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The Distribution Pattern of Machining Errors on Woodworking Machine Tools

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Abstract. The article aims to develop a methodology for calculating and predicting the distribution patterns of wood machining errors to assess the operating conditions of the machine tool according to the technological accuracy criterion. It was analytically proven and experimentally confirmed that Weibull’s law accurately describes the distribution pattern of machining errors on woodworking machines. Based on the results of experimental studies of the accuracy of machining on machines for lengthwise sawing and plano-milling of wood, it was found that the primary indicator of the Weibull distribution law is a shape parameter that takes values within 1.89–3.11. The computational algorithm was developed for statistical modeling of the pattern of the distribution of machining errors according to the Weibull distribution law. It allows for determining the main parameters of the error distribution law and evaluating the operating conditions for the machine tool according to the technological accuracy criterion. The statistical modeling results for the distribution pattern of machining errors are correlated with the experimental data with an accuracy of up to 5 %, which confirms the reliability of the obtained simulation results. The developed approach also minimizes the restoration cost for the machine’s operability.

Keywords: machining accuracy, process innovation, statistical approach, distribution law, machine operability.

1 Introduction

The stricter requirements of the latest technologies of woodworking production regarding the quality of products and the efficient use of raw materials and technical resources necessitate further development of the scientific foundations for the accuracy of wood machining [1].

Compliance with the required level of accuracy in machining wood parts ensures interchangeability in the assembly of furniture and joinery products, their high quality, reduction in material costs, and increase in production efficiency. The high requirements for the accuracy of wood machining by cutting primarily relate to such technological operations as sawing logs into edged lumber with an accuracy of ±0.5 mm and milling bar blanks with an accuracy of ±0.1 mm [2].

The primary way to fulfill such requirements is to calibrate individual parts after final assembly. This requires additional raw material and energy costs, increasing product costs and the duration of the production cycle.

For the components of the technological system “machine – cutting tool – workpiece”, it is the machine that is the most responsible and expensive link, as well as the most complex and constant source of errors that occur in wood machining by cutting [3]. The negative impact of primary machining errors, the source of which is the machine tool, increases over the time of its operation due to the inevitable loss of initial accuracy [4, 5].

Maintaining the operability and restoring the accuracy parameters of woodworking machines is provided by the system of their maintenance and repair [6]. Considering the large number of errors caused by the operation of the machine in the process of wood machining, their random nature, and changes in the laws of distribution over time [7], it is advisable to develop a methodology for modeling and predicting patterns to minimize the cost of restoring operational efficiency and ensuring the maximum service life of the machine.

2 Literature Review

The issue of the accuracy of wood machining on machine tools has been considered in works [8, 9], according to which the source of errors in the dimensions of parts produced in the cutting process is a dynamic system “machine – cutting tool–workpiece” with a large number of factors: geometric accuracy and rigidity of the machine, vibrations of the woodworking machine units and the cutting tool, changes in friction forces in kinematic pairs, thermal deformations of parts and cutting tools, blunting of cutting tools, inhomogeneity of wood structure, and indicators of cutting mode. These factors have both a systematic and a random influence on machining accuracy. In particular, the authors of the paper [2] proved that the patterns of changes in the technological accuracy of the machine during the period of wear resistance of the cutting tool are described by a polynomial dependence. As the results of experimental studies on plano-milling machines, regression models in the form of third-order polynomials were obtained, and it was established that to ensure machining accuracy within the tolerance of ±0.1 mm, the geometric accuracy of the machines must correspond to an exceptionally high class of accuracy.

In [8], by testing the hypotheses about the distribution law of the machining error on a band saw machine, it was found that the distribution does not correspond to the normal distribution law, and the Weibull distribution law describes this dependence more precisely. This confirms the presence of a dominant factor influencing the decrease in the sawing accuracy and the shift in the average value of the dimensions toward an increase. Non-compliance with the normal distribution law of various distributions, which can be used as input data in simulation modeling wood-cutting processes, is typical for such material as wood. In work [9], the distribution of the lengths of defect-free sections for various wood species is described by the Log-Logistic and Burr distribution laws.

The authors of [10] developed the analytical framework of a model of force interaction in a technological system with multi-tool regulation. In machining processes such as turning, milling, and grinding, the accuracy of the obtained dimensions and the error in the shape of the resulting surface is determined by the mechanics of the force interaction between the cutting tool and the workpiece. The interaction of these main elements of the technological system is also significantly influenced by other auxiliary elements (i.e., fixtures, holders, and machine carriages).

Since the force interaction in cutting processes, when operating under standard modes, occurs at the level of elastic deformations, the problem is reduced to the analysis of the elastic-force interaction of a system of bodies with deformable connections.

A few works recognize the importance of mechanics in the reliability of technological machines and that reliability assessment is essential to ensure mechanical equipment’s accuracy and service life. The study [11] proposes a method for assessing the reliability of computer numerical control (CNC) machine tools based on the variable parameter power law model (MVPPLM). The case analysis results based on CNC machine data in the user field tracking test show that MVPPLM has higher accuracy than the traditional method. Therefore, a reliability assessment considering the difference in operating conditions is valuable for engineering applications.

In [12], a model of parametric machine failure is developed according to the accuracy criterion, which makes it possible to determine the duration of inter-adjustment periods of machine operation. It was established that the density of parametric failures of woodworking machines according to the criterion of accuracy corresponds to the α-distribution.

The authors of [13] studied the reliability assessment of mechanical equipment based on a performance-functional model, which will ensure accuracy, proper functioning, and service life. However, for woodworking machines with a long operating time, it is challenging to estimate their service life and reliability on the grounds of traditional statistical inference based on a large sample of data obtained over a long-term operation activity during the overhaul period of operation.

The purpose of the research works [14–16] was to provide optimal conditions for the milling process of the corresponding wood species by studying the influence of the design parameters of the tool and cutting mode on the quality of machining, the evaluation indicator of which is the roughness of the machined surface. In particular, the article [14] investigated design and technological, material, and instrumental factors affecting the quality of the machined surface (average roughness Ra) as well as energy consumption during milling of thermally treated meranti wood. The magnitude of influence of individual factors on the surface roughness was determined in the following order: cutting edge angle, heat treatment of the material, feed rate, and cutting speed.

In [15], regression models were obtained for the dependence of the roughness of the machined surface and the cutting power in the process of helical milling of pine wood on the following factors: helical angle of the cutter, speed of rotation of the head shaft and depth of milling. The influence of input variables and the quantitative relationship between the input data and the change in indicators for assessing machining quality have been determined. The authors of [16] experimentally investigated the influence of milling process parameters (type of milling cutter, spindle rotation speed, feed rate, and cutting depth) on the machined surface roughness of bamboo wood. According to the obtained data, roughness increased with increasing machining depth and feed rate and decreased with increasing spindle rotation speed and the number of knives in the cutter.

The articles [17, 18] present the results of studying tool wear and wood surface roughness machined by plane milling. The dependence of the influence of tool wear on the cutting power and the quality of the machined surface under various milling modes was obtained, which helped to determine the differences and variations in the roughness of the machined surface, which significantly depend on the cutting path and the radius of curvature of the cutting edge of the tool. Based on the study results obtained, it can be concluded that tool wear undoubtedly significantly affects the cutting power and the quality of the machined surface and can be important in determining the cutting mode and the period of tool resistance to wear.

The authors of works [19–21] investigated the wear resistance of cutters, the blades of which were reinforced with various coatings, and also studied the influence of various factors on the roughness of the machined wood surface. Particularly, in [19], the influence of wear resistance of planning tools (ET1, ET2) on the surface roughness of birch wood was studied. These tools were manufactured by surfacing, using the hidden-arc welding (SAW) technique, a mixture of alloying elements (chromium, tungsten, ferromanganese, silicon carbide) applied to the surface under an industrial flow. The results of the experiments showed that the ET2 tool has a higher wear resistance than the commercial tool and is better for planning the machining of birch wood.

The article [20] presents the results of research on the wear resistance of tungsten carbide (WC–Co) cutters with AlCrN coating and without coating, intended for milling oak wood. The samples of oak wood were also tested in three different milling modes. The wear resistance of the cutters was assessed by the optical method when the radius of the cutting edge was measured. The edge's radius and the machined surface's roughness were measured at a cutting length of up to 9050 m. The results showed that cutters with AlCrN coating are more wear-resistant.

In the research work [21], the cutting power, the machined surfaces' surface quality, and the cutting edge's wear were determined during plane milling of oak wood. The experimental tool was a milling head with two interchangeable blades that were treated with different coatings: a 1 µm to 4 µm thick AlTiCrN multilayer coating (blade B) and a 1 µm thick MoC multilayer coating (blade C). The cutting-edge wear parameter (WBW) increased with increasing milling length; blade C reached the highest value (WBW = 54.0 µm at a milling length of 270 m). The machined surfaces' quality parameter (Ra) remained almost unchanged, increasing the milling length to 90 m.

The authors of the works [22, 23] note that introducing automation tools and using robotic systems can improve productivity and machining accuracy. However, these measures cannot exclude the influence of such factors as the technological system's cutting tool wear, thermal, elastic, and contact deformations on the accuracy of manufactured parts.

Thus, based on the results of the analysis of known studies on the accuracy of wood machining, it can be noted that the source of errors in the dimensions of manufactured parts is the dynamic system "machine – cutting tool – workpiece" with many factors that have both a systematic and random nature of the impact on the accuracy of machining. Based on the analysis of known methods for studying machining accuracy, it was established that it is appropriate to use a statistical analytical method at the initial stage of the study. However, it is challenging for woodworking machines with long operating periods to estimate their service life and reliability based on traditional statistical inferences, which involves a large sample of data obtained in long-term operation during the overhaul period.

The available research works do not consider the possibility of assessing and predicting the machine's operable condition according to the technological accuracy criterion, which would minimize the cost of restoring performance and ensure the maximum life of the machine.

This work aims to develop a modeling methodology and predict the patterns of distribution of wood machining errors on machines for lengthwise sawing and plano-milling of wood to assess the operable condition of the machine according to the criterion of technological accuracy and minimize the cost of the restoration of the machine's operability.

3 Research Methodology

Based on the analysis of well-known methods for studying the accuracy of machining on woodworking machines, it is found that at the initial stage of the study, the use of the statistical-analytical method is effective [8, 16]. The assessment of the state of the technological accuracy of the machine at a particular stage of its operation is carried out based on the processing of statistical data obtained from experimental studies in the following sequence: putting forward a hypothesis about the law of distribution of machining errors; estimation of distribution parameters; checking the consistency of the empirical distribution with the chosen theoretical one (testing the hypothesis about the distribution law); assessment of accuracy indicators or verification of compliance with requirements.

In order to improve the statistical and analytical method of researching the technological accuracy of woodworking machines, it is proposed, in addition to the hypothesis of the normal distribution of machining errors, to apply the verification of the hypothesis about the distribution of errors according to the Weibull distribution law, which, in the presence of two parametric characteristics, makes it possible to describe various forms of deviation from the normal distribution adequately.

The density of the error distribution according to the Weibull distribution law [7] is described by the function:

$$\mathrm{f(x)} = \frac{\mathrm{b \cdot x^{b\text{-}1}}}{\mathrm{a^b}} \cdot \mathrm{e}^{\left(\frac{\mathrm{x\text{-}x_0}}{\mathrm{a}}\right)^{\mathrm{b}}}, \tag{1}$$

where x_0 – bias parameter ($0 \leq x_0 < x$); b – form parameter ($b > 0$); a – scale parameter ($a > 0$).

Using the Pearson criterion to test the hypothesis about the correspondence of the empirical distribution of the Weibull distribution law provides more reliable results.

To implement the part of the research on the technological accuracy of woodworking machines which requires mathematical processing of large arrays of statistical data from experimental studies and obtaining high-precision results, the authors of the article developed the computer program "StatToch", the algorithm of which is shown in Figure 1.

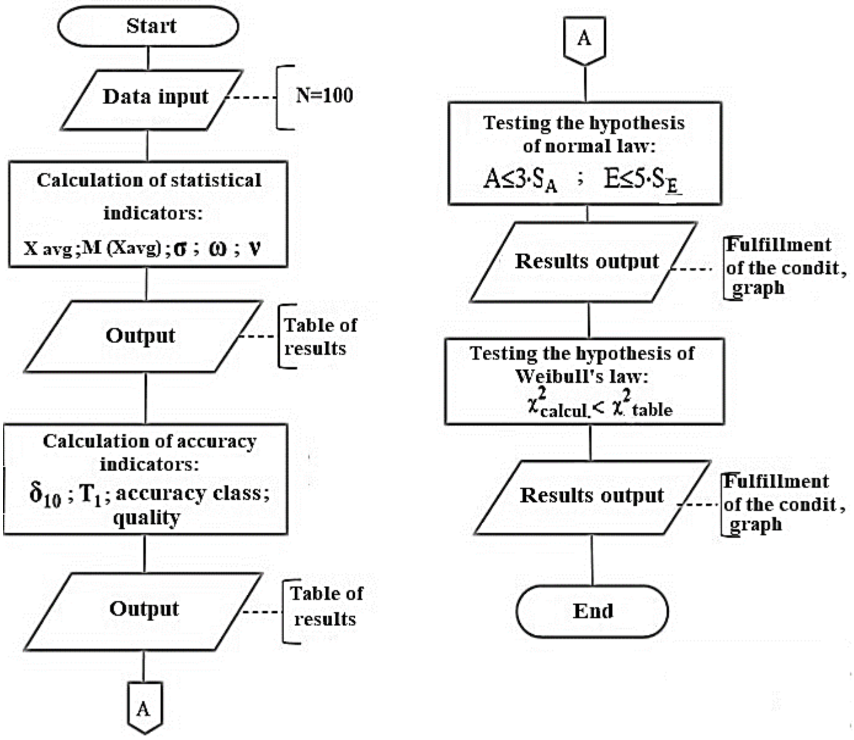


Figure 1 – The calculation algorithm

The program provides for obtaining the values of the main statistical characteristics, establishing the quality of the accuracy of the dimensions of the manufactured parts, the accuracy class of the machine tool, and the law of distribution of machining errors.

The program was created in the MS Excel environment in compliance with the following basic principles: ensuring the universality of the software methodology for a possible study of the technological accuracy of various types of woodworking machine designs; ensuring the efficiency and completeness of the final result of the study; an integrated approach to determining the indicators of technological accuracy of machines and establishing the patterns of the distribution of machining error; the possibility of processing arrays of input data with any number of sample values with confirmation of its representativeness; ensuring visibility of the obtained results through their presentation in graphic form.

Numerical simulation modeling was applied to carry out studies on the determination of stable characteristics of the distribution of machining errors on various types of machine tool designs, which require their repeated reproductions with subsequent statistical processing of the obtained results [17, 18]. The method is because the analyzed dynamic (stochastic) system is replaced by a simulator – a computer program that is used to perform research.

When solving mathematical problems by the Monte Carlo method [24], random variables ξ are modeled and distributed according to different distribution laws. Any random variable ξ is obtained by converting the values of a uniformly distributed random variable γ.

The Monte Carlo simulation of machining errors distributed according to the Weibull distribution law is performed by integrating the error distribution density function (1) to obtain the following dependence:

$$\int_0^x \frac{bx^{b-1}}{a^b} \cdot e^{-\left(\frac{x}{a}\right)^b} dx = \gamma. \tag{2}$$

As a result of calculating the integral (2), we obtain the following dependence:

$$1 - e^{-\left(\frac{x}{a}\right)^b} = \gamma. \tag{3}$$

The mathematical expectation of the machining error value is equal to:

$$x = a \cdot [-\ln(1-\gamma)]^{\frac{1}{b}}. \tag{4}$$

The value of the random variable x can be obtained by transforming the values of the uniformly distributed variable γ, generated by the function (RND) on the computer. The dependence (4) can be written as follows:

$$x = a \cdot [-\ln(1-RND)]^{\frac{1}{b}}, \tag{5}$$

on which random values of machining errors on the machine are played.

To implement the process of modeling machining errors according to equation (5), the algorithm of the computer program “ModToch” was developed (Figure 2).

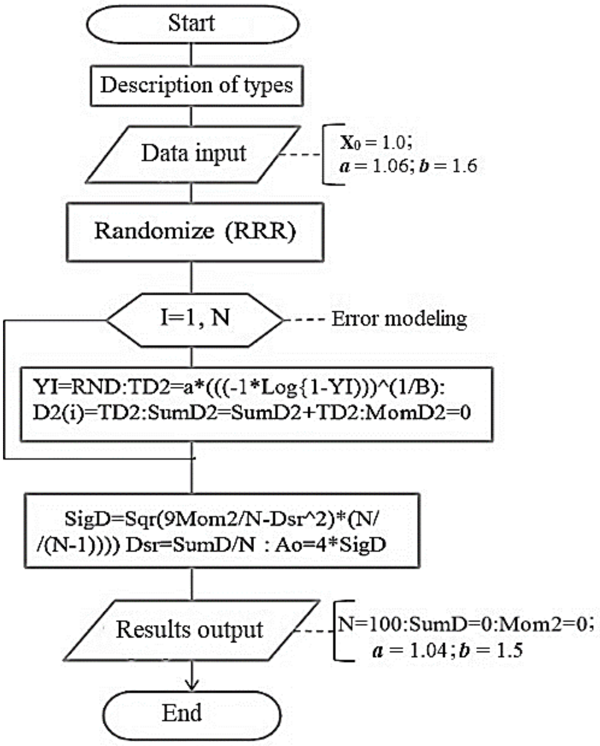


Figure 2 – An algorithm for modeling machining errors

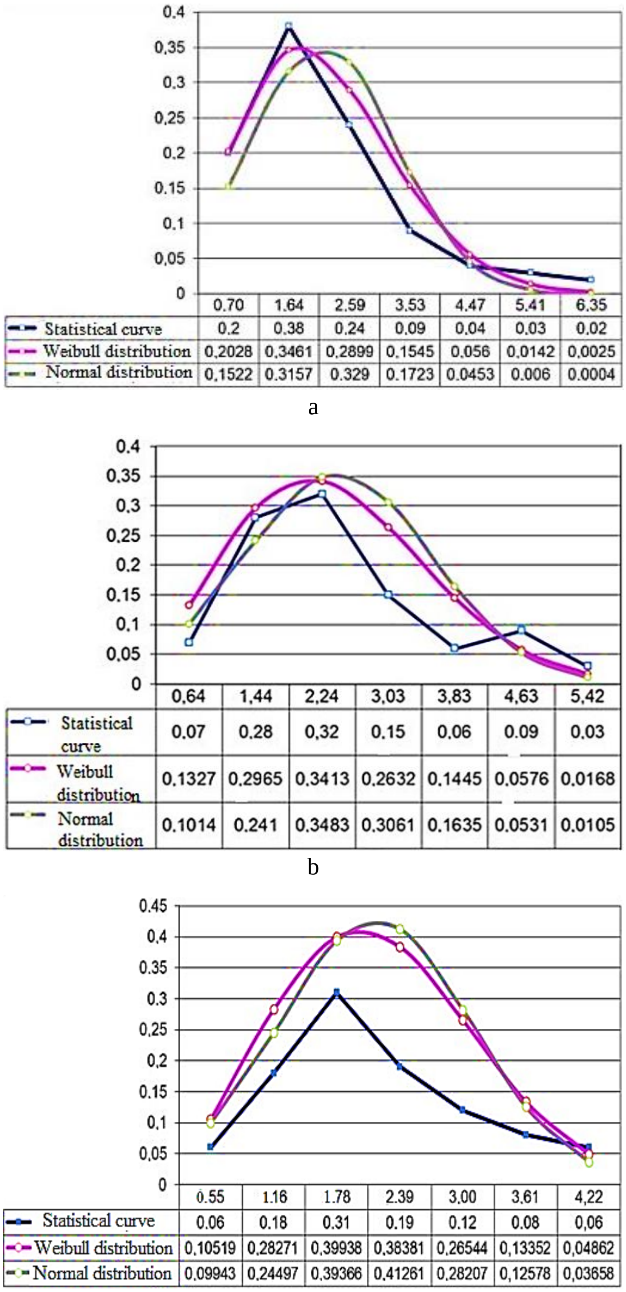
It includes the following blocks: start, description of data types, data input, initiation of the Randomize function (RRR) for the operation of the generator of uniformly distributed RND values, modeling errors from 1 to N by the Weibull distribution law, calculation of the main parameters of the distribution pattern, output of the results.

The program is implemented in the Visual Basic language for applications in the MS Excel environment. The program provides data entry and output of results onto separate sheets of the Excel environment.

4 Results

Previous experimental studies on the accuracy of wood machining were carried out on three machine tools: the band saw “SKTP505-2”, the circular saw “TSDK4-2” and the milling machine “SR6-9”. Based on the obtained statistical data and the results of their processing using the “StatToch” program, for each of the machines, the values of the main statistical characteristics of the samples were obtained to the normal distribution law and the Weibull distribution law, the diagrams of the statistical distribution of errors of manufactured parts dimensions were constructed (Figure 3).

When analyzing the graphical dependencies, it should be noted that all statistical curves have a significant asymmetry relative to the average value, indicating the presence of dominant factors influencing the machining error on these machines.



	0,70	1,64	2,59	3,53	4,47	5,41	6,35
Statistical curve	0,2	0,38	0,24	0,09	0,04	0,03	0,02
Weibull distribution	0,2028	0,3461	0,2899	0,1545	0,056	0,0142	0,0025
Normal distribution	0,1522	0,3157	0.329	0.1723	0.0453	0.006	0.0004

a

	0,64	1,44	2,24	3,03	3,83	4,63	5,42
Statistical curve	0,07	0,28	0,32	0,15	0,06	0,09	0,03
Weibull distribution	0,1327	0,2965	0,3413	0,2632	0,1445	0,0576	0,0168
Normal distribution	0,1014	0,241	0,3483	0,3061	0,1635	0,0531	0,0105

b

	0.55	1.16	1.78	2.39	3,00	3,61	4,22
Statistical curve	0.06	0.18	0.31	0.19	0.12	0.08	0,06
Weibull distribution	0,10519	0,28271	0,39938	0,38381	0,26544	0,13352	0,04862
Normal distribution	0,09943	0,24497	0,39366	0,41261	0,28207	0,12578	0,03658

c

Figure 3 – Distribution of machining errors on the machines “SKTP505-2” (a), “TSDK4-2” (b), and “SR6-9” (c)

Based on the results of testing the hypothesis about the normal distribution law of the machining error on three machines (Figure 3) according to the criteria of asymmetry and kurtosis, it was found that the deviation from the normal distribution by the magnitude of the calculated values of the criteria is almost 2.5 times greater than their permissible values. This indicates that the model of normal distribution of machining errors for these types of machines is inadequate.

Verification of the adequacy of the Weibull distribution law, i.e., the correspondence of the theoretical distribution to the empirical data, was performed using the Pearson test. According to the results of testing the hypothesis about the Weibull distribution law by the Pearson test

($\chi^2 = 9.43 < \chi^2_{tabl} = 9.49$), the adequacy of the models for the distribution of machining errors, which describe the law on each machine, is confirmed.

Thus, based on the results of the studies, it was found that for an adequate description of the probability of distribution of wood machining errors on machine tools, the most rational is Weibull’s law, which is the basis for further studies on the technological accuracy of woodworking machines. Experimental studies on the distribution of wood machining errors were carried out for the main types of machine-tool design of Ukrainian and foreign manufacturers operated at woodworking enterprises of Ukraine: band saws – SKTP505-2, LT-20; circular saws – Barracuda-2, UN-500, TsDK4-2, VK-40; milling machines – SR6-9, S-20.

Based on the results of the studies, the main parameters of the distribution of errors in the dimensions of manufactured parts according to Weibull’s law are determined, and a diagram is built (Figure 4).

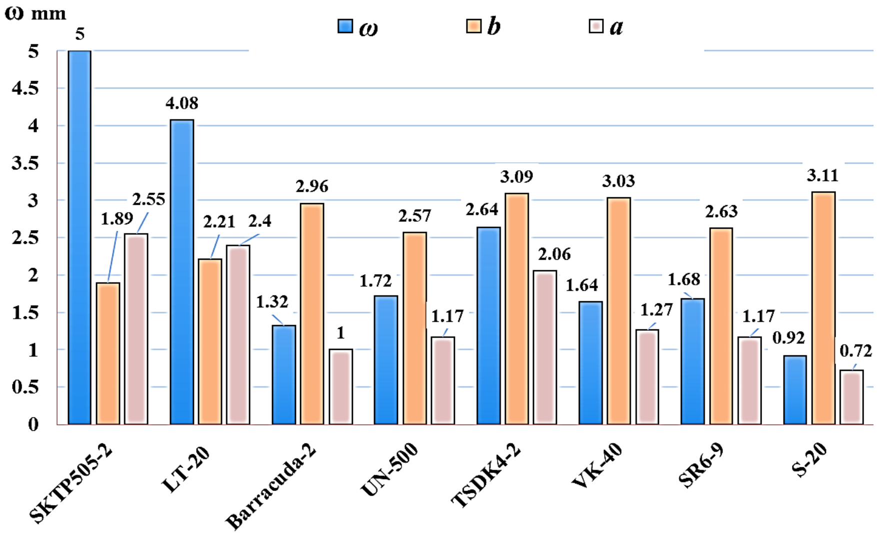
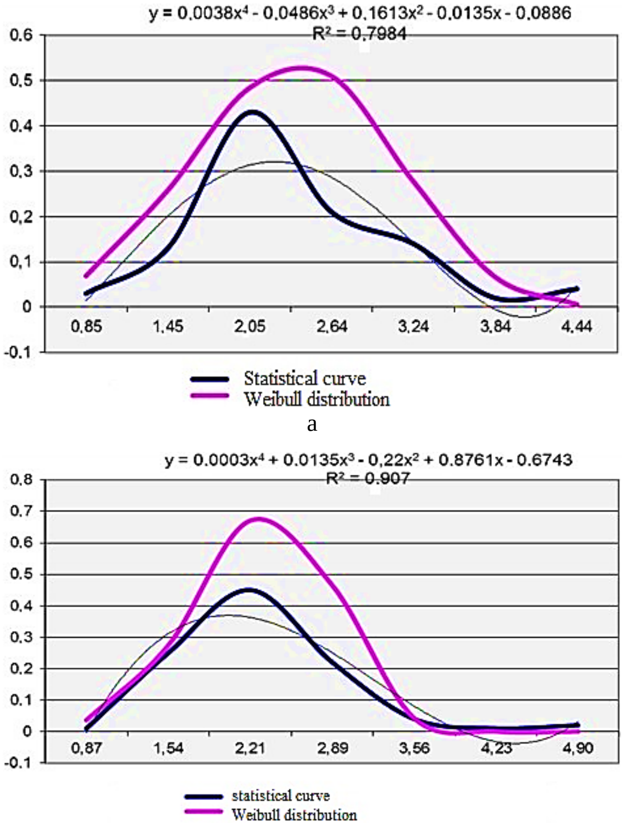


Figure 4 – Operational indicators of the accuracy of machining on the machine tools for sawing and milling wood

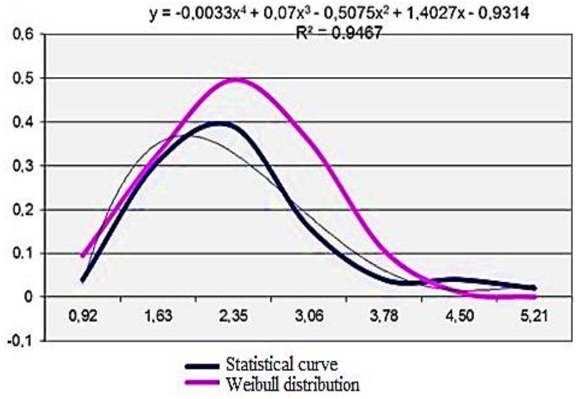
Based on the analysis of technological accuracy results for a number of lengthwise sawing and milling machines, it was found that the leading indicator of Weibull’s law – the shape parameter. For circular saws and plano-milling machines with the value of the shape parameter within the $b = 2.96 - 3.11$, the error distribution is close to normal ($b = 3.3$). In-band saws, the shape parameter takes on values within the $b = 1.89 - 2.21$ and becomes close to the Rayleigh distribution ($b = 2.1$), and the distribution curves become more peaked and asymmetric. The value of the scale parameter a correlates with the values of the scattering field ω of the machining error and corresponds to the value of the mode of the Weibull distribution law. That is, the value of the scale parameter $a = 0.72 - 2.55$ characterizes the average value of the error scattering field, which, according to the results, varies within $\omega = 0.92 - 5.00$ mm. The highest values of the scattering field $\omega = 4.08 - 5.00$ mm are found in band saws, and the lowest values $\omega = 0.92 - 1.68$ mm, are found in plano-milling machines.

The process of statistical modeling of the patterns of distribution of machining errors on woodworking machines (Figure 5) consists of playing random values of machining errors in the amount of 100 and choosing a theoretical dependence, which most accurately (with an error within 5 %) describes the distribution pattern according to the Weibull distribution law.



a

b



c

Figure 5 – Results of simulation of distribution pattern for machining errors on the LT-20 machine under the condition of correlation *R* equal to 0.80 (a), 0.90 (b), and 0.95 (c)

The modeled dependence of the distribution of machining errors is considered reliable if the approximation curve is correlated under the condition $R \geq 0.95$. For this machine (Figure 5 c), the correlation condition (within 5 %) is satisfied by a fourth-degree polynomial.

5 Discussion

Using the simulation program “ModToch”, the simulation of the distribution of machining errors for a number of woodworking machines was performed, and the values of the main parameters of the Weibull distribution law and the machining accuracy indicator – the size of the error scattering field – were determined for each machine. The obtained simulation results are presented as a diagram (Figure 6).

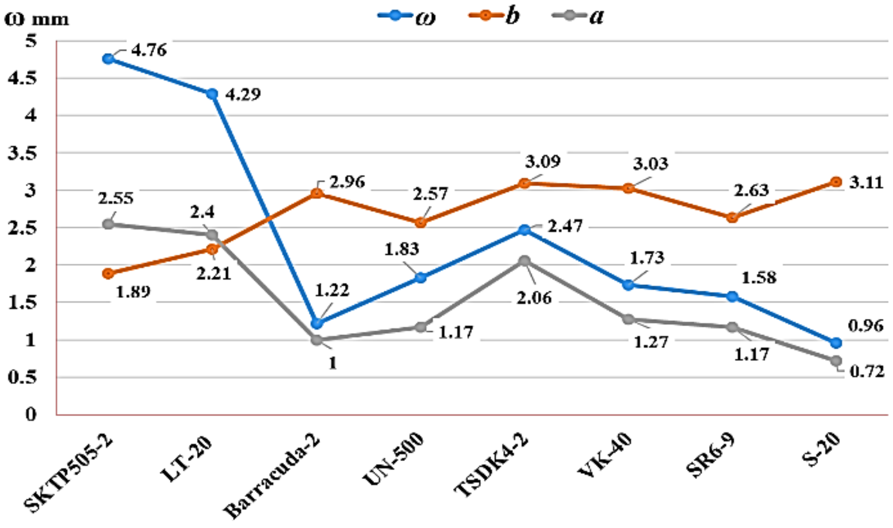


Figure 6 – Results of modeling the machining error distribution

Based on the analysis of the simulation results, it is worth noting that the values of the leading indicators of the Weibull distribution law – shape and scale parameters – are within: $b = 1.89 - 3.11$, $a = 0.72 - 2.55$, and are correlated (Figure 4) with empirical values with an error within 5 % for each of the machines.

The simulated values of the scattering field of errors in the dimensions of manufactured parts on wood sawing and milling machines vary within $\omega = 0.83 - 4.76$ mm and correlate (Figure 7) with operational indicators of technological accuracy of these machines with an error of up to 5 %.

Analyzing the results of the studies on the actual accuracy of machining (Figures 4, 7) on three types of machine tool designs, it is worth noting that the most significant values of the error scattering field $\omega = 4.08 - 5.00$mm are found in band saw machines (SKTP505-2, LT-20), the average values $\omega = 1.32 - 2.64$ mm are found in circular saw machines (Barracuda-2, UN-500, TsDK4-2, VK-40), and the smallest values $\omega = 0.92 - 1.68$ mm – in plano-milling machines (SR6-9, S-20).

When comparing the actual values of the error scattering field with the requirements for the accuracy of wood machining by cutting (for sawing – $\omega \leq 1.0$ mm, for milling – $\omega \leq 0.2$ mm), it was found that on all the machines, the actual indicator values exceed the permissible ones by several times, namely: on band saws – by 5.0 times, on circular saws – by 2.6 times, on plano-milling machines – by 8.4 times.

The low accuracy of machining on all the machines is explained [2, 12] by their operation time without carrying out measures to restore the operable condition according to the criterion of technological accuracy.

Therefore, based on the results of the analysis, it can be stated that there is a need for further research on the assessment and predicting changes in the technological accuracy of various types of machine tools during the overhaul period of operation and the development of technical solutions for restoring the operable condition of the machines according to the machining accuracy.

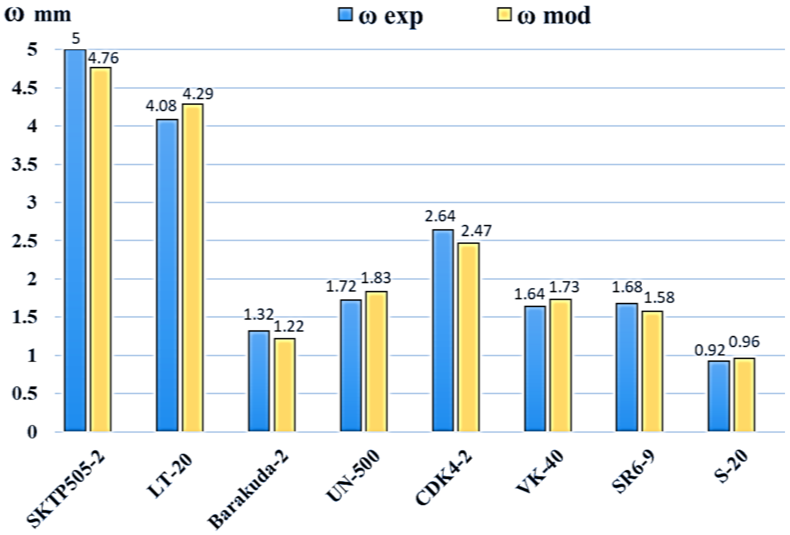


Figure 7 – Comparison of the empirical machining accuracy indicators obtained on the machines with the simulation results

6 Conclusions

It has been analytically proven and experimentally confirmed that the distribution pattern of machining errors on machines for lengthwise sawing and plano-milling of wood is reliably described by Weibull’s law.

The “StatToch” program has been developed to perform statistical analysis and processing of experimental data. It allows for obtaining the values of the main statistical characteristics, establishing the accuracy of the size of the manufactured parts, the accuracy class of the machine, and the law of the distribution of machining errors. According to the results of experimental studies on the accuracy of machining on machines for lengthwise sawing and milling of wood, it was found that the primary indicator of the Weibull distribution law is a shape parameter that takes values of $b = 1.89 - 3.11$.

The program “ModToch” has been developed for statistical modeling of the distribution pattern of machining errors according to the Weibull distribution law, which allows for determining the value of the main parameters of the error distribution law and evaluating the operable condition of the machine according to the criterion of technological accuracy. The results of statistical modeling of the distribution patterns of machining errors are correlated with the data of experimental studies with an accuracy of 5 %, confirming the simulation results’ reliability.

The developed methodology can be used in further research to assess and predict the operable condition of various types of machines according to the criterion of technological accuracy, which provides the basis for designing and improving machine designs with improved technical characteristics in terms of machining accuracy, as well as the ability to minimize the cost of restoring operational efficiency and ensure the maximum service life of machines.

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