance of this statistic.
- WKL variance is higher for lower E values. This is due to the fact that at the lower board, the value of E does not have such a significant effect as feed rate, which therefore increases the variance of WKL.
- Similar effect of E can also be seen for WKR, where even at very high values of E, lowering of WKR variance follows.
- Figures a, b, c show that the variance of WKL and WKU with increased E value is getting equal, which then also results in lowering of WKR variance.
- All three figures show that the effect of E is exponentially stabilizing similar to P effect.
- The most important information is that the intersection of boxes in Figure 4c with WKR=1 is obtained for E = 107 MJ/m^2.

From the results in Figure 5, the following can be concluded:

- WKU, WKL, WKR variance decrease with increased value of E.
- Figures a, b, c show that the variance of WKL and WKU with increased E value is getting equal, which then also results in lowering of WKR variance.
- All three figures show that the effect of E is exponentially stabilizing similar to P effect.
- The most important information is that the intersection of boxes in Figure 5c with WKR=1 is obtained for E > 187 MJ/m^2.

The results presented clearly show that optimal E value for HDF as the densest material is higher in comparison with beech plywood characterized by a little bit lower density. It should be noted here that Figures 4 and 5 present box-whisker plots and thus values of WKU, WKL, and WKR, regardless of P, v values which only fulfil the condition of WKR, are equal to some specific value. Such graph tells how variance is changing and which is the mean value, but it does not

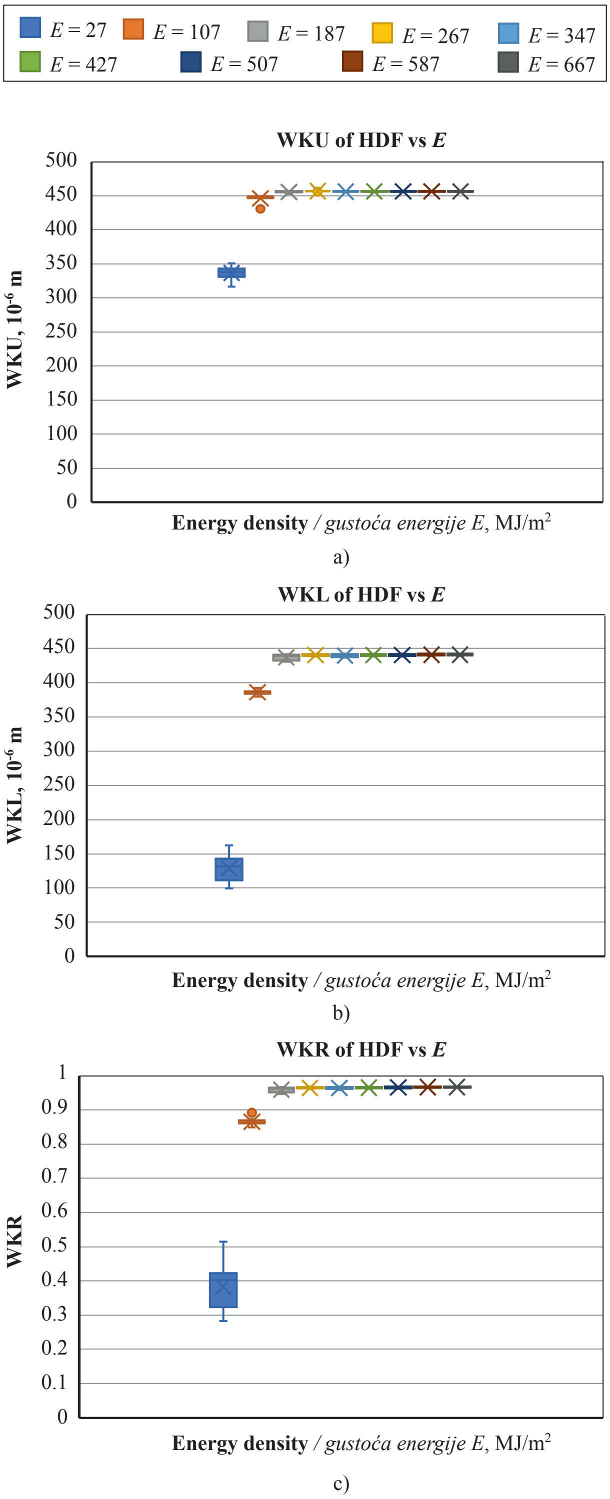


Figure 5 Effect of energy density E values on parameters of cutting kerf of HDF: WKU (a), WKL (b), and WKR (c)
Slika 5. Utjecaj gustoće energije E na parametre geometrije reza HDF-a: WKU (a), WKL (b) i WKR (c)

Table 4 Optimal values of P, v and E for beech plywood, HDF
Tablica 4. Optimalne vrijednosti P, v i E za bukovu furnirsku ploču i HDF

Parameter *Parametar*	**Beech plywood** *Bukova furnirska ploča*	**HDF**
$P_{optimal}$ (W)	200-300	300-500
$v_{optimal}$ (mm/s)	10-15	5-10
$E_{optimal}$ computed (MJ/m^2)	133	200-667
$E_{optimal}$ Figures 4-5 (MJ/m^2)	107	187-667

tell which *P, v* values are the best. This graph is qualitative. For finding optimal values of *P, v* and *E*, data must be processed "point by point".

3.4 Optimization of *P*, v and *E* values for agglomerates used
3.4. Optimizacija vrijednosti *P*, v i *E* za ispitivane drvne materijale

As mentioned above, the condition of optimal cut is where WKR is closest to 1 and minimum WKL and WKU values are reached as listed in Table 4 for both measured and predicted data.

From Table 4, the following can be concluded:

- For beech plywood, optimal values of *P* are between 200 and 300 W and for HDF between 300 and 500 W.
- Optimal feed rate *v* changes from material to material but feed rates higher than 20 mm·s^{-1} are not proper for any material.
- The lowest feed rates are optimal for HDF.
- The optimal value of *v* for beech plywood is higher than for HDF.
- In terms of quality, it can be said that for more dense materials lower *v* is optimal.
- It can be concluded that HDF needs significantly higher energy density to reach optimal quality of cut, versus plywood material.
- Compared optimal values of *E* obtained point-by-point and those obtained from the dependence of WKR vs *E* are in good agreement. It should be mentioned here that *E* values used in Figures 4 to 5 were discrete and point-by-point continuous.

In the final part of experimental results, we compare optimal values of *P*, *v* and *E*, obtained from the results on the same laser apparatus to highlight differences between studied materials and density of materials. For comparison of approaches, Figure 6 shows the graph of optimal *P* versus optimal *v* for different materials and for different cutting directions performed by the same laser machine with the same interval of used *P, v* values.

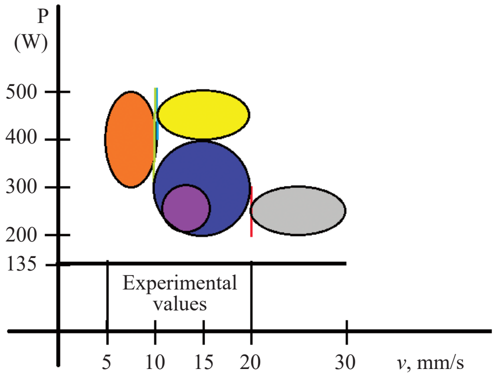


Figure 6 Optimal *P*, *v* values of different wood materials and different cutting directions
Slika 6. Optimalne *P* i *v* vrijednosti za različite drvne materijale i različite smjerove rezanja

For easy comparison of materials and densities, Table 5 and Figure 6 show density, denomination of materials together with the used color and cutting direction (⊥ across fibers direction and ∥ in fibers direction).

From Figure 6 and Table 5, it can be concluded that optimal laser power values are obtained outside of experimental values. Also, it follows that except spruce cut across fibers, optimal feed rates are within the used *v* values. Furthermore, materials with higher densities have optimal feed rates lower than less dense materials. From Figure 6, it follows that optimal laser power for beech plywood is less than for massive beech. Almost all more dense materials have higher values of optimal laser powers.

Thus, wooden materials with higher density, got higher optimal powers (*P*) and lower optimal feed rates (*v*), which at same diameter of beam on the upper surface led to the increase of optimal energy densities *E*. However optimal values of *P*, *v* and *E* for which kerf is symmetric, and kerf widths are minimal, cannot be justified only versus density as many other parameters affect the laser cutting of wooden materials as anisotropy of wood, homogeneity of wood, microstructure of wood and many others.

Table 5 Wooden materials used in Figure 6
Tablica 5. Drvni materijali prikazani na slici 6.

Material *Materijal*	**HDF**	**Beech plywood** *bukova furnirska ploča*	**Beech**$_\perp$ *bukovina*$_\perp$	**Beech**$_\parallel$ *bukovina*$_\parallel$	**Oak**$_\perp$ *hrastovina*$_\perp$	**Oak**$_\parallel$ *hrastovina*$_\parallel$	**Spruce**$_\perp$ *smrekovina*$_\perp$	**Spruce**$_\parallel$ *smrekovina*$_\parallel$
Colour *Boja*	Orange *narančasta*	Purple *ljubičasta*	Blue line *plava linija*	Green line *zelena linija*	Blue *plava*	Yellow *žuta*	Grey *siva*	Red line *crvena linija*
Density, kg/m^3 *Gustoća,* kg/m^3	800-1040	700-900	697	697	764	764	400	400
Cutting direction *Smjer rezanja*	-	-		90° 0°	90°	0°	90°	0°

4 CONCLUSIONS
4. ZAKLJUČAK

Based on the analysis of experimental measurements and the subsequent predictions generated by artificial neural networks (ANN) as detailed in the tables, the following conclusions can be drawn:

- The ANN models demonstrate high predictive accuracy, with correlation coefficients exceeding 97 % and maximum MAPE values of 6.2 %, indicating their effectiveness in estimating the influence of laser power (*P*) and feed rate (*v*) on the kerf widths (WKU, WKL) and the kerf width ratio (WKR).
- All optimal models are multilayer perceptron (MLP) type, featuring 2 input neurons *P, v* and 3 output neurons representing WKU, WKL, and WKR using BFGS Quasi-Newton training method.
- The optimal value of *P* for beech plywood is lower than for HDF.
- It is further seen that the optimal value of *v* changes from material to material, with higher wood density corresponding to a better performance at lower values of *v*.
- The optimal energy density *E*, like for solid wood, increases with increasing wood density.
- Dependences on WKU, WKL and WKR for both measurement and predicted data are in good agreement with the trends obtained by many other authors.
- The identified optimal values of P, v for different wood-based materials, can be effectively applied in practical settings to reduce the number of experimental tests required, thereby material consumption and energy expenditure during laser cutting process.

Acknowledgements – Zahvala

This work was supported by the Slovak Research and Development Agency under the Contract No. APVV-20-0159, No. APVV-22-0030, and by the VEGA Agency of the Ministry of Education, Research, Development and Youth of the Slovak Republic and the Slovak Academy of Sciences, Grants No. 1/0323/23 and 1/0077/24 and 1/0577/22.

5 REFERENCES
5. LITERATURA

1. Aniszewska, M.; Maciak, A.; Zychowicz, W.; Zowczak, W.; Muhlke, T.; Christoph, B.; Lamrini, S.; Sujecki, S., 2020: Infrared Laser Application to Wood Cutting. Materials, 13 (22): 5222. https://doi.org/10.3390/ma13225222
2. Barcikowski, S.; Ostendorf, A.; Bunte, J., 2004: Laser cutting of wood and wood composites – Evaluation of cut quality and comparison to conventional wood cutting techniques. In: Proceedings of the 1st Pacific International Conference on Laser Materials Processing, Micro, Nano and Ultrafast Fabrication. Melbourne, Australia.
3. Barcikowski, S.; Koch, G.; Odermatt, J., 2006: Characterisation and modification of the heat affected zone during laser material processing of wood and wood composites. Holz als Roh und Werkstoff, 64: 94-103. https://doi.org/10.1007/s00107-005-0028-1
4. Barnekov, V. G.; McMillin, C. W.; Huber, H. A., 1986: Factors influencing laser cutting of wood. Forests Products Journal, 36: 55-58.
5. Barnekov, V. G.; Huber, H. A.; McMillin, C. V., 1989: Laser machining wood composites. Forests Products Journal, 39: 76-78.
6. Basar, G.; Der, O., 2025: Multi-objective optimization of process parameters for laser cutting polyethylene using fuzzy AHP-based MCDM methods. Proceedings of the Institution of Mechanical Engineers. Part E: Journal of Process Mechanical Engineering, 239 (4): 2295-2309. https://doi.org/10.1177/09544089251319202
7. Basar, G.; Der, O.; Guvenc, M. A., 2025: AI-powered hybrid metaheuristic optimization for predicting surface roughness and kerf width in CO_2 laser cutting of 3D-printed PLA-CF composites. Journal of Thermoplastic Composite Materials, 38 (7): 2688-2717. https://doi.org/10.1177/08927057251344183
8. Bedelean, B.; Ispas, M.; Racasan, S., 2023: Applying the artificial neural network and response surface methodology to optimize the drilling process of plywood. Applied Sciences, 13 (20): 11343. https://doi.org/10.3390/app132011343
9. Corleto, R.; Gaff, M.; Sethy, A. K.; Kelkar, B. U.; Nemeth, R.; Ditommaso, G.; Kamboj, G.; Todaro, L.; Rezaei, F., 2025: Effects of CO_2 laser parameters on quality of laser cut beech wood (*Fagus sylvatica* L.) surface and extent of heat affect zone. Journal of the Indian Academy of Wood Science, 22: 67-77. https://doi.org/10.1007/s13196-024-00361-2
10. Der, O.; Ordu, M.; Basar, G., 2024: Optimization of cutting parameters in manufacturing of polymeric materials for flexible two-phase thermal management systems. Materials Testing, 66 (10): 1700-1719. https://doi.org/10.1515/mt-2024-0127
11. Der, O., 2025: Multi-output prediction and optimization of CO_2 laser cutting quality in FFF-printed ASA thermoplastics using machine learning approaches. Polymers, 17 (14): 1910. https://doi.org/10.3390/polym17141910
12. Eltawahni, H. A.; Olabi, A. G.; Benyounis, K. Y., 2011: Investigating the CO_2 laser cutting parameters of MDF wood composite material. Optics and Laser Technology, 43 (3): 648-659. https://doi.org/10.1016/j.optlastec.2010.09.006
13. Eltawahni, H. A.; Rossini, N. S.; Dassisti, M.; Alrashed, K.; Aldaham, T. A.; Benyounis, K. Y.; Olabi, A. G., 2013: Evaluation and optimization of laser cutting parameters for plywood materials. Optics and Laser Engineering, 51 (9): 1029-1043. https://doi.org/10.1016/j.optlaseng.2013.02.019
14. Hernández-Castaneda, J. C.; Sezer, H. K.; Lin, L., 2011: The effect of moisture content in fibre laser cutting of pine wood. Optics and Lasers in Engineering, 49 (9-10): 1139-1152. https://doi.org/10.1016/j.optlaseng.2011.05.008
15. Keles, O.; Oner, U., 2010: A study of the laser cutting process: Influence of laser power and feed rate on cut quality. Lasers in Engineering, 20 (5): 319-327.
16. Lazov, L.; Narica, P.; Valiniks, J.; Pacejs, A.; Deneva, H.; Klavins, D., 2017: Optimization of CO_2 laser parameters for wood cutting. In: Environment. Technology. Resources. Proceedings of the International Scientific and

Practical Conference, vol. 3, 168-173. https://doi.org/10.17770/etr2017vol3.2624
17. Lum, K. C. P.; Ng, S. L.; Black, I., 2000: CO_2 laser cutting of MDF: 1. Determination of process parameter settings. Optics & Laser Technology, 32 (1): 67-76. https://doi.org/10.1016/S0030-3992(00)00020-7
18. Lum, K. C. P.; Ng, S. L.; Black, I., 2000: CO_2 laser cutting of MDF: 2. Estimation of power distribution. Optics & Laser Technology, 32 (1): 77-87. https://doi.org/10.1016/S0030-3992(00)00021-9
19. Martínez-Conde, A.; Krenke, T.; Frybort, S.; Muller, U., 2017: Review: Comparative analysis of CO_2 laser and conventional sawing for cutting of lumber and wood-based materials. Wood Science and Technology, 51: 943-966. https://doi.org/10.1007/s00226-017-0914-9
20. Nath, S.; Waugh, D.; Ormondroyd, G.; Spear, M.; Pitman, A.; Curling, S.; Mason, P., 2020: Laser incising of wood: A Review. Lasers in Engineering, 45 (4-6): 381-403.
21. Nukman, Y.; Saiful, R. I.; Azuddin, M.; Aznijar, A.-Y., 2008: Selected malaysian wood CO_2 – Laser cutting parameters and cut quality. American Journal of Applied Sciences, 5 (8): 990-996. https://doi.org/10.3844/ajassp.2008.990.996
22. Özşahin, Ş.; Singer, H., 2019: Development of an artificial neural network model to minimize power consumption in the milling of heat-treated and untreated wood. Kastamonu University Journal of Forestry Faculty, 19 (3): 317-328. https://doi.org/10.17475/kastorman.662699
23. Pikuma, B.; Lapshovs, N.; Pavlovs, I.; Katkovskis, R.; Adijans, I.; Lazov, L., 2019: Investigation of the influence of laser beam parameters on the plywood laser cut geometric characteristics. In: РАДИАЦИОННАТА БЕЗОПАСНОСТ В СЪВРЕМЕННИЯ СВЯТ, Rezekne, Latvia. https://doi.org/10.34660/INF.2023.93.48.039
24. Ready, J. F.; Farson, D. F.; Feeley, T., 2001: LIA Handbook of Laser Materials Processing. Springer Verlag, Berlin, Heidelberg.
25. Ružiak, I.; Igaz, R.; Kubovský, I.; Gajtanska, M.; Jankech, A., 2022: Prediction of the effect of CO_2 laser cutting conditions on spruce wood cut characteristics using an artificial neural network. Applied Sciences, 12 (22): 11355. https://doi.org/10.3390/app122211355
26. Ružiak, I.; Igaz, R.; Kubovský, I.; Tudor, E. M.; Gajtanska, M.; Jankech, A., 2024: ANN prediction of laser power, feed rate and number of cut annual rings and their influence on selected cutting characteristics of spruce wood for CO_2 laser processing. Materials, 17 (13): 3333 https://doi.org/10.3390/ma17133333
27. Ružiak, I.; Krišťák, Ľ.; Adijans, I.; Kubovský, I.; Richvalská, J.; Štefančin, L.; Gajtanska, M.; Tudor, E. M.; Todaro, L., 2025: Enhancing CO_2 laser cutting efficiency for diverse wood species using artificial neural networks. Forests, 16 (6): 881. https://doi.org/10.3390/f16060881
28. Tiryaki, S.; Malkocoglu, A.; Özsahin, S., 2014: Using artificial neural networks for modeling surface roughness of wood in machining process. Construction and Building Materials, 66: 329-335. https://doi.org/10.1016/j.conbuildmat.2014.05.098
29. Tiryaki, S.; Malkocoglu, A.; Özsahin, S., 2016: Artificial neural network modeling to predict optimum power consumption in wood machining. Drewno, 59 (196): 109-125. https://doi.org/10.12841/wood.1644-3985.140.08
30. Tiryaki, S., Özşahin, Ş.; Aydın, A., 2017: Employing artificial neural networks for minimizing surface roughness and power consumption in abrasive machining of wood. European Journal of Wood and Wood Products, 75: 347-358. https://doi.org/10.1007/s00107-016-1050-1
31. Xu, Y.; Wang, B.; Shen, Y., 2017: Study on laser cutting technology of bamboo. Wood Research, 62: 645-658.
32. Yung, K. Ch.; Choy, H. S.; Xiao, T.; Cai, Z., 2021: UV laser cutting of beech plywood. The International Journal of Advanced Manufacturing Technology, 112: 925-947. https://doi.org/10.1007/s00170-020-06376-6
33. Zhou, B. H.; Mahdavian, S. M., 2004: Experimental and theoretical analyses of cutting nonmetallic materials by low power CO_2-laser. Journal of Materials Processing Technology, 146 (2): 188-192. https://doi.org/10.1016/j.jmatprotec.2003.10.017

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