Interpreting Research Results for the Physical and Mechanical Properties of Wood: An Approach Not Dependent on a Juvenile/Mature Wood Boundary

Tomislav Sinković, Branimir Jambreković, and Tomislav Sedlar *

The interpretation and presentation of research on the physical and mechanical properties of wood in the radial direction is important for the estimation of technological properties in primary wood processing. It is common practice to define the boundary between the juvenile and mature wood zone of tree growth because of the differences in wood properties in these two zones. The juvenile and mature wood zones can be determined statistically based on the significance of the difference in the properties in a particular zone. This paper presents the insufficiency in the statistical determination of the boundary between juvenile and adult wood. Such limitations detract from the potential value and technological exploitation of wood as raw material. Statistical tests yielded zones that were too wide for the transition of juvenile wood to mature wood. Representations of the distribution of properties in the radial direction also complement the knowledge for assessing the technological properties based on the researched use of the presentation of polynomials of the second degree and the display of the Tukey HSD test in the form of comparison tables. The graphical representations by groups of the tested annual rings of fir wood also help to assess the technological properties.

Keywords: Physical and mechanical properties of wood; Statistical methods; Technological properties

*Contact information: Wood Technology Department, Faculty of Forestry and Wood Technology, University of Zagreb, Svetošimunska cesta 23, Zagreb, Croatia; *Corresponding author: tsedlar@sumfak.unizg.hr*

INTRODUCTION

Research on the physical and mechanical properties of wood can be conducted on two types of samples: wood from trees sourced from sustainable forest management, which tend to have a distribution of properties in the radial direction (from pith to bark), and wood with controlled characteristics, which tend to have an annual ring width, a certain wood density, and other physical or mechanical properties significant for certain technologies of wood processing. The difference in the results of these two types of research samples is substantial, and it can influence the variability of the obtained results. In analyzing the samples from trees to obtain the distribution of properties in the radial direction, the variability of the results will be significantly greater because of the nature of forming wood cells in the tree in the radial direction (Govorčin *et al.* 1998, 2003). Therefore, it is necessary to consider the juvenile, mature, and overmature phases of tree growth. In these three growth phases, the tree that forms cambium is significantly different by its anatomical, physical, mechanical, and technological properties (Passialis and Kiriazakos 2004; Wang and Stewart 2012). To select samples for the research of controlled properties as the macroscopically most specific criterion, which is the annual ring width and the share of the latewood and the assumed wood density (Kličić *et al.* 2011; Sedlar *et al.* 2020), it is necessary to limit the influence of these factors on the variability of the physical and mechanical properties of such samples. The variability of the research results wields a considerable impact on the presentation of research results for the purpose of their use.

The final purpose of the presentation of the research of the physical and mechanical properties of wood is the definition of the technological properties for wood processing. The analysis of samples with defined characteristics yields results with less variability. Their application in wood processing is helpful within the framework of the defined characteristics of wood. In the case of research on samples from trees from sustainable forest management, the results of the properties will be significantly more variable. This variability shows that wood material is natural and there is significance in the presentation of the results for the forming of technological properties of wood. Considerably greater variability of results is challenging for the presentation of results, which will be useful for forming the technological properties of wood. Significant variability of research results on the physical and mechanical properties of wood and their presentation challenges the researcher with the choice of how to present those results. These results have implications for sawmilling wood processing and subsequently for wood seasoning. The anatomical, physical, and mechanical properties of wood are the basic parameters for forming the technological processing and beneficial uses of wood (Ištok *et al.* 2017; Bektaş *et al.* 2020; Sedlar *et al.* 2021).

The aim of this paper is to point out that the statistical difference in the physical and mechanical properties of juvenile and mature wood is not an accurate reflection of the realistic distribution of these properties in the radial direction. As a result, statistical analyses are often misleading with respect to the border between the juvenile and mature wood. Furthermore, depending on the level of statistical analysis, this “border” often moves through several decades of three growths. An optimal method needs to be identified for presenting research results on samples from trees from sustainable forest management in the radial direction. In this article, the term optimal means using wood based on its properties in the radial direction for products that is well suited to the requirements of these properties concerning the radial arrangement. Defining these methods can improve the research on the physical and mechanical properties of wood for forming technological properties of such wood for processing. The sawmilling wood processing of logs is the beginning of the optimal use of wood based on research results of the physical and mechanical properties for a targeted and the valuable use of wood. The relationship between the purely statistical and statistical and technological presentation of the results of research of physical and mechanical properties of wood from logs is important for the optimal processing and application of wood.

EXPERIMENTAL

The research results on the physical and mechanical properties of wood to define the optimal method of presenting the results were conducted on silver fir (*Abies alba* Mill.) from Gorski Kotar in Croatia (Sinković 1995a,b,c). The samples for the research of the physical and the mechanical properties were taken from trees grown in the forest by the selective cultivation method, which has been used in Croatia for a long time on mountain terrains. The total of ten trees were classified into four thickness classes: trees with diameter at a breast height of 21 to 30 cm (100, 98, 78, and 108 years old), trees with diameter at a breast height of 31 to 40 cm (114 and 120 years old), trees with a diameter at a breast height of 41 to 50 cm (111 and 117 years old), and trees with diameter at a breast height of over 60 cm (110 and 130 years old). The research was conducted based on relevant standards for researching the physical and mechanical properties of wood. The results were based on measurements of the annual ring width, the oven-dry density, and the bending in the radial direction.

The fundamental matrix calculator in Microsoft Office Excel 2018 (Redmond, WA, USA) and the statistical software Statistics 13 (IBM, Armonk, NY, USA) were used to present the results of the physical and mechanical properties of the wood specimens. For the presentation of the statistical values, a second-degree polynomial distribution was used. According to statistical premises, the use of third-degree polynomials is not appropriate. However, the nature of the formation of wood tissue in a tree is closer to representing third-degree polynomials because the wood is formed in three phases- juvenile, mature, and overmature. The management time of the investigated trees was 125 years, so they were not in the overmature phase yet. Thus, using second-degree polynomials was appropriate for the formed wood. In theory, a second-degree polynomial is a parabola with a minimum and two maxima, or vice versa- one maximum and two minima. Still, due to the limitation of 125 annual rings, only a part of the parabola was obtained, which is an indicator of data in this area. These computer packages performed basic statistical testing of the whole set of results as well as testing the significance of the difference between the mean values of the two sets of results within a tree according to zones, or rather according to sets of results chosen on the radial distance of the position of the samples.

RESULTS AND DISCUSSION

The annual ring width in selective forest management shows a more considerable width value in the juvenile phase, whereas by transitioning to the adult wood phase, the width decreases to a steady value that has little change with distance out to the bark (Koubaa *et al.* 2005; Alteyrac *et al.* 2006; Mvolo *et al.* 2015; Palermo *et al.* 2015). The basic statistical parameters for observing the annual ring width in the radial direction provided the values shown in Table 1.

Table 1. The Results of Statistical Processing of the Values for Annual Ring Width at the Breast Height and Summarized for all Thickness Classes

Thickness Class	Number of Annual Rings	Minimum (mm)	Mean (mm)	Maximum (mm)	Standard Deviation
I	96	0.4	1.24	3.3	0.824
II	112	0.8	1.61	4.2	0.665
III	106	0.3	1.98	4.7	1.193
IV	125	0.6	2.13	5.1	1.091
ALL CLASSES	439	0.3	1.77	5.1	1.026

It is expected that the distribution of the annual ring width in trees cultivated in sustainable forest management results in significant variation, as is shown by the standard deviation. However, it is unclear whether this statistical interpretation of the results shows the objective distribution of the annual ring width in radial direction if the natural growth phases of the tree are not known.

The standard can also be applied for the commercial presentation of the characteristics of raw wood material. The results of the raw wood material characteristics were measured according to the BS EN standard 1309-3 (2018), which expresses the average annual ring width based on 75% of the radius and the number of annual rings on that length. This standard refers to a measurement of the annual ring width only outside the juvenile wood zone. In the commercial presentation of the results, the variability of the annual ring width is smaller than in the statistical presentation, *i.e.*, the raw material is less demanding for processing. A more visually discernible distribution of the width of the annual ring in the radial direction is shown in Fig. 1.

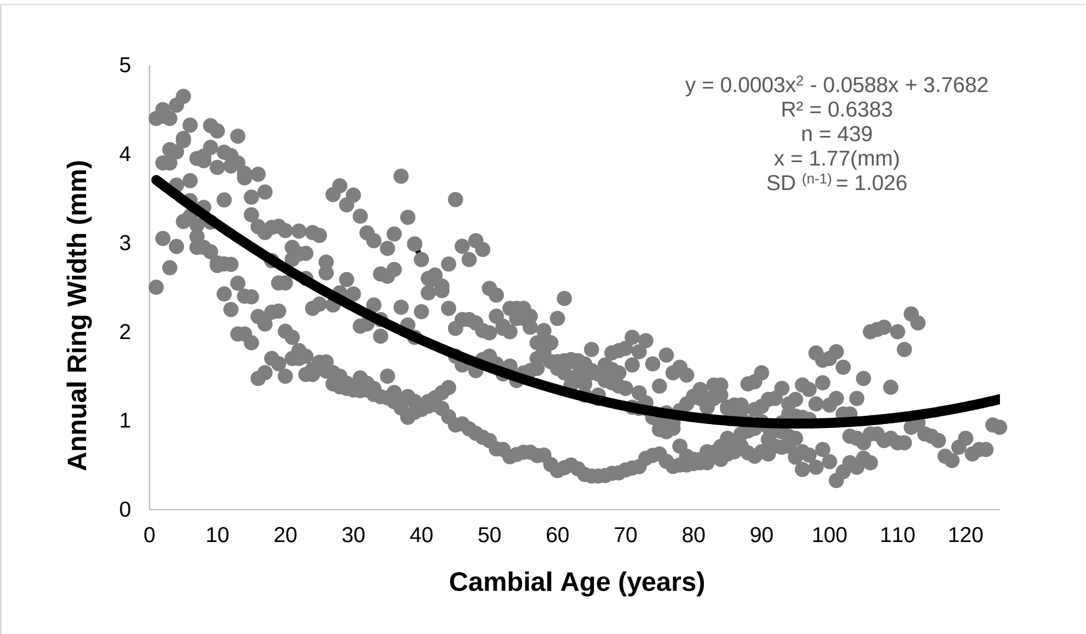

Fig. 1. Distribution of annual rings width in the radial direction, from pith to bark, of fir-wood summarized for all thickness classes (I-IV)

Comparing the two methods of presentation in Table 1 and Fig. 1, the statistical representation of the mean and the standard deviation show the same values of the annual ring width in the radial direction. However, the presentation in Fig. 1 clearly illustrates the distribution of the width of the annual ring in the radial direction, from pith to bark, in researched trees. The statistical presentation in Table 1 does not provide the actual distribution of the results according to the nature of the wood growth in trees compared to the representation in Fig. 1. It is not enough to take into consideration the quality of the raw wood material only based on the statistical results of the mean value of the annual ring width (Table 1). It is essential to consider the presentation in Fig. 1, which shows all the variability of the values according to the age of the tree or log. The influence of the annual ring width on the use of fir wood is significant due to its relationship with the physical and mechanical properties of wood. Based on the standards and calculations of wood characteristics, the wood around the pith is not considered. It is worth investigating whether the wood around the pith can be used with all its “negative properties” due to the large share in juvenile wood that is technologically “more demanding” than adult wood. Figure

1 also shows the presence of wood with a greater annual ring width located in the juvenile wood area with the unique possibility of determining the zones from which sawn timber of specific characteristics can be produced. The juvenile wood zone boundary, or the maximum deviations of the mean values of wood zones around the pith and the rest of the wood to the bark is shown in the results of the oven-dry density, the maximal tangential shrinkage, and the static bending strength. All three of these properties are essential for the processing and technological applications of wood.

The oven-dry density is one of the most common physical properties in the presentation of raw wood material characteristics. The density distribution in the oven-dry condition in the radial direction, from pith to bark, shows its distribution and provides technological insight to the required physical and mechanical properties. Based on the findings explained in the example of the annual ring width, the statistical data of oven-dry density divided into thickness classes will not be presented, but the summary values along with their basic statistical values can be seen in Fig. 2.

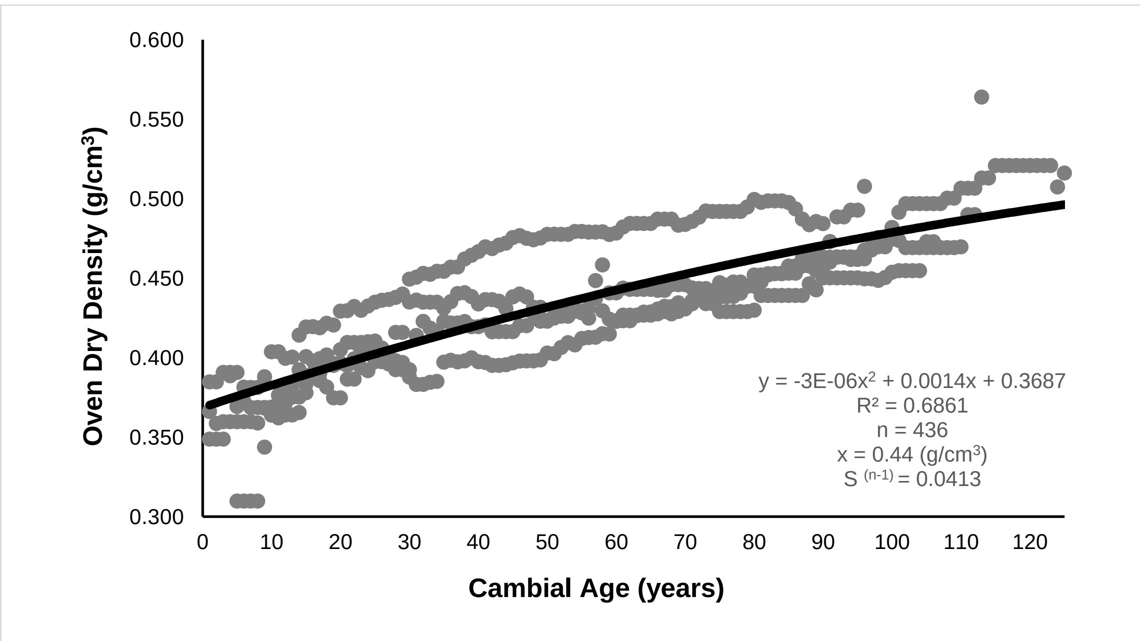

Fig. 2. Distribution of oven-dry density in the radial direction for fir wood summarizing for all thickness classes

A graphical representation of the change in the oven-dry density in the radial direction, from pith to bark, can be seen in Fig. 2. By determining the significant difference between the mean values of the juvenile and mature wood zones, the existence of the two zones was shown. The detection of the approximate boundary of juvenile and mature wood zones has a significant impact on the formation of technological properties of the wood processing of each zone. It is necessary to point out that this boundary cannot be exact in one annual ring. Like all other phenomena in nature, the process of wood transition from the juvenile to mature wood is a process that lasts a certain number of years, depending on all the influencing factors that affect the growth of the tree (Zobel and Jett 1995; Cameron *et al.* 2015; Fernandes *et al.* 2017; Sedlar *et al.* 2019). Figure 3 shows the mean values of the oven-dry density divided into groups of annual rings in the radial direction.

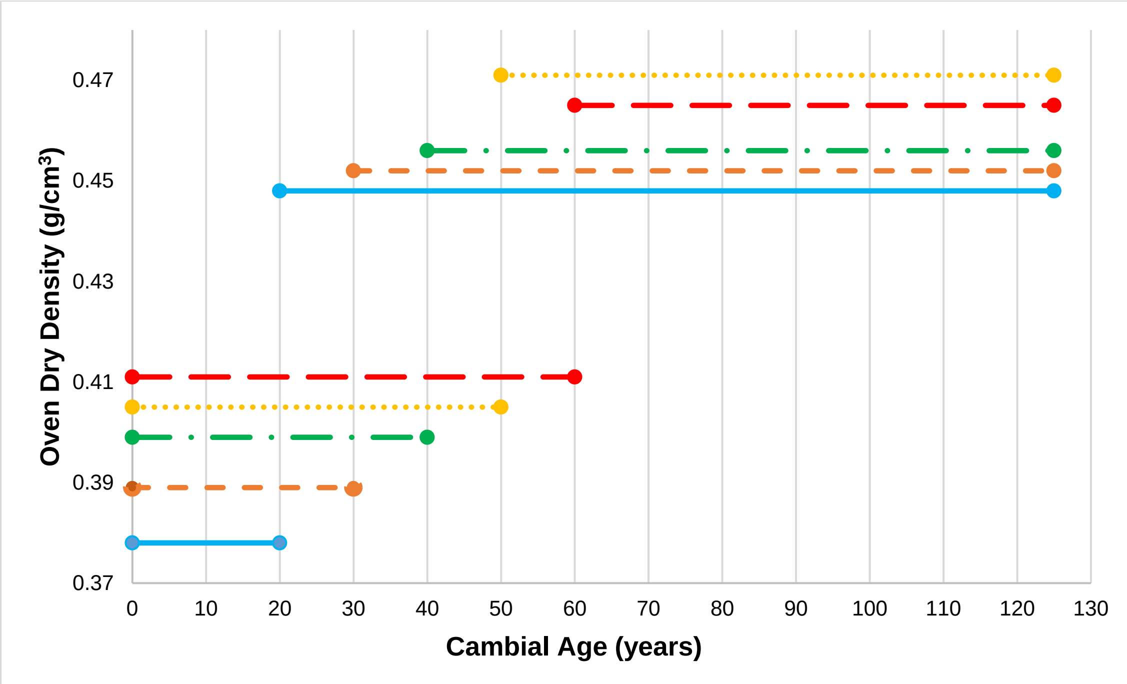

Fig. 3. The mean values of the oven-dry density divided into groups of annual rings in the radial direction, from pith to bark

The presentation in Fig. 3 is followed with Table 2, which shows the statistical analysis of the data and the significant difference in the mean values of the oven-dry density determined with a *t*-test by the groups of annual rings (0 to 20 and 21 to 125, 0 to 30 and 31 to 125 and 0 to 40 and 41 to 125, 0 to 50 and 51 to 125, 0 to 60 and 61 to 125).

Based on the values of the p-variances in Table 2, the *t*-test was conducted on the annual ring groups 0 to 30 and 31 to 125, and 0 to 40 and 41 to 125. The statistical analysis with a *t*-test showed that the mean values of the oven-dry density differed significantly in annual ring groups 0 to 30 and 31 to 125 and 0 to 40 and 41 to 125. Statistically measured, the boundary between the juvenile and mature wood was between the 30th and 40th annual ring. Statistically, the other groups of annual rings (0 to 20 and 21 to 125, 0 to 50 and 51 to 125, 0 to 60 and 61 to 125) could not be tested by the *t*-test. Instead, it was necessary to perform the Mann-Whitney U test on these groups. Technologically, the differences in the mean values of the oven-dry density between all the annual ring groups (0 to 20 and 21 to 125, 0 to 30 and 31 to 125 and 0 to 40 and 41 to 125, 0 to 50 and 51 to 125, 0 to 60 and 61 to 125) were significant. Therefore, the Mann-Whitney U test was performed to test whether the juvenile and the mature wood boundary was between the 30th and 40th annual rings. Table 3 shows the relevant values of the Mann-Whitney U test.

The Mann-Whitney U test showed that the parameter *p*-level in all the compared groups was less than 0.05, which shows a significant difference in all the tested groups. These results indicated that the zone of the juvenile wood from the aspect of the oven-dry density spreads up to the 60th annual ring from pith to bark. This conclusion does not correspond to the results found in literature (Govorčin *et al.* 1998; Zobel and Sprague 1998; Koubaa *et al.* 2005; Alteyrac *et al.* 2006; Mvolo *et al.* 2015; Sedlar *et al.* 2019).

Table 2. Statistical Analysis (*t*-test) of the Mean Values of Oven-Dry Density Between the Groups of Annual Rings

Group of Annual Rings (Group 1 and Group 2)	Mean (Group 1)	Mean (Group 2)	*t*-value	df	p	Valid N (Group 1)	Valid N (Group 2)	Std. Dev. (Group 1)	Std. Dev. (Group 2)	F-ratio Variances	p Variances
0 to 20 and 21 to 125	0.378	0.448	-17.32	434	0	76	360	0.025	0.033	1.718	0.005
0 to 30 and 31 to 125	0.389	0.452	-19.21	434	0	116	320	0.027	0.031	1.312	0.089
0 to 40 and 41 to 125	0.399	0.456	-18.67	434	0	156	280	0.031	0.030	1.045	0.745
0 to 50 and 51 to 125	0.405	0.471	-22.16	424	0	196	230	0.033	0.028	1.436	0.008
0 to 60 and 61 to 125	0.411	0.465	-17.73	434	0	236	200	0.034	0.028	1.557	0.001

Table 3. Statistical Analysis (Mann-Whitney U test) of the Mean Values of the Oven-Dry Density Between the Groups of Annual Rings

Group of Annual Rings (Group 1 and Group 2)	Rank Sum	Rank Sum	U	Z	*p*-level	Z-adjusted	*p*-level	Valid N	Valid N
0 to 20 and 21 to 125	3886.0	91380.0	960.0	-12.7432	0	-12.7435	0	76	360
0 to 30 and 31 to 125	8931.0	86335.0	2145.0	-14.1184	0	-14.1187	0	116	320
0 to 40 and 41 to 125	16305.0	78961.0	4059.0	-14.0982	0	-14.0985	0	156	280
0 to 50 and 51 to 125	22284.0	68667.0	2978.0	-15.4454	0	-15.4458	0	196	230
0 to 60 and 61 to 125	33010.0	62256.0	5044.0	-14.1535	0	-14.1538	0	236	200

Bending strength is one of the most important mechanical properties of wood that determines the usefulness of wood, especially from the aspect of the position of wood from pith to bark. The differences in the static bending strength values from pith to bark are significant. The determination of the transition boundary from juvenile wood to mature wood remains essential for the usefulness of wood from a specific position in the radial direction in construction elements. The distribution of the bending strength in the radial direction is shown in Fig. 4.

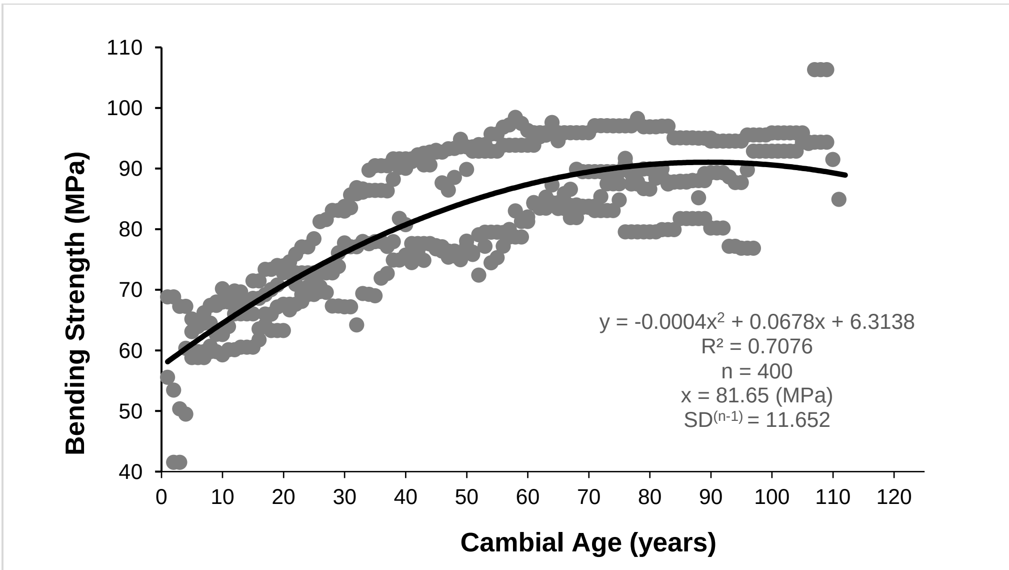

Fig. 4. The distribution of the bending strength in the radial direction, from pith to bark, for fir wood. Presented as a summary for all the thickness classes

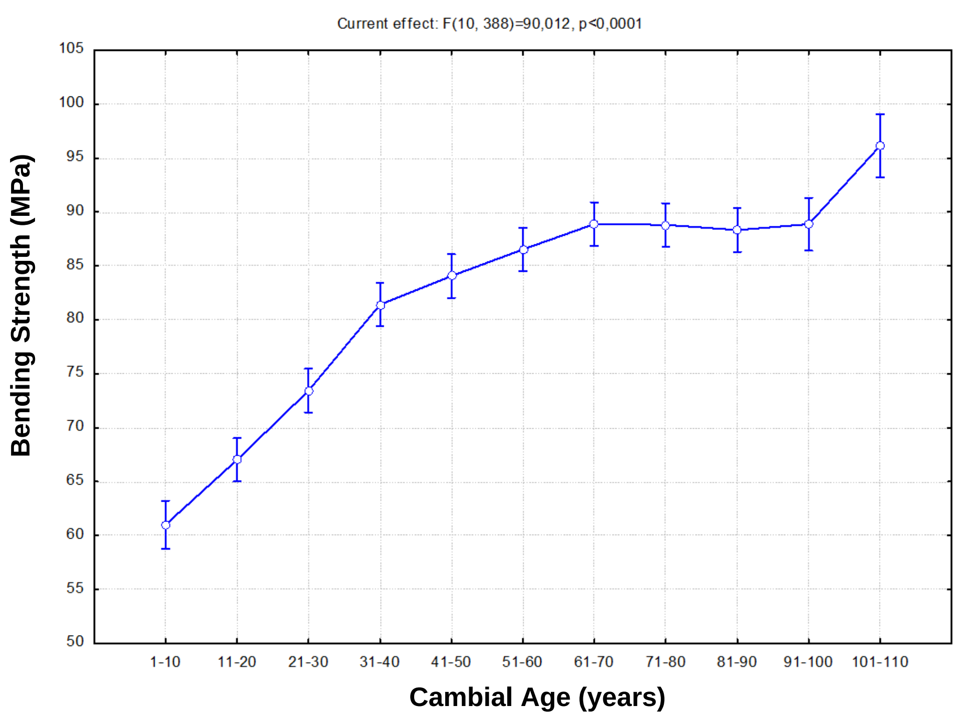

Fig. 5. The mean values of the bending strength by groups of annual rings in the radial direction

Table 4. Statistical Analysis (HSD Tukey test) of the Mean Values of the Bending Strength Between the Groups of Annual Rings

Cell No.	Tukey HSD test, variable Var2 (BS 10 annual rings in grup) Approximate Probabilities for Post Hoc Tests Error: Between MS = 42,044, df = 388,00											
	Var3	**{1} 61,002**	**{2} 67,013**	**{3} 73,429**	**{4} 81,406**	**{5} 84,059**	**{6} 86,525**	**{7} 88,878**	**{8} 88,802**	**{9} 88,323**	**{10} 88,865**	**{11} 96,150**
1	1 to 10		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
2	11 to 20	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
3	21 to 30	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
4	31 to 40	<0.001	<0.001	<0.001		0.76284	0.01808	0.00002	<0.001	<0.001	<0.001	<0.001
5	41 to 50	<0.001	<0.001	<0.001	0.76284		0.83539	0.03601	0.0424	0.11024	0.1005	<0.001
6	51 to 60	<0.001	<0.001	<0.001	0.018	0.83539		0.87311	0.89480	0.97794	0.9360	<0.001
7	61 to 70	<0.001	<0.001	<0.001	<0.001	0.0360	0.87311		1.00000	0.99999	1.0000	0.0027
8	71 to 80	<0.001	<0.001	<0.001	<0.001	0.0424	0.89480	1.00000		1.00000	1.0000	0.0023
9	81 to 90	<0.001	<0.001	<0.001	<0.001	0.11024	0.97794	0.99999	1.00000		1.0000	0.0007
10	91 to 100	<0.001	<0.001	<0.001	<0.001	0.10049	0.93601	1.00000	1.00000	1.00000		0.0081
11	101 to 110	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.00230	0.0007	0.0081	

The Tukey HSD test was applied for statistical processing of the results of bending strength. Figure 5 shows a graphical representation of the results of the statistical processing by the Tukey HSD test.

Table 4 shows the statistical parameters of testing the significance of mean values of bending strength by groups of annual rings in the radial direction from pith to bark. From the statistical perspective, the juvenile wood zone expanded from the 30th to the 70th annual ring. It is also clear that the zone from 101 to 110 annual rings was significantly different from all the preceding groups. From the technological point of view, the zone of the juvenile wood based on the static bending strength ranged from 30 to 70 annual rings from pith to bark.

CONCLUSIONS

1. It is impossible to determine the range of the annual rings in which the transition from the juvenile zone to the adult wood zone occurs on the investigated properties. Depending on the property, the range of transition from juvenile to mature wood ranges from 30th to 70th annual rings, which is too wide.
2. By observing the range for each individual property, it is possible to form technological parameters of processing, but in general, this is not possible for all properties.
3. When considering the results of statistical testing of the significant difference in properties by annual ring groups, to form the technological parameters of wood processing, it is necessary to consider the presentation of distribution trend of the results, from pith to bark.
4. The statistical analyses of the results of the individual traits were not sufficient for characterization of wood properties in the radial direction. The only ones that were sufficient for the formation of technological parameters for the processing of fir-wood from selective cultivation.
5. Based on the research, using the presentation of the second-degree polynomials, and the presentation of the Turkey HSD test in the form of tables, the comparison and the graphical representation by groups of the tested annual rings can provide enough relevant parameters for forming the technological properties of the processing of fir-wood from selective cultivation.

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