APEM journal
Advances in Production Engineering & Management | **ISSN 1854-6250**
Volume 20 | Number 2 | June 2025 | pp 191–204 | Journal home: apem-journal.org
https://doi.org/10.14743/apem2025.2.535 | Original scientific paper

Impact of machining parameters on surface roughness in CNC hardwood milling: A multivariate approach

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A B S T R A C T

Wood processing remains a manufacturing field that relies heavily on craftsmanship and the experience of skilled workers. Although Computer Numerical Control (CNC) techniques have introduced significant progress in wood manufacturing, one of the main challenges remains the natural variability of wood. Variations in grain direction, density, moisture content, and other wood properties can result in inconsistent cutting behavior, increased surface roughness, and dimensional inaccuracies. Furthermore, the growing need to conserve natural resources continuously drives innovation in wood processing. This paper investigates CNC machining of hardwoods with a particular focus on evaluating surface roughness as a key quality parameter. Aiming to achieve better surface roughness leads to eliminating or reducing sanding operations. Cutting conditions, tool path optimization, and time efficiency during hardwood processing remain crucial factors in the furniture industry. Finished wooden components are typically assembled from multiple pieces using joining techniques; however, unlike in the forestry industry, the quality of the prepared samples is not systematically monitored and is often assessed solely by human judgment. Consequently, the impact of variable parameters, such as feed speed, timber species, fiber orientation, during the cutting and workpiece preparation was evaluated by multivariate statistical analysis. The study of milling curvilinear shapes in hardwoods (ash, oak, walnut) revealed that the annual growth ring section is the most significant factor affecting the quality of the finished product. Consequently, the adapted tool path according to the materials growth ring section would be advantageous while milling curvilinear shapes of the hardwood materials.

A R T I C L E I N F O

Keywords:
CNC milling;
Hardwood processing;
Surface roughness;
Fiber orientation;
Multivariate analysis;
MANOVA;
Wood machining quality

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Article history:
Received 14 May 2025
Revised 13 July 2025
Accepted 15 July 2025

1. Introduction

The challenge for wood product manufacturers is to make a profit and remain competitive, when on the one hand, they need to execute the processes at the lowest cost and within the shortest time, and, on the other hand, deal with a highly variable raw material [1]. Each step of the wood processing chain influences both material utilization and product cost [2]. Unlike the forest industry, where processes are increasingly automated, a large portion of manufacturing operations in the wood products sector still relies on human operators performing visual inspections. Transferring this task to the automated systems would require machines capable of handling the considerable variability in material quality and the inherent heterogeneity of wood [1]. Unlike metals, wood is an anisotropic, non-uniform, and hygroscopic material, which makes its behavior during machining highly unpredictable [3]. These properties introduce additional complexity in cutting operations, making wood machining significantly more difficult to control and model compared to conventional metal cutting processes. For example, a recent study has indicated that wood moisture significantly influences the shear angle during cutting, thereby affecting the behavior of the chip as it slides along the rake face [4].

The wood properties, even of the same species, differ according to the climate [5], annual rings and strength depending on the fibers [6]. Consequently, the surface characteristics of wood after machining result from a complex, time-dependent interaction between the raw material and the machining process [7]. The surface after the machining results from sequential cutting, such as sawing, planning, milling, sanding, or advanced methods, such as laser and water-jet cutting [8]. The techniques mentioned aim to remove the excess of the material and achieve the desired surface quality. Moreover, the aesthetic function of the wood surface dominates the highly customer-oriented market [9]. Consequently, wood machining is an integral part of production process in the wood industry, where the surface generated by the cutting techniques directly affects the sequence of operations that follow, especially surface finishing by coating or painting [10]. However, the machining quality is still based on subjective standards, such as sensing the surface by hand or visual inspection; therefore, the same machining quality can have different quality ratings for different people [11]. Otherwise, the measured surface roughness of the wood is the superposition of anatomical roughness and machining roughness [11, 12]. Moreover, the surface roughness of the machined wood depends on various parameters [13], such as variables of the machining process [14], dynamic properties of the cutting system [15], a tooth geometry of the saw blade [16], species [17], and the grain orientation during the machining [18]. It has been observed that the surface roughness of the machined sample is affected by the number of cutting edges, its geometry as well as material used to manufacture the cutting tool [19] and its overall wear [20, 21].

The large number of factors affecting surface quality requires appropriate data analysis methods, particularly statistical techniques. Largely used Taguchi method combines engineering and statistical methods to attain rapid improvements in quality and cost by optimizing the product design and manufacturing processes [22]. As it was mentioned earlier about the properties of wood and the heterogeneity of this natural material, it is important to check the quality of the interception parameters during the machining of wood. Multivariate analysis of variance (MANOVA) is a well-established extension of analysis of variance (ANOVA) that generalizes the method from a single to multiple dependent variables [23]. Specifically, MANOVA is a statistical technique used to assess the effects of one or more independent variables on two or more dependent variables [24].

The aforementioned characteristics of wood manufacturing may explain why advanced monitoring techniques are commonly applied in the forest industry and their use in the wood products industry remains limited or largely unexplored [2]. Fewer studies examine the challenges occurring in the later part of the wood processing chain regarding the influence of the raw material on the manufacturing process [1]. For example, Sandak *et al.* [10] revealed the idea of the algorithm for implementing a monitoring system alerting machine operation about the excessive surface irregularities, resulting from the machining process. However, the presented algorithm does not consider the appearance of wood surface changes due to the burns, which tend to progress. Therefore, adapting the machining process to the material properties, particularly with respect to fiber orientation when processing curvilinear contours, can be advantageous. Moreover, since wood properties vary with fiber orientation, the wood industry may benefit from adjusting machining speed according to the tool path and the specific wood material. Consequently, adapting the tool path when processing hardwood could result in both reduced production time and increased tool longevity. Additionally, the fact that wooden products are often composed of multiple workpieces has not been thoroughly examined. This study investigates the effect of multiple factors on surface quality during hardwood milling.

2. Materials and methods

2.1 Milling experimental set-up

This part of the article discusses the setup of experimentation of milling curvilinear shapes of hardwood timber. The experimental design was focused on the increase of feed speed and the investigation on how the increased speed impacts the surface quality of different hardwood species: ash (*Fraxinus*), oak (*Quercus*), and walnut (*Juglans*). The flowchart according to which the investigation was carried out is shown in Fig. 1.

Hardwood milling experiments were carried out using a 5-axis interpolating NC machining center, the Sprinter R3CU, manufactured by Greda, Italy. This machining center was equipped with Esa Automation controller, having two electric spindles and one automatic spindle for tooling replacement; it can be used for milling and turning operations as well. The milling experiments were performed by using a milling tool (company Caul, ø 80 mm and working height of 102 mm) with 4 indexable carbide inserts per circumference (dimensions 14 × 14 × 2 mm, made by Ceratizit, Luxembourg, in total 20 inserts), see Fig. 2a. Each carbide indexable insert, featuring specialized cutting edges, was secured using the dynamometer key with an applied torque of 4 Nm.

The workpieces (187 × 92 × 100 mm) were made by gluing two parts according to the general solid wood gluing technologies, see Fig. 2b. Dispersive adhesive Jowacoll 103.05, compliant with EN204D3 class requirements, was used for gluing two samples. The process involved layered gluing, where two lamellae are glued one on top of the other to form a single blank. Before gluing, the wood must be properly prepared. The wood moisture content must be between 8-12%. The blanks must be precisely planned to ensure smooth surfaces and full-surface contact between the lamellae—this is essential for achieving a high-quality bond. Thus, as it is a common practice in wood processing in the field of furniture manufacturing, hardwood samples were composed from parts so-called A and B. Hardwood samples for curvilinear milling were mounted on a special template on the machining center table using stepped holes (ø 25 × 50 mm and ø 10 × 50 mm). The tool paths were programmed using software EasyWood ®version6.8f1. Consequently, the workpiece was machined in two stages, realizing two contours, see Fig. 2c. The first milling tool path, the rough milling, removed the maximum excess of the material at the corners. Thus, the second milling tool path was the finishing operation achieving the final curvilinear shape.

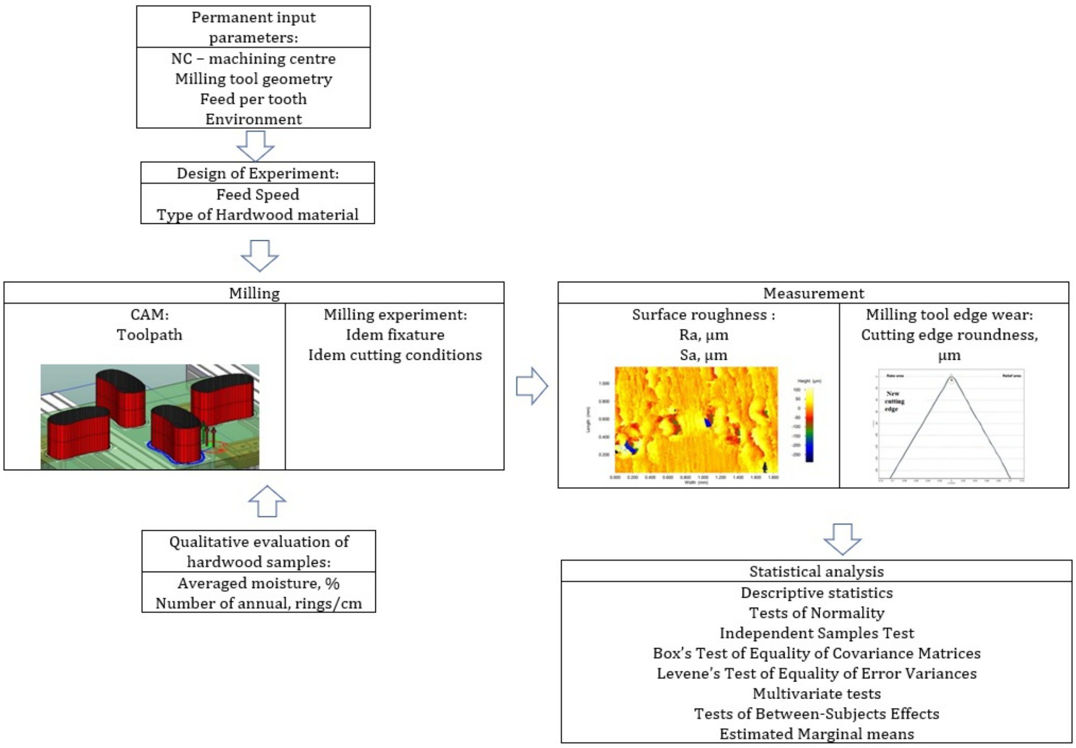


Fig. 1 Flowchart of the methodology

a) b) c)

Fig. 2 Milling process preparation:
a) tooling, b) glued hardwood sample, c) programmed toolpath

The conditions of milling were chosen to evaluate the impact of feed speed on the quality of surface of all the selected hardwood (oak, ash, walnut), particularly used for luxury furniture. At the first step, all the samples were machined by rough milling according to the cutting conditions: spindle rotation equal to 10,000 rpm, feed speed equal to 2.2 m/min, feed per knife equal to 0.05 mm/knife. Finishing milling was performed by changing feed speed and evaluating the surface quality for each hardwood sample. Milling down technique was used for the investigation. The applied variable cutting conditions are presented in Table 1.

The wood properties are presented in Table 2. The moisture measurements were performed according to the Lithuanian standard LST EN 13183-1 (European standard EN 13183-1:2002) using electric low temperature furnace SNOL 58/350. Natural durability ratings of the selected hardwood species from BS EN 350 [25] are presented in Table 2.

When the milling tool follows the tool path (Fig. 2c), the machining of wood faces variables processing conditions due to the distribution of annual growth rings. As shown in Fig. 3, the milling tool cuts along the fiber (tangential section) on the side surfaces of the sample. Accordingly, the fiber is cut across (cross-section) by the milling tool at the corners of the sample. Thus, the investigation of this work was focused on how the increase of the feed speed impacts the surface quality of three hardwood species. Moreover, the full sample, as is the common case in wood manufacturing field, was glued from two selected samples. The dispersive adhesive Jowacoll 103.05 was used for gluing two samples. The process involved layered gluing, where two lamellae are glued one on top of the other to form a single blank. Before gluing, the wood was properly prepared. As this factor is the human factor, this research reveals the investigation on how to evaluate the impact of sample's uniformity on the final quality of the part.

Fig. 3 represents the samples of the investigation: workpieces, glued of two samples, made from three different hardwood species. Consequently, the surface roughness measurements were performed according to the annual growths section, which was categorized from the visual inspection.

Table 1 Variable factors for finishing milling, according to the design of experiment, impacting the final surface quality

Feed speed (m/min)	1.8	3.6	5.4
Workpiece material	ash	oak	walnut
Fiber direction during cutting	Cutting along the fiber (tangential section)	-	Cutting across the fiber (cross-section)
Sample of workpiece	part A	-	part B

Table 2 Physical characteristics of hardwood species properties

Hardwood material	Class of durability rating	Averaged moisture (%)	Number of annual rings/cm	Average density (kg/m^3)
Ash (*Fraxinus*)	5	7.47	3.5-6.5	698
Oak (*Quercus*)	2	7.57	3.5-5	729
Walnut (*Juglans*)	1	4.68	2.5-3	696

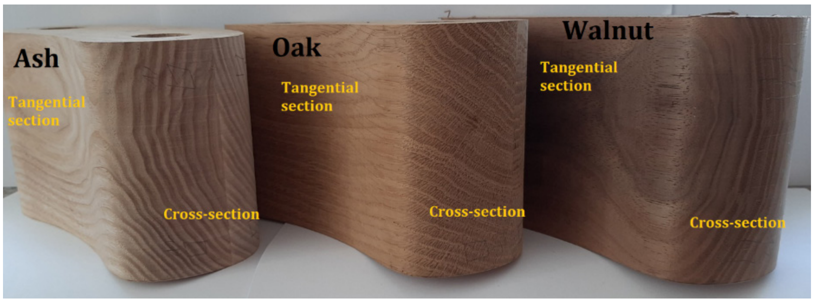


Fig. 3 Curvilinear parts of hardwood timber and views of annul growth rings

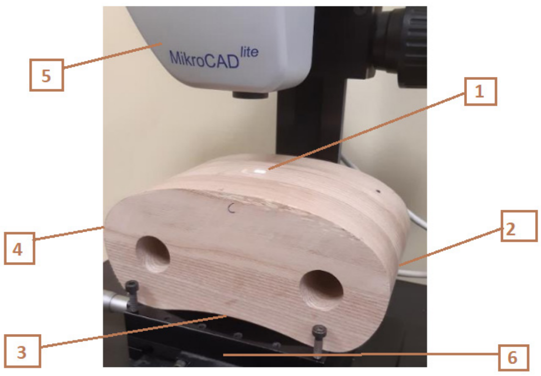
2.2 The investigation of the surface roughness quality

An optical measuring device, MicroCAD Lite by GFMesstechnik GmbH (Germany), was used in the research for the accurate analysis of the surface roughness after hardwood machining and investigation of the milling tool's cutting edge. The following programs were applied: MicroCAD Lite – ODSCAD for cutting tools measurement, ODSCAD for surface roughness measurements, and GFM 3D Viewer for showing 3D scanned photos. Table 3 presents the MicroCad Lite system parameters used for the qualitative investigation of surface roughness after milling.

Surface roughness measurement set-up is presented in Fig. 4. As can be seen in Fig. 4a, sides surfaces/faces of the samples correspond to the along fiber cutting (tangential section), while the corners of the samples faced the cutting across the fiber (cross-section). Moreover, as workpieces were composed from two glued parts, according to the visual selection, the surfaces roughness measurements were decomposed according to the glued part (called A and B in this investigation). Consequently, Fig. 4b represents detailed schematics of surface measurement points. To sum up, surface roughness measurements were performed on samples of three different timber species, which were processed by changing feed speed. Accordingly, the surface roughness was measured on the same side of cutting across the fiber (cross-section) and along the fiber (tangential section), at two positions.

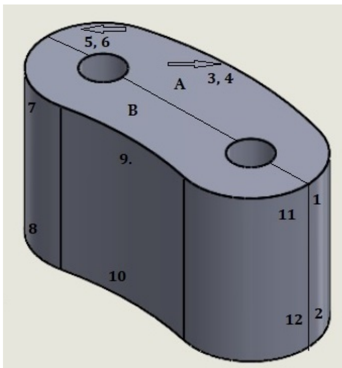
Table 3 MicroCad Lite system parameters

Measuring volume	1.8 × 1.2 × 1.0 mm^3
Point density	2.5 μ
Height resolution	0.1 μ
Measuring points	752 × 482
Measuring time	2 s



a)

1, 3 – surface measurements along the fiber (II to fiber),
2, 4 – surface measurements across the fiber (⊥ to fiber),
5 – an optical measurement system MikroCAD Lite, mounted on adjustable stand,
6 – a micrometric table



b)

Surface roughness measurement positions, according to the fiber direction of glued parts A and B

Fig. 4 The set-up for the investigation of surface roughness

According to the presented set-up (Fig. 4), surface roughness measurements were carried out under controlled microclimatic conditions at a temperature of 20 ± 1 °C and a relative humidity of 50 ± 5%. Prior to the measurements, the specimens were conditioned for 24 hours. The surface roughness was quantified by the arithmetic mean surface roughness (Ra). The arithmetic mean height (Sa) was evaluated, which additionally provides a comprehensive view of surface texture by analyzing height variations across the entire measured surface area. Each experiment was performed with non-dull milling tool. The sharpness of the insert's cutting edge was measured before processing, with a radius of 5.7 μm was found. The new tool cutting edge was measured using an optical measurement system MikroCAD (Fig. 4a). The effective cutting length during the experimentation was approximately 15.6 m.

2.3 Multivariate analysis of variance

The irregular properties of wood, sample preparation, the varying characteristics of hardwood material, and the need to examine the impact of cutting speed on surface roughness require the use of multivariate analysis of variance (MANOVA) to evaluate the quality of the interaction parameters. MANOVA, like all parametric tests, is based on three main assumptions [23]:

- Independence of observations – the data must consist of completely random samples, with each observation independent of the others.
- Multivariate normality – the dependent variables should follow a multivariate normal distribution within each group.
- Homogeneity of variance–covariance matrices – since MANOVA involves more than one dependent variable, it requires not only equality of variances across groups, but also equality of covariances between the dependent variables. This condition is tested using the variance–covariance matrix.

MANOVA together with well-known criteria such as the Wilks' Lambda, Lawley-Hotelling trace, and Pillai's trace is used for checking the quality of the solutions [24]. A modification of Hotelling T^2 – statistics criterion used in MANOVA is the so-called Pillai's trace criterion [24]. It has been emphasized that Pillai's trace test statistic gives more robust results in cases of both homogeneous and heterogeneous variances for two variables, as well as in analyses involving three variables [26]. Moreover, Pillai's trace test statistics give more robust results in unbalanced samples [26]. Additionally, in Student's t distribution, Pillai's trace test statistic gives more robust results when variances are homogeneous [26]. The aforementioned statistics are common for testing hypothesis. MANOVA examines whether the average vectors from two or more groups come from the same sample distribution using appropriate test statistics. A test statistic is used to assess a particular hypothesis through sample data obtained from one or more populations. The hypothesis for the mean vectors is formulated as follows [26]:

$$\begin{gathered} H_0: \mu_1 = \cdots = \mu_k = 0, \\ H_1: \mu_1 \neq \mu_j, \\ i < j, i,\ j = 1, 2, \ldots, k. \end{gathered} \tag{1}$$

The hypothesis can be tested using the previously mentioned test statistics. In the next stage, the hypothesis was tested by Pillai's Trace Test Statistic, defined as follows [28]:

$$T = \sum_{i=1}^{s} \frac{\lambda_i}{1 + \lambda_i}. \tag{2}$$

Moreover, the F distribution was used to test the T statistics as well. The performed statistical analysis is displayed in a flowchart in Fig. 1.

3. Results

3.1 Experiments

The milling experiments were carried out according to the full factorial experimental design, which allows the investigation of all combinations of levels of the variable input parameters. In the Design of Experiments (DoE), three feed speed levels (1.8, 3.6, and 5.4 m/min) were assumed for finishing milling, along with three material types: ash (*Fraxinus*), oak (*Quercus*), and walnut (*Juglans*). Surface roughness measurements were performed at the same position of the sample for all 3 hardwood samples after the finishing processing; then, the feed speed was changed. Surface measurements positions are depicted at Fig. 3b; thus, the measured variable output parameters Ra and Sa were dependent according to the grain section during cutting and glued part. The measurement results for different combinations of input parameters are presented in Table 4.

Table 4 Surface roughness measurement results

Feed speed: 1.8 (m/min)								
		Ash		Oak		Walnut		
Measurement position, no	Glued part	Ra (μm)	Sa (μm)	Ra (μm)	Sa (μm)	Ra (μm)	Sa (μm)	Fiber direction during milling
1	A	28.2	26.6	2.8	4.1	3.8	5.1	Across
2	A	23.8	18.3	2.5	4.4	5.5	6.9	Across
3	A	15.7	28.1	3.9	5.6	5.7	6.4	Along
4	A	7.3	7.1	8.2	8.2	8.3	8.9	Along
5	A	5.3	8.3	4.4	7.5	3.4	4.7	Across
6	A	8.4	9.5	9.1	9.3	3.2	3.5	Across
7	B	4.1	4.3	4	5.8	3.1	3.7	Across
8	B	7.6	10.3	2.8	5.4	2.8	4.5	Across
9	B	8.6	12.2	5.1	7.2	6.5	7.4	Along
10	B	7.0	13.7	4.8	6.5	4.6	6.0	Along
11	B	5.7	7.0	5.4	9.1	2.6	4.1	Across
12	B	2.3	3.0	4.0	9.2	3.2	4.0	Across
Feed speed: 3.6 (m/min)								
1	A	3.0	4.5	2.9	3.9	3.8	4.6	Across
2	A	2.7	4.9	2.7	4.8	3.9	4.8	Across
3	A	3.9	4.5	5.3	8.2	5.7	5.9	Along
4	A	6.1	6.5	5.4	5.8	4.4	20.1	Along
5	A	5.9	9.8	6.4	8.1	2.8	4.5	Across
6	A	2.8	3.8	10	12.1	3.4	4.3	Across
7	B	11	23.5	4.7	18.1	5.4	5.5	Across
8	B	3.0	4.8	8.8	14.1	4.6	6.0	Across
9	B	5.2	5.3	3.5	14.1	5.1	7.6	Along
10	B	6.3	9.5	10.9	17.9	4.8	8.7	Along
11	B	9.9	14.6	3.4	4.2	2.6	3.1	Across
12	B	3.5	5.8	5.8	8.4	3.4	4.2	Across
Feed speed: 5.4 (m/min)								
1	A	2.8	3.7	3.0	3.5	3.5	5.3	Across
2	A	11.3	14.5	8.6	7.8	4.3	5.3	Across
3	A	6.6	8.5	4.2	6.4	4.3	6.7	Along
4	A	11	12.3	5.1	5.3	6.0	9.3	Along
5	A	7.6	12.4	5.5	11.5	3.3	4.0	Across
6	A	4.3	6.3	3.6	7.1	3.1	3.7	Across
7	B	2.6	3.0	3.3	19.8	3.5	4.1	Across
8	B	2.9	5.1	3.5	18.6	3.4	4.4	Across
9	B	4.6	10.6	5.7	5.9	3.9	4.9	Along
10	B	4.8	12.4	7.4	7.0	8.0	9.0	Along
11	B	3.2	3.9	3.0	5.8	3.9	4.4	Across
12	B	2.9	6.7	3.0	5.9	3.1	3.6	Across

3.2 Statistical analysis of hardwood milling processing

The statistical analysis of the measurement results was performed using SPS software, whereby a model with the main effects and two-factor interactions was selected. Accordingly, a model is obtained that allows the modelling of complex relationships between the input and output parameters. The statistical analysis for the evaluation of the effect of parameters was performed in several steps, as it is presented in the flowchart of the investigation (Fig. 1).

At the first step, the descriptive statistics evaluated the means of variables and standard deviations. Thus, in the next stage, the measured data after the experimentation was treated for the evaluation of outliners. Outliers are extraordinary data that were separated from the main body of the data. Outliers are marked with an asterisk and circle on a box plot. Each whisker extends to the last value that is not an outlier. The results are presented in Fig. 5.

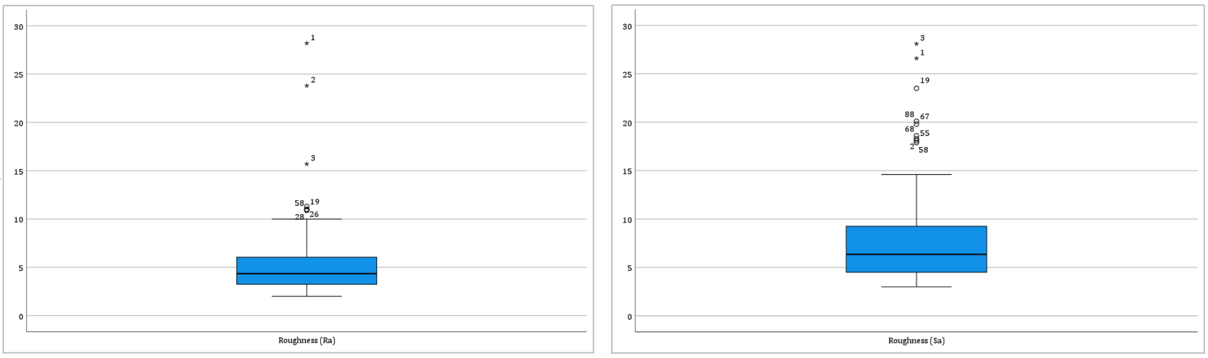


Fig. 5 Measurement data preparation

As is presented in Fig. 5, all measured data contained outliers, which were eliminated. Thus, for next step, after eliminating the outliers, the data were approximated according to the standard normal distribution. The results obtained are presented in Fig. 6.

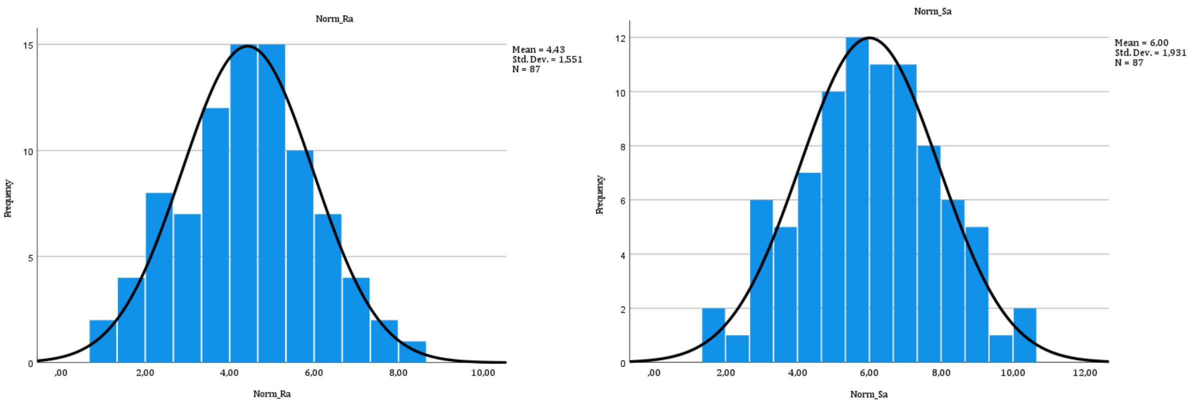


Fig. 6 Approximated data according to normal distribution

An Independent Samples Test was performed to assess whether the populations are independent with respect to the dependent variables, surface roughness (Ra) and arithmetic mean height (Sa). The results of the analysis are presented in Table 5.

Table 5 Independent Samples Test

		Levine's Test for Equality of Variances		*t*-test for Equality of Means						
		F	Sig.	t	df	Sig. 2'tailed	Mean Differ.	Std. Error Differ.	95 % Confidence Interval of the Difference Lower	Upper
Ra Sa	Equal variances assumed	3.875	.051	-5.929	172	<.001= 1.6252 E-8	-1.57448	.26554	-2.09862	-1.05034
Ra Sa	Equal variances not assumed			-5.929	164.357	<.001= 1.7406 E-8	-1.57448	.26554	-2.09880	-1.05017

Levene's test and *t*-test estimate the equality of variances in groups. Equal variance was assumed between the groups Ra and Sa according to *t*-test, *p*-value (Sig.) = 0.051, *p*-value > α. A significant difference was obtained between the Ra and Sa groups because the two-tailed *t*-test *p*-value (*p*, Sig.) is lower than the established significance level, $\alpha = 0.05$. For the interpretation and statistical analysis of data, Box's test of Equality of Covariance of Matrices was performed, as well as the Levene's test of Equality of Error Variances. The significance level of $\alpha = 0.001$ was taken in the analysis of Box's Test; this method is sensible and resistant to the disturbances of equality of covariance matrices. The results of Box's test are presented in Table 6. As it is presented *p*-value (Sig.) = 0.599 and *p*-

value (Sig.) > α; thus, covariance matrices are equal in the groups. Consequently, the equality of covariance of matrices is carried out, and the condition of sphericity of covariances is satisfied.

Additionally, Levene's Test complements the Box's Test and confirms the correctness of the data distribution. Levene's Test of Equality of Error Variances demonstrates that *p*-value (Sig.) > α; thus, the dispersions of dependent variables do not differ across the groups. The confirmation, according to the Levene's Test, is presented in Table 7. Based on Levene's Test, the null hypothesis was accepted, indicating that the error variance of the dependent variables, based on the median and with adjusted degrees of freedom for Norm_Ra and Norm_Sa, is equal across groups.

Table 6 Box's test of equality of covariance matrices

Box' s M	F	df1	df2	Sig.
43.314	0.920	33	1973.075	0.599

Table 7 Levene's Test of Equality of Error Variances[a]

		Levene's Statistic	df1	df2	Sig.
Norm_Ra	Based on Mean	2.075	29	52	.011
	Based on Median	1.084	29	52	.391
	Based on Median and with adjusted df	1.084	29	16.445	.443
	Based on trimmed mean	1.964	29	52	.017
Norm_Sa	Based on Mean	2.320	29	52	.004
	Based on Median	1.584	29	52	.074
	Based on Median and with adjusted df	1.584	29	16.445	.164
	Based on trimmed mean	2.231	29	52	.006

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Wood + Part + Direction + Speed + Wood * Part + Wood * Direction + Wood * Speed + Part * Direction + Part * Speed + Direction * Speed + Wood * Part * Direction + Wood * Part * Speed + Wood * Direction * Speed + Part * Direction * Speed + Wood * Part * Direction * Speed

Table 8 Multivariate tests results: Pillai's Trace

Effect	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[c]
Wood	.144	2.013	4.000	104.000	.098	.072	8.051	.586
Part	.067	1.830[a]	2.000	51.000	.171	.067	3.659	.364
Direction	.369	14921[a]	2.000	51.000	.000	.369	29.843	.999
Feed Speed	.072	.969	4.000	104.000	.428	.036	3.878	.298
Wood * Part	.121	1.681	4.000	104.000	.160	.061	6.723	.500
Wood * Direction	.159	2.252	4.000	104.000	.068	.080	9.008	.641
Wood * Feed speed	.149	1.046	8.000	104.000	.407	.074	8.369	.464
Part * Direction	.062	1.698[b]	2.000	51.000	.193	.062	3.395	.341
Part * Feed speed	.064	.855	4.000	104.000	.494	.032	3.420	.264
Direction * Feed speed	.061	.813	4.000	104.000	.520	.030	3.251	.252
Wood * Part * Direction	.054	.728	4.000	104.000	.575	.027	2.910	.228
Wood * Part * Feed speed	.172	1.223	8.000	104.000	.293	.086	9.783	.539
Wood * Direction * Feed speed	.233	1.717	8.000	104.000	.103	.117	13.737	.718
Part * Direction * Feed speed	.020	.261	4.000	104.000	.902	.010	1.045	.105
Wood * Part * Direction * Feed speed	.122	1.692	4.000	104.000	.158	.061	6.766	.503

a. Exact statistic

b. The statistic is an upper bound on F that yields a lower bound on the significance level.

c. Computed using alpha = .05

Multivariate Tests, performed according to *Pillai's Trace*, *Wilks' Lambda*, *Hotelling's Trace* and *Roy's Largest Root* tests, presented the statistical significance in groups. Additionally, no significant interaction between factors was observed, as the results show *p* (Sig.) < 0.001. The results are presented in Table 8.

The results of the Tests of Between-Subjects Effects provide a more detailed assessment of the effect of each factor, as well as the interaction of these factors, on each dependent variable. The results are presented in Table 9.

Table 9 Tests of between-subject effects results

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Norm_Ra	111.497[a]	33	3.379	1.870	.021
	Norm_Sa	147.160[b]	33	4.459	1.359	.158
Intercept	Norm_Ra	1,476.664	1	1,476.664	817.177	.000
	Norm_Sa	2,683.528	1	2,683.528	817.739	.000
Wood	Norm_Ra	1.103	2	.551	.305	.738
	Norm_Sa	9.646	2	4.823	1.470	.239
Part	Norm_Ra	.904	1	.904	.500	.482
	Norm_Sa	.608	1	.608	.185	.669
Direction	Norm_Ra	52.597	1	52.597	29.107	.000
	Norm_Sa	47.522	1	47.522	14.481	.000
Feed speed	Norm_Ra	4.009	2	2.005	1.109	.337
	Norm_Sa	2.975	2	1.487	.453	.638
Wood * Part	Norm_Ra	7.498	2	3.749	2.075	.136
	Norm_Sa	5.300	2	2.650	.807	.451
Wood * Direction	Norm_Ra	.491	2	.245	.136	.873
	Norm_Sa	9.006	2	4.503	1.372	.263
Wood * Speed	Norm_Ra	5.987	4	1.497	.828	.513
	Norm_Sa	4.754	4	1.188	.362	.834
Part * Direction	Norm_Ra	.514	1	.514	.284	.596
	Norm_Sa	1.050	1	1.050	.320	.574
Part * Speed	Norm_Ra	4.948	2	2.474	1.369	.263
	Norm_Sa	2.519	2	1.259	.384	.683
Direction * Speed	Norm_Ra	1.782	2	.891	.493	.614
	Norm_Sa	9.357	2	4.678	1.426	.250
Wood * Part * Direction	Norm_Ra	.294	2	.147	.081	.922
	Norm_Sa	3.406	2	1.703	.519	.598
Wood * Part * Speed	Norm_Ra	3.161	4	.790	.437	.781
	Norm_Sa	7.296	4	1.824	.556	.696
Wood * Direction * Speed	Norm_Ra	6.281	4	1.570	.869	.489
	Norm_Sa	9.943	4	2.486	.757	.558
Part * Direction * Speed	Norm_Ra	.581	2	.290	.161	.852
	Norm_Sa	.353	2	.177	.054	.948
Wood * Part * Direction * Speed	Norm_Ra	2.563	2	1.281	.709	.497
	Norm_Sa	1.895	2	.947	.289	.750
Error	Norm_Ra	93.966	52	1.807		
	Norm_Sa	170.646	52	3.282		
Total	Norm_Ra	1,879.685	86			
	Norm_Sa	3,395.187	86			
Corrected Total	Norm_Ra	205.463	85			
	Norm_Sa	317.806	85			

a. R Squared = .543 (Adjusted R Squared = .252)
b. R Squared = .463 (Adjusted R Squared = .122)
c. Computed using alpha = .05

Tests of Between-Subject Effects results demonstrate that the statistical significance is seen in the impact of cutting direction, as *p*-value (Sig.) < α. Thus, additionally, the figures below represent the results of estimated marginal means (EMM) of each subject. It is possible to estimate more accurate picture of the group differences. Fig. 7 demonstrates the effect of fiber direction during the cutting. Statistical significance is observed for all the species of the tested hardwood. The major effect is particularly observed for Ra. Smaller but significant effect is observed on the areal surface roughness Sa. The results have proved that the cutting of hardwood fibers across the fibers (cross-section) is more advantageous compared to cutting along the fibers (tangential section).

Fig. 8 illustrates the effect of glued parts on the measured surface quality after machining. The results show that, for parts assembled from two samples, the 2D-measured surface roughness Ra is noticeably affected. In contrast, the surface roughness Sa indicates that the areal surface roughness was not significantly influenced by gluing parts from two different samples. As confirmed by EMM analysis, no statistical significance was observed in either case. These findings highlight the need for automatic monitoring of samples in furniture production. At the current level of furniture manufacturing, similarly shaped parts glued from two hardwood samples (ash, oak, walnut) are typically assembled based on visual inspection by the worker. The effect of feed speed is presented next, as shown in Fig. 9.

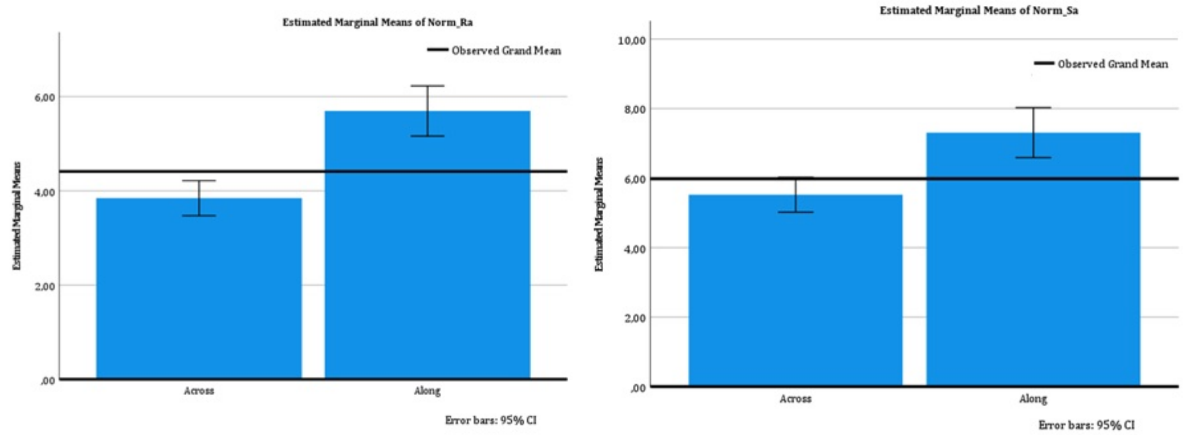


Fig. 7 Estimated Marginal Means for the effect of wood's fiber section during cutting

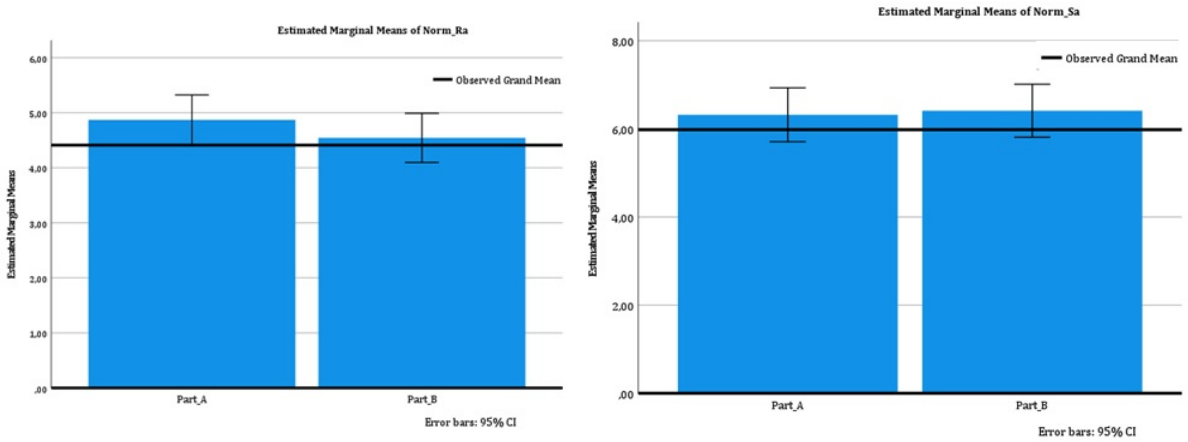


Fig. 8 Estimated Marginal Means for the effect of glued part

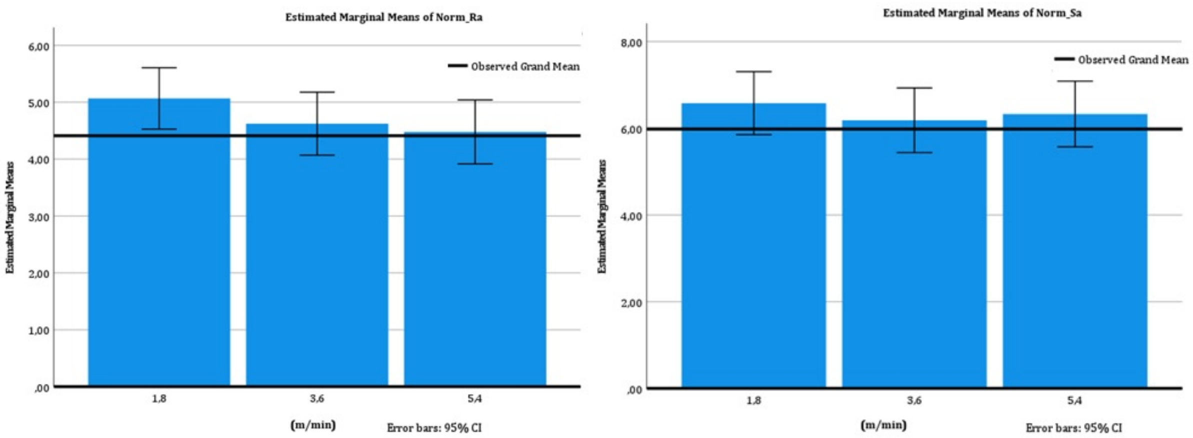


Fig. 9 Estimated Marginal Means for the effect of feed speed

The results have not shown statistical significance on Ra and Sa. Nevertheless, the conclusions can be drawn from the results of EMM on Ra, and particularly on Sa. As illustrated in Fig. 8, in wood processing, no clear trend of "higher cutting speed, better surface quality" was observed—a phenomenon well known in high-speed metal machining. Next, the overall effect of wood species on surface quality is presented in Fig. 10.

Statistical analysis, and particularly the investigation of EMM of the effect of hardwood timber, revealed that wood, rated as very durable (walnut) and durable (oak), is processed easier, and the surface quality is better. The EMM results for the effect of all hardwood species do not show statistical significance for either Ra or Sa.

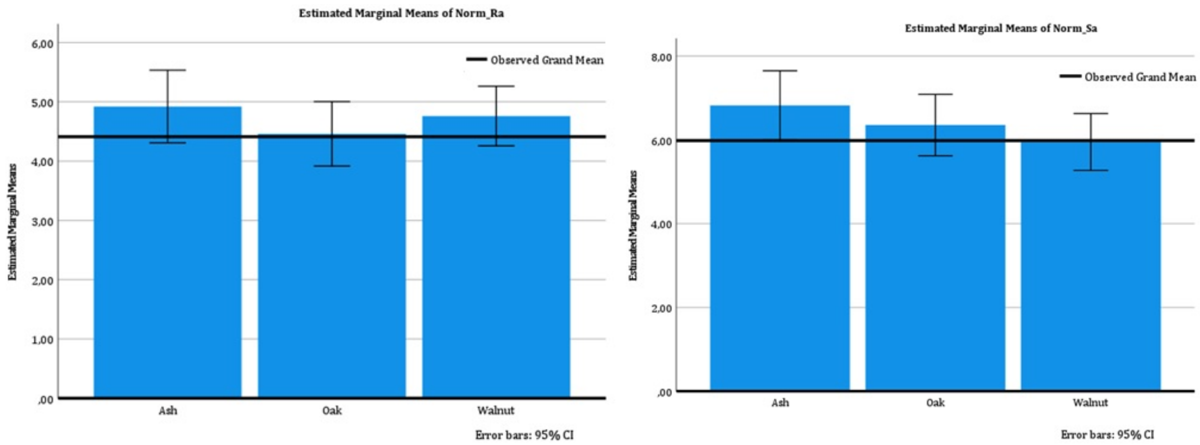


Fig. 10 Estimated Marginal Means for the effect of hardwood species

Moreover, changes in cutting tool geometry have an impact on the quality of machined surfaces. This aspect has been investigated in scientific literature by other authors, and it has been established that variations in cutting angles significantly affect machining outcomes [27, 28]. Consequently, presented study revealed the impact of machining parameters on surface roughness with one milling tool and one set-up. As the quality of machined surfaces improves [29, 30], the consumption of time, energy, and other resources decreases. After planning or milling, the surface quality of certain wood products is sufficiently high, making sanding unnecessary; they can be finished directly or even used without any additional surface treatment. In such cases, eliminating the sanding operation helps to save time, energy, and sanding materials. When processing soft hardwoods (e.g., birch, beech, alder) or softwoods (e.g., spruce, pine, larch), the results may differ. However, in wood cutting theory, differences between wood species of biological origin can be addressed by applying appropriate correction coefficients [31-33]. Additionally, other authors [34] were investigating a similar topic, aiming for effective wood processing in the furniture industry. Unlike other studies, the present research was conducted under non-idealized cutting conditions while milling curvilinear shapes. Additionally, the impact of extensive craftsmanship in wood manufacturing and visual inspections was considered in the presented study.

4. Conclusion

The results of the experimental investigation of hardwood milling, along with the multivariate statistical analysis (MANOVA) of surface quality measurements, demonstrated a statistical dependence between feed speed, hardwood species, annual growth rings, and workpiece preparation. The study included a wide range of hardwood materials—ash (*Fraxinus*), oak (*Quercus*), and walnut (*Juglans*)—classified according to their durability ratings (classes 5, 2, and 1, respectively).

The results of Pillai's Trace statistics and the Tests of Between-Subjects Effects revealed that the hardwood grain section is the most significant factor, showing statistical significance and strongly influencing surface quality during hardwood processing. The study showed that from technological point of view, the hardwood processing of tangential sections leads to rougher surfaces compared to cross-sections. Consequently, presented findings of this study can be effectively applied in the furniture industry to reduce production time, while applying adapted tool path with concerned cutting conditions. Moreover, it can be emphazised, that the preparation of wooden samples is primarily carried out with aesthetic considerations in mind. This raises the question of whether the priority should be aesthetics or technological efficiency when preparing workpieces from multiple samples in the hardwood furniture industry.

The statistical analysis also demonstrated that preparing a workpiece by gluing two parts may have a greater impact on surface roughness Ra than on Sa; however, this effect was not statistically significant.

In the present study, within the feed speed range of 1.8, 3.6, and 5.4 m/min, no statistical significance was observed during hardwood milling. When analyzing average surface roughness Ra, a decrease in surface roughness was observed with increasing feed speed. However, the areal surface roughness Sa indicates that at certain feed speeds, the surface roughness stabilizes and may even worsen as the feed speed increases.

The presented multivariate analysis demonstrated that hardwood processing is multifactor technology, where the surface quality is primarily influenced by the annual growth section. Other conclusions regarding the effects of different factors may require further investigation with an increased sample size to be confirmed or refuted.

References

[1] Salim, R., Johansson, J. (2016). The influence of raw material on the wood product manufacturing, *Procedia CIRP,* Vol. 57, 764-768, doi: 10.1016/j.procir.2016.11.132.

[2] Broman, O., Fredriksson, M. (2012). Wood material features and technical defects that affect yield in a finger joint production process, *Wood Material Science & Engineering*, Vol. 7, No. 4, 167-175, doi: 10.1080/17480272.2012.699461.

[3] Wodzicki, T.J. (2001). Natural factors affecting wood structure, *Wood Science and Technology*, Vol. 35, No. 1, 5-26, doi: 10.1007/s002260100085.

[4] Orlowski, K.A., Chuchala, D., Sinn, G. (2022). Analyses of shear angle in orthogonal cutting of pine wood, *Drvna Industrija.,* Vol. 73, No. 3, 309-315, doi: 10.5552/drvind.2022.0022.

[5] Jankowska, A. (2020). Understanding of surface roughness of wood based on analysis its structure and density, *Annals of Warsaw University of Life Sciences SGGW Forestry and Wood Technology*, Vol. 111, 27-31, doi: 10.5604/01.3001.0014.6421.

[6] Juodeikienė, I., Norvydas, V. (2005). Compression strength of oak and ash wood perpendicular to grain, *Materials Science,* Vol. 11, No. 1, 40-44.

[7] Sinn, G., Sandak, J., Ramananantoandro, T. (2009). Properties of wood surfaces – Characterisation and measurement. A review COST Action E35 2004-2008, Wood machining – micromechanics and fracture, *Holzforschung,* Vol. 63, No. 2, 196-203, doi: 10.1515/HF.2009.016.

[8] Thoma, H., Peri, L., Lato, E. (2015). Evaluation of wood surface roughness depending on species characteristics, *Maderas. Ciencia y tecnología*, Vol. 17, No. 2, 285-292, doi: 10.4067/S0718-221X2015005000027.

[9] Manuel, A., Leonhart, R., Broman, O., Becker, G. (2015). Consumers' perceptions and preference profiles for wood surfaces tested with pairwise comparison in Germany, *Annals of Forest Science*, Vol. 72, No. 6, 741-751, doi: 10.1007/s13595-014-0452-7.

[10] Sandak, J., Orlowski, K.A., Sandak, A., Chuchala, D., Taube, P. (2020). On-line measurement of wood surface smoothness, *Drvna Industrija,* Vol. 71, No. 2, 193-200, doi: 10.5552/drvind.2020.1970.

[11] Đukić, I., Merhar, M., Jovanović, J. (2023). Analysis of theoretical machined surface roughness profile after sawing solid oak wood (Quercus robur L.) along the grain with a circular saw, *Wood Material Science & Engineering*, Vol. 18, No. 4, 1534-1544, doi: 10.1080/17480272.2022.2158130.

[12] Csiha, C., Krisch, J. (2000). Vessel filtration - A method for analyzing wood surface roughness of large porous species, Drevarsky Vyskum, Vol. 45, No. 1, 13-21.

[13] Kilic, M., Hiziroglu, S., Burdurlu, E. (2006). Effect of machining on surface roughness of wood, *Building and Environment,* Vol. 41, No. 8, 1074-1078, doi: 10.1016/j.buildenv.2005.05.008.

[14] Gurau, L., Mansfield-Williams, H., Irle, M. (2007). Separation of processing roughness from anatomical irregularities and fuzziness to evaluate the effect of grit size on sanded european oak, *Forest Products Journal*, Vol. 57, No.1-2, Article No. 110.

[15] Okai, R. (2009). Influence of vibration coupling between bandsaw frame and feed-carriage system on sawdust spillage and surface quality of workpiece during sawing, *European Journal of Wood and Wood Products*, Vol. 67, No. 2, 189-195, doi: 10.1007/s00107-009-0319-z.

[16] Meulenberg, V., Ekevad, M., Svensson, M., Broman, O. (2022). Minor cutting edge force contribution in wood bandsawing, *Journal of Wood Science,* Vol. 68, Article No. 18, doi: 10.1186/s10086-022-02023-8.

[17] Skaljic, N., Lucic, R.B., Cavlovic, A.O., Obucina, M. (2009). Effect of feed speed and wood species on roughness of machined surface, *Drvna Industrija,* Vol. 60, No. 4, 229-234.

[18] Goli, G., Sandak, J. (2016). Proposal of a new method for the rapid assessment of wood machinability and cutting tool performance in peripheral milling, *European Journal of Wood and Wood Products,* Vol. 74, No. 6, 867-874, doi: 10.1007/s00107-016-1053-y.

[19] Dobrzvnski, M., Orlowski, K.A., Biskup, M. (2019).Comparison of surface quality and tool-life of glulam window elements after planing, *Drvna Industrija,* Vol. 70, No. 1, 7-18, doi: 10.5552/drvind.2019.1741.

[20] Kminiak, R., Gasparik, M., Kvietkova, M. (2015). The dependence of surface quality on tool wear of circular saw blades during transversal sawing of beech wood, *BioResources*, Vol. 10, No. 4, 7123-7135, doi: 10.15376/biores.10.4.7123-7135.

[21] Bendikiene, R., Keturakis, G. (2017). The influence of technical characteristics of wood milling tools on its wear performance, *Journal of Wood Science,* Vol. 63, No. 6, 606-614, doi: 10.1007/s10086-017-1656-x.

[22] Sofuoglu, S.D. (2015). Determination of optimal machining parameters of massive wooden edge-glued panels made of European larch (Larix decidua Mill.) using Taguchi design method, *BioResources*, Vol. 10, No. 4, 7772-7781, doi: 10.15376/biores.10.4.7772-7781.

[23] Lipovetsky, S. (2015). MANOVA, LDA, and FA criteria in clusters parameter estimation, *Cogent Mathematics*, Vol. 2, No. 1, Article No. 1071013, doi: 10.1080/23311835.2015.1071013.
[24] Tabachnick, B.G., Fidell, L.S., Ullman, J.B. (2007). *Using multivariate statistics*, Vol. 5. Pearson Boston, USA.
[25] Coulson, J.(2021). *A handbook for the sustainable use of timber in construction*, John Wiley & Sons, Hoboken, USA.
[26] Ates, C., Kaymaz, O., Kale, H.E. , Tekindal, M.A. (2019). Comparison of test statistics of nonnormal and unbalanced samples for multivariate analysis of variance in terms of type-I error rates, *Computational and Mathematical Methods in Medicine*, Vol. 2019, No. 1, Article No. 2173638, doi: 10.1155/2019/2173638.
[27] Curti, R., Marcon, B., Denaud, L., Collet, R. (2018). Effect of grain direction on cutting forces and chip geometry during green beech wood machining, *BioResources*, Vol. 13, No. 3, 5491-5503, doi: 10.15376/biores.13.3.5491-5503.
[28] Curti, R., Marcon, B., Denaud, L., Togni, M., Furferi, R., Goli, G. (2021). Generalized cutting force model for peripheral milling of wood, based on the effect of density, uncut chip cross section, grain orientation and tool helix angle, *European Journal of Wood and Wood Products,* Vol. 79, 667-678, doi: 10.1007/s00107-021-01667-5.
[29] Ritter, M.A., Skog, K., Bergman, R.(2024). Science supporting the economic and environmental benefits of using wood and wood products in green building construction, *General technical report FPL-GTR-206,* Vol. 206, Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, USA, doi: 10.2737/FPL-GTR-206.
[30] Mydlarz, K., Mydlarz, S., Wieruszewski, M. (2021). Economic and environmental aspects of technologies for surface treatment of selected wood-based composites, *BioResources*, Vol. 16, No. 2, 2696-2713, doi: 10.15376/biores.16.2.2696-2713.
[31] Sahin, C.K., Topay, M., Var, A.A. (2020). A study on suitability of some wood species for landscape applications: surface color, hardness and roughness changes at outdoor conditions, *Wood Research*, Vol. 65, No. 3, 395-404, doi: 10.37763/wr.1336-4561/65.3.395404.
[32] Kamperidou, V., Aidinidis, E., Barboutis, I. (2020). Impact of structural defects on the surface quality of hardwood species sliced veneers, *Applied Sciences,* Vol. 10, No. 18, Article No. 6265, doi: 10.3390/app10186265.
[33] Jankowska, A., Kozakiewicz, P., Zbiec, M. (2021). The effects of slicing parameters on surface quality of European beech wood, *Drvna Industrija,* Vol. 72, No. 1, 57-63, doi: 10.5552/drvind.2021.2013.
[34] Demir, A., Cakiroglu, E.O., Aydin, I. (2022). Determination of CNC processing parameters for the best wood surface quality via artificial neural network, *Wood Material Science & Engineering*, Vol. 17, No. 6, 685-692, doi: 10.1080/17480272.2021.1929466.