Šumarski list br. 11–12, CXXXIII (2009), 589-603

DIAMETER STRUCTURE MODELS OF BLACK POPLAR SELECTED CLONES IN THE SECTION *AIGEIROS* (DUBY) OBTAINED BY THE WEIBULL DISTRIBUTION

MODELI DEBLJINSKE STRUKTURE SELEKCIONIRANIH KLONOVA CRNE TOPOLE SEKCIJE *AIGEIROS* (DUBY) DOBIVENI WEIBULL-OVOM DISTRIBUCIJOM

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ABSTRACT: The present study was performed in an experimental plantation with six 20-year-old black poplar clones in the Section Aigeiros *(Duby). The diameter structure models were constructed using the Weibull probability density distribution with three parameters based on periodical measurements of diameters at breast height. The unidentified parameters were calculated by the so-called "hybrid system" (Knoebel, et al, 1986): location parameter (a) was calculated by percentile method, scale parameter (b) and shape parameter (c) were calculated by moments method. The applied method of estimating the location parameter (a) showed that in 90.6 % of the study sample, the parameter "a" ranged between 50 and 90 %, and in 52.4 % of the sample, "a" ranged from 80 to 90 % of the minimal diameter. With higher plantation ages, location parameter (a) and scale parameter (b) also increased with small oscillations, which was confirmed by the significance of the correlation coefficient of 0.71 and 0.73 respectively. This was shown by the shift of the curve of diameter structure model to the right, towards larger diameters, and in a wider range of diameters at breast height with a lower relative frequency of the modal degree. In the initial period, F-ratio of all three parameters of diameter structure model decreased and reached the minimal value in the eighth year, and the predominantly increasing trend started in the twelfth year, which points to the changes in diameter structure of the study clones depending on the age. The plantation growth elements (dg, G) and the Kolmogorov-Smirnov test, as well as the analysis of variance test and LSD test for the percentage of the number of trees with diameters at breast height above 40 cm, confirmed the grouping of diameter structure models of the study poplar clones in two groups. This makes it possible to define the differentiated management procedures with individual groups.*

Key words: black poplar, clones, diameter structure, Weibull distribution.

1. INTRODUCTION – Uvod

The main parameters which characterise poplar plantation production are: poplar clone (cultivar) and its bioecological and development-production characteristics, the site with its specificities, and the technologies of plantation establishment, tending and protection, including also plantation density depending on the specific purpose. All the above parameters are interdependent, but the correct selection of poplar cultivar is of primary importance for the optimal use of site potential.

Compared to natural ecosystems, poplar plantations of selected new cultivars and clones ensure multiple

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increases in the dendromass quantity and value. By the establishment of intensive plantations after the Second World War in Serbia, in a relatively short period (20–25 years), annual poplar and willow felling volume increased 12 times, and by improving the assortment structure, the value of wood volume increased almost 20 times compared to the pre-war period (Marković, et al., 1995). However, plantation establishment with one clone over large areas soon resulted in susceptibility to pathogen and pest attacks. For this reason, one of the strategic directions of further poplar research was the continuing creation (selection) of new poplar clones and their putting to production. These processes were accompanied by the quantification of productivity at the designated sites and for the selected plantations management procedures.

The quantification of differences between genotypes is usually defined by mean values of growth elements: diameter (d), height (h), and the derived elements, basal area (G), and volume (V). Also, the study of internal stand (plantation) structure makes it possible to analyse the state and to project the future development which leads to a more reliable identification of productivity differences. In this process, modern forest management planning applies the models of tree and stand (plantation) growth, based on real and testable data which also include the data on ecological conditions and growth characteristics of forest trees. The first step in the design of stand models is the model of diameter structure.

Diameter structure modelling in even-aged stands (and plantations) applies the Weibull probability density function. The mathematical model of the function was defined by Weibull, (1951) in his study of the reliability of material hardness. It was introduced to forestry by Bailey and Dell (1973) who constructed the model of stand diameter structure. Since then, the Weibull distribution has been widely implemented in forestry because it can describe a wide range of unimodal distributions and it can be adapted to both negative and positive skewness (Bailey and Dell, 1973; Ганина, 1984; Zarnoch and Dell, 1985; Knowe, et al., 1994; Kotar, 2005). According to Bailey and Dell, (1973), Ганина (1984), a special characteristic of *Weibull distribution* is the fact that its parameters have a biological interpretation. The significance of the Weibull distribution in the construction of diameter structure model in poplar plantations was reported by Andrašev et al. (2003, 2004), Andrašev (2008).

The objective of this study was to investigate the suitability of the Weibull distribution for the construction of diameter structure models of newly selected poplar clones, Section *Aigeiros* (Duby), by applying the so-called "hybrid system" of predicting the model parameters from the sample. Also, the objective was to study the change in model parameters depending on plantation age and poplar clone, and also their relation to plantation growth elements (d_g, G).

2. MATERIAL – Objekt istraživanja

The research was performed in a 20-year-old test plantation consisting of several clones (cultivars) of black poplar in the Section *Aigeiros* (Duby). The plantation is located on the experimental field of the Institute for Lowland Forestry and Environment (former Poplar Research Institute) near Novi Sad, planting space 5 × 5 m (400 trees per hectare), plant type 2+0. The plantation soil is fluvisol, sandy-loamy form (Škorić et al., 1985) and can be considered as medium suitable for poplar growing. The following poplar clones (cultivars) were researched:

1 $S_{6\text{-}36}$ (*Populus deltoides* Bartr. ex Marsh.) – cultivar registered in Serbia in 1987;

2 $NS_{1\text{-}3}$ (*Populus deltoides* Bartr. ex Marsh.) – cultivar registered in Serbia in 1998;

3 $NS_{11\text{-}8}$ (*Populus* × *euramericana* (Dode) Guinier) × (*Populus deltoides* Bartr. ex Marsh.) – cultivar registered in Serbia in 1998;

3 Pannonia (*Populus* × *euramericana* (Dode) Guinier) – cultivar registered in Serbia in 1998;

5 PE 19/66 (*Populus deltoides* Bartr. ex Marsh.) – in selection procedure;

6 $S_{6\text{-}7}$ (*Populus deltoides* Bartr. ex Marsh.) – in selection procedure.

Each clone in the test plantation consisted of six rows, with 20–25 trees per row. The fringe rows were not included in measurement and processing, because of the mutual influences. From the aspect of the experiment, each row represents a replicate (altogether 4 replicates) for the statistical processing of the results.

3. METHOD – Metoda rada

Diameters at breast height of all trees were periodically measured (to the nearest 1 *mm*) after one, two, five, eight, twelve, seventeen and twenty years from the test plantation establishment. The number of trees in the plantation decreased over time due to different causes: after 20 years, minimum 85 % of the initial number of trees remained in each row (replicate) (Table 1). Their diameters measured at the above ages were used for the construction of the diameter structure model. This was done to avoid the impact of changes in parameters due to the decrease in the number of trees. As the same trees were measured throughout the study period, the parameter changes in diameter structure models can mostly be assigned to the process of tree growth, i.e. to the specific response to environmental conditions (primarily soil conditions and tree competition) of each genotype.

The sample of trees used for the construction of the diameter structure model (total 168 samples) comprised the measured diameters at breast height (mean value of two cross measurements) in each row (4 repetition), for each clone (6 clones) and measurement year (7 years). Basal area, as the sum of basal areas of all trees, and the stand quadratic mean diameter were calculated for each tree samples.

Table 1 Number of trees of studied clones by repetitions after planting and after 20 years.

Tablica 1. Broj stabala istraživanih klonova po ponavljanjima pri osnivanju nasada i nakon 20 godina.

Clone *Klon*	Number of trees after planting per repetitions *Broj stabala nakon sadnje po ponavljanjima*				Number of trees after 20 years per repetitions *Broj stabala nakon 20 godina po ponavljanjima*			
	I	II	III	IV	I	II	III	IV
S_{6-36}	25	25	25	25	23	24	24	24
$NS_{1.3}$	22	22	22	22	21	20	21	20
NS_{11-8}	25	25	25	25	23	23	24	23
Pannonia	25	25	25	25	22	24	22	24
PE19/66	20	20	20	20	19	17	19	19
S_{6-7}	25	25	25	25	24	23	22	23

The selected model was the Weibull distribution with three parameters. The mathematical model of the Weibull distribution is defined as follows:

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} e^{-\left(\frac{x-a}{b}\right)^c} \quad a,\ b,\ c>0;\ x>a \qquad (1)$$

where: *a* – location parameter; *b* – scale parameter; *c* – shape parameter. The mathematical model of the Weibull cumulative distribution is expressed as:

$$F(x) = \int_0^{+\infty} f(x)dx = 1 - e^{-\left(\frac{x-a}{b}\right)^c} \quad a,\ b,\ c>0;\ x>a \qquad (2)$$

Location parameter (*a*) defines the location distribution in the coordinate system, i.e. its distribution along the abscissa. Scale parameter (*b*) is equal to 63 % of the distribution of unknown value (*x*) in the increasing order, i.e. about 63 % of the trees have diameter at breast height lower than the sum of parameters "*a*" and "*b*". Shape parameter (*c*) defines the distribution skewness: for $c<1$ the distribution decreases, and for $c>1$ it has bell shape. In the interval $1<c<3.6$ the distribution is positively skewed, for $c>3.6$ it is negatively skewed, and for $c=3.6$ it approximates the normal probability density function (PDF).

If the location parameter (*a*) is equal to zero the mathematical model turns into the so-called two-parameter model of the Weibull distribution, defined by the expression:

$$f(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} e^{-\left(\frac{x}{b}\right)^c} \quad b,\ c>0;\ x>0 \qquad (3)$$

and the cumulative model:

$$F(x) = 1 - e^{-\left(\frac{x}{b}\right)^c} \quad b,\ c>0;\ x>0 \qquad (4)$$

The parameters of the Weibull probability density function can be estimated in several ways (from sample trees), depending on the desired estimation of two (*b*, *c*) or all three parameters (*a*, *b*, *c*). The unidentified parameters of the Weibull distribution were estimated using the so-called "hybrid system", i.e. the method of moments estimation in combination with the percentile method (K n o e b e l, et al, 1986). Location parameter (*a*) in diameter structure modelling is directly related to minimal diameter and can vary from 0 (zero) to d_{min}. So the parameter "*a*" was calculated by the percentile method, with the following percentiles of the minimal diameter: 0.00; 0.01; 0.05; 0.10; 0.15; 0.20; 0.25; 0.30; 0.35; 0.40; 0.45; 0.50; 0.55; 0.60; 0.65; 0.70; 0.75; 0.80; 0.85; 0.90; 0.95; 0.99; 1.00.

Scale parameter (*b*) and shape parameter (*c*) were estimated by the moments method. They were estimated by subtracting the measured values (diameters at breast height) from the previously defined parameter "*a*". This method is based on the following equations of the first ($\bar{x}$) and the second ($\overline{x^2}$) common moment of the Weibull two-parameter distribution:

$$\bar{x} = \int_0^{+\infty} x f(x;b,c)dx = b\Gamma\left(1+\frac{1}{c}\right) \qquad (5)$$

$$\overline{x^2} = \int_0^{+\infty} x^2 f(x;b,c)dx = b^2\Gamma\left(1+\frac{2}{c}\right) \qquad (6)$$

where $\Gamma(\cdot)$ – gamma function.

The assessed variance () of the Weibull distribution is expressed as:

$$\hat{s}^2 = \overline{x^2} - \bar{x}^2 = b^2\left(\Gamma\left(1+\frac{2}{c}\right) - \Gamma^2\left(1+\frac{1}{c}\right)\right) \qquad (7)$$

and the coefficient of variation ():

$$\hat{c}_v = \frac{s}{\bar{x}} = \frac{\sqrt{\Gamma\left(1+\frac{2}{c}\right) - \Gamma^2\left(1+\frac{1}{c}\right)}}{\Gamma\left(1+\frac{1}{c}\right)} \qquad (8)$$

By calculating the first and the second common moment, and also the coefficient of variation from the sample and by inserting in formula 8, the coefficient of variation is the function of only one parameter (*c*), so it can be estimated by an iteration procedure. The combination of secant method and bisection method was applied with the previously set precision of 10^{-6} (Conte and de Boor, 1980).

The value of parameter *"c"* was applied to obtain the value of parameter "*b*" in the relation:

$$b = \frac{\bar{x}}{\Gamma\left(1+\frac{1}{c}\right)} \tag{9}$$

Parameter "*a*" was calculated for each of the above percentiles in each replicate and the parameters "*b*" and "*c*" by the moments method. Then the empirical diameter structure and the model were compared using Anderson-Darling statistic (A^2) (Anderson and Darling, 1954):

$$A^2 = \frac{-1}{n}\sum_{i=1}^{n}(2i-1)\left[\ln\left(F(x_i)\right)+\ln\left(1-F(x_{n+1-i})\right)\right]-n \tag{10}$$

where: *F(x)* – cumulative model of diameter structure; *n* – number of samples.

The percentiles of minimal diameter were selected based on the minimal value of A^2 statistic in all 4 replicates within the same clone and plantation age.

For each of the selected percentiles of minimal diameter within each clone and plantation age, all three parameters of the Weibull distribution were re-estimated for each replicate. The diameter structure model and the empirical distribution were tested by non-parametric Kolmogorov-Smirnov test, using |D| statistics:

$$|D| = \max\left[F_1(x) - F_2(x)\right] \tag{11}$$

where: $F_1(x)$ – cumulative model of diameter structure; $F_2(x)$ – empirical cumulative diameter structure in the increasing order.

The obtained parameters of the Weibull distribution per individual replicates were applied in the assessment of differences between the study clones at certain ages (years after planting), using the analysis of variance test and the least significant difference test (LSD), at the 5 % risk level.

Finding the value of the unknown parameters of the model of Weibull diameter distribution, by the above method, was performed programming in Visual Basic, which is an integral part of the Excel package. For a statistical assessment STATISTICA, ver. 7.0 software package was used.

4. RESULTS – Rezultati istraživanja

4.1. Growth elements of the study clone plantations – *Elementi rasta nasada istraživanih klonova*

The clones attained close stand quadratic mean diameters (d_g) only in the first and the second years after planting (Table 2, Diagram 1*a*), which is the consequence of the uniform dimensions of the applied planting material, and also of the low increment, especially in the first year after planting (Andrašev et al. 2006).

Table 2 Stand quadratic mean diameter (d_g) and the results of the analysis of variance test and LSD test at the risk level of 0.05 for the clones per years of measurement.

Tablica 2. Srednji promjer po temeljnici (d_g) i rezultati testa analize varijance i testa NZR na razini rizika od 0,05 istraživanih klonova po godinama izmjere

Clone *Klon*	Plantation age after planting - *Starost nasada nakon sadnje*						
	1 year *1. god.*	2 years *2. god.*	5 years *5. god.*	8 years *8. god.*	12 years *12. god.*	17 years *17. god.*	20 years *20. god.*
	d_g [cm]						
S_{6-36}	2.9 (0.06)[1] ab[2]	6.5 (0.16) ab	17.2 (0.57) c	23.4 (0.48) cd	28.1 (0.39) b	33.1 (0.88) bc	35.0 (1.03) bc
$NS_{1.3}$	3.3 (0.08) a	6.5 (0.14) ab	18.7 (0.79) ab	24.9 (1.11) b	28.5 (1.49) b	32.4 (1.77) bc	34.6 (2.16) bc
NS_{11-8}	2.8 (0.24) b	6.2 (0.36) b	17.7 (1.09) bc	24.7 (0.90) b	29.4 (1.14) ab	34.4 (1.25) b	36.8 (1.20) b
Pannonia	3.0 (0.16) ab	6.5 (0.22) ab	15.9 (0.50) d	22.8 (0.15) d	28.4 (0.37) b	33.7 (0.89) b	35.6 (1.31) bc
PE19/66	3.3 (0.13) a	6.9 (0.24) a	19.0 (0.56) a	26.4 (0.61) a	31.0 (1.05) a	36.7 (1.37) a	40.3 (1.79) a
S_{6-7}	3.0 (0.09) ab	6.8 (0.20) ab	18.4 (0.87) ab	24.2 (0.89) bc	28.2 (1.80) b	31.3 (1.83) c	33.7 (2.05) c
F	2.29^{ns}	1.93^{ns}	10.73^{***}	11.93^{***}	3.68^{*}	7.65^{***}	8.06^{***}

[1] Values in parentheses represent the standard deviation – *Vrijednosti u zagradi predstavljaju standardnu devijaciju.*

[2] The same letters indicate that there is no statistically significant differences between the clones tested by least significant differences at the risk level of 0.05 – *Ista slova znače da ne postoje statistički značajne razlike između klonova po testu najmanje značajne razlike na razini rizika od 0,05.*

[ns] non significant – *nije signfikantno*; * significant at the risk level of 0,05 – *signfikantno na razini rizika od 0,05*; ** significant at the risk level of 0,01 – *signfikantno na razini rizika od 0,01*; *** significant at the risk level of 0,001 – *signfikantno na razini rizika od 0,001.*

The clones were differentiated by mean diameter in the fifth year after planting and it lasted to the end of the study period of 20 years.

The clone differentiation per attained basal areas per hectare (*G*), which indicates indirectly the differences in volume per hectare, also, occurs in the fifth year and lasts through the eighth year (Table 3, Diagram 1*b*). At the age of 12, the values of basal area per hectare were very close for all six study clones (24.2–26.3 $m^2 \cdot ha^{-1}$) with F-ratio of the analysis of variance amounting to only 0.53. With the increasing plantation age, the differences between clones in basal areas per hectare increase and at the age of 20, the differences were significant at the risk level of 0.05.

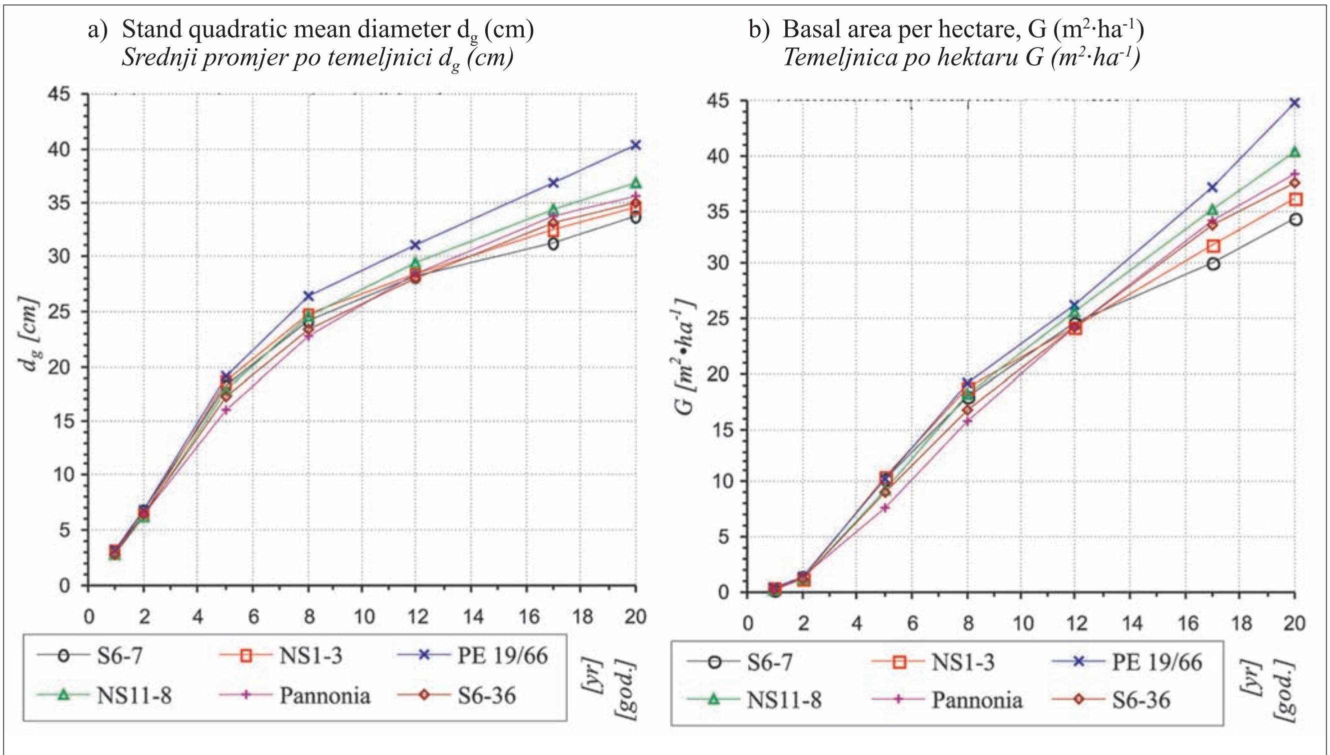

Diagram 1 Mean values of the stand quadratic mean diameter (dg) and total basal area per hectare (G) of the clones depending on plantation age.

Grafikon 1. Srednje vrijednosti prsnog promjera po temeljnici (dg) i ukupne temeljnice po hektaru (G) istraživanih klonova u zavisnosti od starosti nasada

Table 3 Basal area per hectare (G) and the results of the analysis of variance test and LSD test at the risk level of 0.05 for the clones per years of measurement.

Tablica 3. Temeljnica po hektaru (G)) i rezultati testa analize varijance i testa NZR na razini rizika od 0,05 istraživanih klonova po godinama izmjere.

Clone *Klon*	Plantation age after planting – *Starost nasada nakon sadnje*						
	1 year *1. god.*	2 years *2. god.*	5 years *5. god.*	8 years *8. god.*	12 years *12. god.*	17 years *17. god.*	20 years *20. god.*
	G_g [$m^2 \cdot ha^{-1}$]						
S6-36	0.27(0.02)[1]bc[2]	1.31 (0.11) a	9.10 (0.73) b	16.83(0.55) bc	24.34 (1.01) a	33.67(1.22)abc	37.63 (1.42) bc
NS1.3	0.32 (0.03) ab	1.24 (0.11) a	10.47 (0.99) a	18.69(2.32) ab	24.19 (3.17) a	31.56(4.32) bc	36.13 (5.42) bc
NS11-8	0.24 (0.06) b	1.22 (0.17) a	9.35 (1.13) ab	18.12(1.65) ab	25.70 (2.40) a	35.10(2.90) ab	40.31 (2.92) ab
Pannonia	0.27 (0.01) bc	1.33 (0.12) a	7.62 (0.69) c	15.67 (0.80) c	24.32 (1.15) a	34.23(1.62)abc	38.29 (2.42) bc
PE19/66	0.34 (0.06) a	1.48 (0.14) a	10.57 (0.12) a	19.12 (1.05) a	26.30 (1.64) a	37.09 (3.08) a	44.70 (4.36) a
S6-7	0.28 (0.01) ab	1.46 (0.05) a	10.34 (1.32) ab	17.99 (1.77) ab	24.61 (3.74) a	30.14 (4.09) c	34.32 (4.11) c
F	2.15ns	1.85ns	5.54**	2.94*	0.53ns	2.59ns	3.85*

[1] Values in parentheses represent the standard deviation – *Vrijednosti u zagradi predstavljaju standardnu devijaciju.*

[2] The same letters indicate that there is no statistically significant differences between the clones tested by least significant differences at the risk level of 0.05 – *Ista slova znače da ne postoje statistički značajne razlike između klonova po testu najmanje značajne razlike na razini rizika od 0,05.*

[ns] non significant – *nije signfikantno*; [*] significant at the risk level of 0,05 – *signfikantno na razini rizika od 0,05*; [**] significant at the risk level of 0,01 – *signfikantno na razini rizika od 0,01*; [***] significant at the risk level of 0,001 – *signfikantno na razini rizika od 0,001*.

Test results of the analysis of variance of repeated measurements showed a high (G) and very high (d_g) significant interactions clone×year which indicates that the investigated clones had different increments of the quadratic mean diameter and total basal area per hectare in the study period (Table 4, Diagram 1).

Throughout the period of 20 years, the clone PE 19/66 attained the best results both in stand quadratic mean diameter (d_g), and in total basal area per hectare (G) and it is differentiated from the other clones by LSD test at the 5 % risk level.

Clone Pannonia attained the lowest sizes of the stand quadratic mean diameter and the total basal area per hectare in the period to the eighth year. In further development, its increment was more intensive compared to other clones and at the age of 20 years, its mean diameter and total basal area per hectare were greater compared to the clones S_{6-7}, NS_{1-3} and S_{6-36}.

The growth of clone NS_{11-8} was also more intensive with the increased age.

Table 4 Test results of the analysis of variance of repeated measurements of the quadratic mean diameter and total basal area per hectare.

Tablica 4. Rezultati testa analize varijance ponovljenih mjerenja srednjeg promjera po temeljnici i ukupne temeljnice po hektaru.

	Sum of Square	Degr. of Freed.	Mean Square	F	p
Stand quadratic mean diameter - d_g [cm] – *Srednji promjer po temeljnici - d_g [cm]*					
Intercept	77431.36	1	77431.36	17478.1	0
Clone	147.31	5	29.46	6.65	0.00114
Error	79.74	18	4.43		
Year	23945.81	6	3990.97	8612.37	0
Clone × Year	120.13	30	4.00	8.64	0
Error	50.05	108	0.46		
Basal area per hectare – G [$m^2 \cdot ha^{-1}$] – *Temeljnica po hektaru – G [$m^2 \cdot ha^{-1}$]*					
Intercept	50759.86	1	50759.86	1461.36	0
Clone	134.79	5	26.96	0.77614	0.57951
Error	625.22	18	34.73		
Year	30971.14	6	5161.86	1267.97	0
Clone × Year	240.87	30	8.03	1.97228	0.00602
Error	439.66	108	4.07		

4.2. Diameter structure models obtained by the weibull distribution

Modeli debljinske strukture dobiveni weibull-ovom distribucijom

4.2.1. Location parameters (a) of the Weibull diameter structure model

Definiranje parametara položaja (a) modela Weibull-ove debljinske strukture

Table 5 presents the percentile minimum diameter with a minimum value of Anderson-Darling statistics (A^2), and mean values and standard deviations of Anderson-Darling statistics of studied clones in certain years of surveying. Diagram 2 shows the percentage of the percentiles of minimal diameter for the definition of location

Table 5 Percentile values of the minimum diameter ($\%d_{min}$) that have the least value of Anderson-Darling (A^2) statistic of examined clones by years of survey.

Tablica 5. Vrijednost percentila minimalnog promjera ($\%d_{min}$) koji imaju najmanju vrijednost Anderson-Darling statistikue (A^2) istraživanih klonova po godinama izmjere.

Clone *Klon*	$\%d_{min}$							A^2 [1]						
	Age of the plantation after planting *Starost nasada nakon sadnje*							Age of the plantation after planting *Starost nasada nakon sadnje*						
	1.	2.	5.	8.	12.	17.	20.	1.	2.	5.	8.	12.	17.	20.
S_{6-36}	0.85	0.90	0.85	0.85	0.90	0.90	0.90	0.33(0,15)[2]	0.60 (0,06)	0.66 (0,21)	0.67 (0,12)	0.49 (0,29)	0.28 (0,10)	0.31 (0,16)
$NS_{1.3}$	0.90	0.90	0.85	0.75	0.65	0.65	0.55	0.36 (0,17)	0.26 (0,03)	0.71 (0,26)	0.46 (0,23)	0.59 (0,21)	0.37 (0,17)	0.51 (0,39)
NS_{11-8}	0.60	0.55	0.75	0.80	0.80	0.85	0.85	0.71 (0,25)	0.43 (0,27)	0.51 (0,10)	0.46 (0,11)	0.43 (0,19)	0.45 (0,10)	0.38 (0,04)
Pannonia	0.10	0.45	0.70	0.85	0.90	0.80	0.75	0.56 (0,28)	0.50 (0,26)	0.43 (0,14)	0.56 (0,27)	0.59 (0,31)	0.20 (0,03)	0.21 (0,03)
PE19/66	0.80	0.70	0.90	0.90	0.90	0.70	0.60	0.23 (0,06)	0.36 (0,04)	0.60 (0,21)	0.39 (0,27)	0.36 (0,13)	0.36 (0,09)	0.28 (0,08)
S_{6-7}	0.45	0,70	0.95	0.80	0.75	0.60	0.60	0.23 (0,06)	0.29 (0,01)	0.55 (0,11)	0.57 (0,29)	0.55 (0,37)	0.55 (0,41)	0.40 (0,24)

[1] mean values of Anderson-Darling statistic – *srednje vrijednosti Anderson-Darling statistike.*

[2] Values in parentheses represent the standard deviation – *Vrijednosti u zagradi predstavljaju standardnu devijaciju.*

parameter (*a*) of the Weibull diameter structure model. Only 7.2 % of the samples ranged between 0–50 % of the minimal diameter, and only 2.4 % of the samples ranged above 90 %. The greatest number of samples ranged between 80–90 % of the minimal diameter.

The comparison of the model of cumulative distribution and empirical cumulative distribution by non-parametric Kolmogorov-Smirnov test confirmed the similarity of all 168 samples. The calculated |D| statistics value ranged from 0.098 to 0.378 which corresponds to the probability from 0.2254 to 0.9998.

The correlation coefficient of the percentiles of minimal diameter ($\%d_{min}$), as the assessment of location parameter (*a*) of the Weibull distribution, and plantation age was not significant (R=0.018^{ns}).

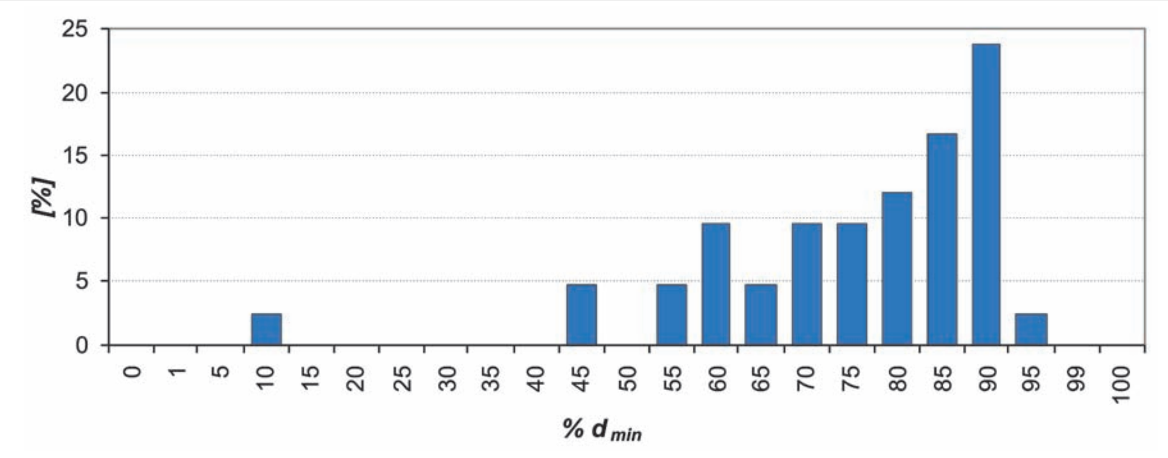

Diagram 2 Percentage of some percentiles of minimal diameter in the assessment of location parameter (a) of the Weibull model of diameter structure.

Grafikon 2. Postotno učešće pojednih percentila minimalnog promjera pri definiranju parametra položaja (a) modela Weibull-ove debljinske strukture.

4.2.2. Comparison of parameters of diameter structure model between clones

Usporedba parametara modela debljinske strukture između klonova

Depending on plantation age, the results of the analysis of variance test showed mostly significant differences between the parameters of Weibull diameter structure model (Tables 6, 7 and 8). In the initial period, F-ratio of all three parameters of the Weibull diameter structure model showed the decreasing trend and the minimal value occurred in the eighth year, and the predominantly increasing trend started in the twelfth year. In the eighth year, there were no significant differences between parameter "*c*" of the diameter structure model,

Table 6 Mean values of location parameter (a) of the Weibull diameter structure model and the results of the analysis of variance test and LSD test at the risk level of 0.05 of study clones per years of measurement.

Tablica 6. Srednje vrijednosti parametra položaja (a) modela Weibull-ove distribucije prsnih promjera i rezultati testa analize varijance i testa NZR na razini rizika od 0,05 istraživanih klonova po godinama izmjere.

Clone *Klon*	Plantation age after planting - *Starost nasada nakon sadnje*						
	1 year *1. god.*	2 years *2. god.*	5 years *5. god.*	8 years *8. god.*	12 years *12. god.*	17 years *17. god.*	20 years *20. god.*
S6-36	1,67 (0.09)[1] b[2]	4,65 (0.30) a	12,75 (0.69) b	17,42 (0.85) b	22,72 (0.86) a	26,56 (0.98) a	27,98 (1.12) a
NS1.3	2,23 (0.20) a	4,81 (0.43) a	13,18 (1.77) b	15,19 (2.48) c	14,62 (2.88) c	15,71 (2.36) c	13,9 (1.98) e
NS11-8	0,91 (0.18) c	2,54 (0.20) d	10,88 (0.75) c	16,4 (1.39) bc	18,4 (2.69) b	23,18 (3.74) b	24,63 (4.09) b
Pannonia	0,16 (0.01) d	2,10 (0.12) e	9,1 (0.57) d	17 (0.00) bc	22,5 (1.27) a	23,08 (1.31) b	22,29 (1.41) bc
PE19/66	2,09 (0.02) a	4,05 (0.15) b	15,98 (0.45) a	20,92 (0.45) a	24,75 (0.52) a	21,08 (0.76) b	19,59 (0.73) cd
S6-7	0,76 (0.05) c	3,46 (0.36) c	15,2 (1.10) a	16,6 (1.20) bc	17,62 (2.33) b	15,34 (2.17) c	16,41 (2.43) de
F	190.29***	61.1***	27.11***	8.75***	14.88***	17.45***	21.66***

[1] Values in parentheses represent the standard deviation – *Vrijednosti u zagradi predstavljaju standardnu devijaciju.*

[2] The same letters indicate that there is no statistically significant differences between the clones tested by least significant differences at the risk level of 0.05 – *Ista slova znače da ne postoje statistički značajne razlike između klonova po testu najmanje značajne razlike na razini rizika od 0,05.*

[ns] *non significant* – nije signfikantno*; * significant at the risk level of 0,05* – signifikantno na razini rizika od 0,05*;* ** *significant at the risk level of 0,01* – signfikantno na razini rizika od 0,01*; *** significant at the risk level of 0,001* – signifikantno na razini rizika od 0,001.

which points out the changes in diameter structure of the study clones depending on the age.

With higher plantation ages, location parameter (a) and scale parameter (b) also increased with small oscillations, which was confirmed by the significance of the correlation coefficient of 0.71 and 0.73 respectively (Diagram 3). This was shown by the shift of the curve of diameter structure model to the right, towards larger diameters, and in a wider range of diameters at breast height with a lower relative frequency of the modal degree (Diagram 4). The changes in shape parameter (c) were smaller, which was confirmed by the correlation coefficient of 0.36 (Diagram 3). However, its significance at the risk level of 0.001 indicates the increasing trend with plantation age, i.e. the change in the shape of diameter structure positive skewness, or approximately normal distribution, to the negative skewness.

Table 7 Mean values of scale parameter (b) of the Weibull diameter structure model and the results of the analysis of variance test and LSD test at the risk level of 0.05 of study clones per years of measurement.

Tablica 7. Srednje vrijednosti parametra skaliranja (b) modela Weibull-ove distribucije prsnih promjera i rezultati testa analize varijance i testa NZR na razini rizika od 0,05 istraživanih klonova po godinama izmjere.

Clone *Klon*	Plantation age after planting – *Starost nasada nakon sadnje*						
	1 year *1. god.*	2 years *2. god.*	5 years *5. god.*	8 years *8. god.*	12 years *12. god.*	17 years *17. god.*	20 years *20. god.*
S6-36	1,37 (0.18)[1] c[2]	1,96 (0.48) c	4,83 (0.61) bc	6,46 (0.53) c	5,93 (0.56) c	7,11 (0.18) c	7,64 (0.16) d
NS1.3	1,16 (0.27) c	1,87 (0.41) c	5,99 (1.74) ab	10,51 (1.76) a	14,87 (1.59) a	17,9 (0.96) a	22,22 (0.57) a
NS11-8	1,94 (0.08) b	3,89 (0.22) ab	7,38 (0.83) a	8,94 (0.88) b	11,88 (1.99) b	12,13 (2.97) b	13,27 (3.46) c
Pannonia	2,76 (0.24) a	4,42 (0.29) a	7,3 (0.59) a	6,33 (0.14) c	6,49 (1.36) c	11,43 (1.57) b	14,36 (1.96) c
PE19/66	1,46 (0.24) c	3,25 (0.57) b	3,59 (0.58) c	5,99 (1.11) c	6,81 (1.47) c	16,76 (2.09) a	22,04 (2.59) a
S6-7	2,5 (0.32) a	3,99 (0.59) a	3,42 (0.82) c	8,18 (0.61) b	11,41 (1.11) b	16,94 (1.04) a	18,34 (1.21) b
F	30.65***	23.56***	13.51***	13.31***	26.83***	23.97***	31.58***

[1] *Values in parentheses represent the standard deviation* – Vrijednosti u zagradi predstavljaju standardnu devijaciju.

[2] *The same letters indicate that there is no statistically significant differences between the clones tested by least significant differences at the risk level of 0.05* – Ista slova znače da ne postoje statistički značajne razlike između klonova po testu najmanje značajne razlike na razini rizika od 0,05.

[ns] *non significant* – nije signifikantno*; * significant at the risk level of 0,05* – signifikantno na razini rizika od 0,05*; ** significant at the risk level of 0,01* – signifikantno na razini rizika od 0,01*; *** significant at the risk level of 0,001* – signfikantno na razini rizika od 0,001.

Table 8 Mean values of shape parameter (c) of the Weibull diameter structure model and the results of the analysis of variance test and LSD test at the risk level of 0.05 of study clones per years of measurement.

Tablica 8. Srednje vrijednosti parametra oblika (c) modela Weibull-ove distribucije prsnih promjera i rezultati testa analize varijance i testa NZR na razini rizika od 0,05 istraživanih klonova po godinama izmjere.

Clone *Klon*	Plantation age after planting – *Starost nasada nakon sadnje*						
	1 year *1. god.*	2 years *2. god.*	5 years *5. god.*	8 years *8. god.*	12 years *12. god.*	17 years *17. god.*	20 years *20. god.*
S6-36	2,235(0.20)1 b2	2,044 (0.27) b	3,714(0.59)abc	4,373 (1.37) a	2,971 (0.45) c	3,618 (0.86) b	3,519 (0.81) b
NS1.3	2,084 (0.57) b	2,513 (0.68) b	4,146(1.39) ab	4,963 (1.06) a	5,398 (1.09) a	5,131 (1.57) b	5,123(0.99) ab
NS11-8	3,099 (0.95) b	4,451 (1.03) a	4,831(1.16) ab	4,74 (1.56) a	4,415(1.18) ab	3,556 (0.80) b	3,493 (0.64) b
Pannonia	5,378 (1.90) a	5,133 (0.93) a	5,04 (0.98) a	4,077 (0.46) a	3,425(0.70) bc	5,539(1.44) ab	5,712(1.42) ab
PE19/66	2,95 (0.40) b	4,961 (0.58) a	3,53 (0.59) bc	3,372 (0.19) a	3,228(0.30) bc	5,618(0.70) ab	6,563 (1.07) a
S6-7	4,677 (1.00) a	4,175 (0.89) a	2,378 (0.79) c	4,949 (1.30) a	5,69 (1.46) a	7,986 (3.86) a	7,287 (3.09) a
F	7.12***	11.23***	4.08*	1.23ns	5.88**	2.98*	3.96*

[1] *Values in parentheses represent the standard deviation* – Vrijednosti u zagradi predstavljaju standardnu devijaciju.

[2] *The same letters indicate that there is no statistically significant differences between the clones tested by least significant differences at the risk level of 0.05* – Ista slova znače da ne postoje statistički značajne razlike između klonova po testu najmanje značajne razlike na razini rizika od 0,05.

[ns] *non significant* – nije signifikantno*; * significant at the risk level of 0,05* – signifikantno na razini rizika od 0,05*;* [**]*significant at the risk level of 0,01* – signifikantno na razini rizika od 0,01*; *** significant at the risk level of 0,001* – signifikantno na razini rizika od 0,001.

The differences between the parameters of the Weibull diameter structure model of poplar clones per years of measurement were significant, and the least significant difference test at the 5 % risk level grouped the study clones in several groups.

Plantation age affects the trend of parameters of the diameter structure model. In the initial period of plantation development (five years) there was a sharp increase in the location parameter (*a*), after which its trend changed depending on the clone. In the initial period, the increase in the scale parameter (*b*) of the Weibull diameter structure model was lower and also the differences between the clones were lower. The increase in parameter "b" in the following period was considerably greater in the majority of the clones, but the clone S_{6-36} showed the trend of a very slow increase. The differences between the study clones were the lowest in the shape parameter (*c*).

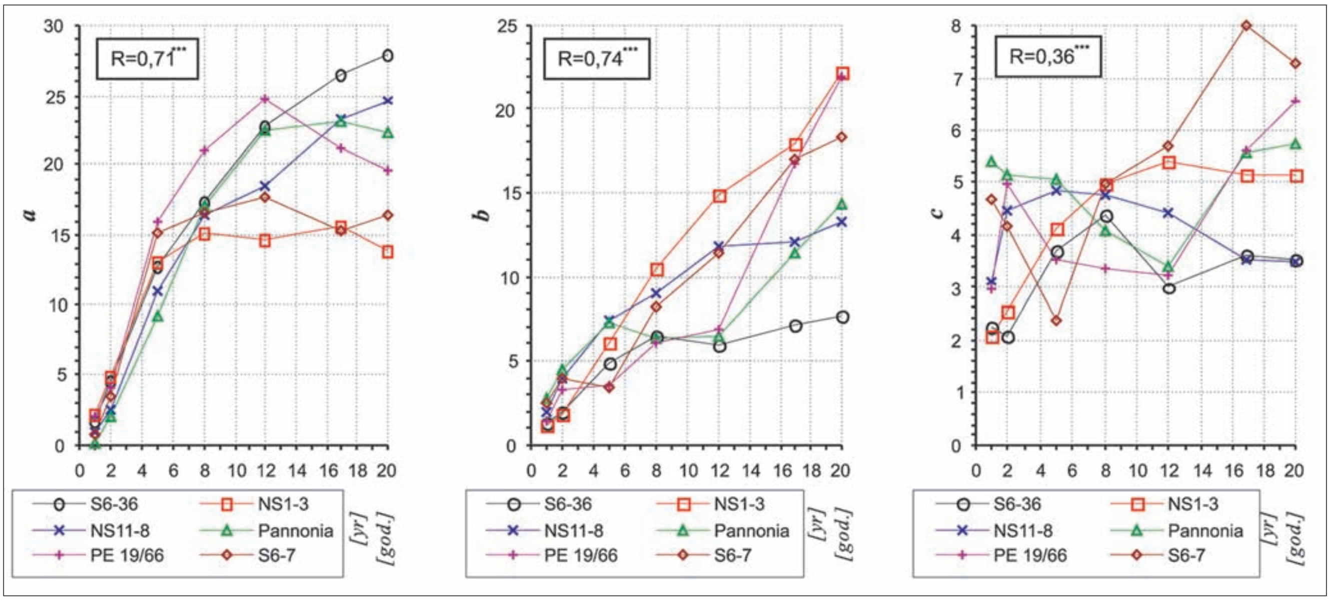

Diagram 3 Changes in the mean values of the parameters of the Weibull diameter structure model depending on plantation age.
Grafikon 3. Promjena srednjih veličina parametara modela debljinske strukture po Weibull-u u zavisnosti od starosti nasada

4.2.3. Construction of the Weibull diameter structure model

Konstrukcija modela debljinske strukture po Weibull-ovoj distribuciji

Diagram 4 presents the models of diameter structures of the study clones per years. The Diagram shows the changes in the shape of diameter structure with advancing age, as well as the differences between the clones. It can be concluded that some clones had similar models of diameter structure, especially in the period after the age of 12, which indicates the possibility of their grouping in the definition of management procedures.

Aiming at the objective assessment of similarities and differences between the Weibull diameter structure models of poplar clones, the non-parametric Kolmogorov-Smirnov test was applied at the plantation age of 17 and 20 years (Table 9). The test results showed significant differences only between diameter structure models of the clone PE 19/66 and the clones S_{6-7}, NS_{1-3}, S_{6-36} in the 17th year, and between the clone PE 19/66 and clones S_{6-7}, NS_{1-3}, S_{6-36} and Pannonia in the 20th year.

Table 9 Value of |D| statistics by Kolmogorov-Smirnov test and the comparison of differences in the Weibull diameter structure models in the 17th and 20th year of poplar plantation age.
Tablica 9. Vrijednosti |D| statistike po testu Kolmogorov-Smirnova i usporedba razlika modela debljinskih struktura po modelu Weibull-a u 17. i 20. godini starosti nasada istraživanih klonova topola.

	Clone – *Klon*	20 years – *20. godina*					
		S_{6-36}	NS_{1-3}	NS_{11-8}	Pannonia	PE 19/66	S_{6-7}
17 years *17. godina*	S_{6-36}	-	0.2039^{ns}	0.28^{ns}	0.1454^{ns}	0.6623^{**}	0.18^{ns}
	NS_{1-3}	0.1993^{ns}	-	0.1925^{ns}	0.195^{ns}	0.5266^{**}	0.1941^{ns}
	NS_{11-8}	0.2626^{ns}	0.1963^{ns}	-	0.1718^{ns}	0.3923^{ns}	0.35^{ns}
	Pannonia	0.1771^{ns}	0.24^{ns}	0.1529^{ns}	-	0.5641^{**}	0.2641^{ns}
	PE 19/66	0.5758^{*}	0.4972^{*}	0.3131^{ns}	0.4661^{ns}	-	0.7144^{***}
	S_{6-7}	0.2525^{ns}	0.1988^{ns}	0.3939^{ns}	0.3875^{ns}	0.6869^{***}	-

^{ns} *non significant* – nije signifikantno; **significant at the risk level of 0,05* – signifikantno na razini rizika od 0,05; ***significant at the risk level of 0,01* – signifikantno na razini rizika od 0,01; ****significant at the risk level of 0,001* – signifikantno na razini rizika od 0,001.

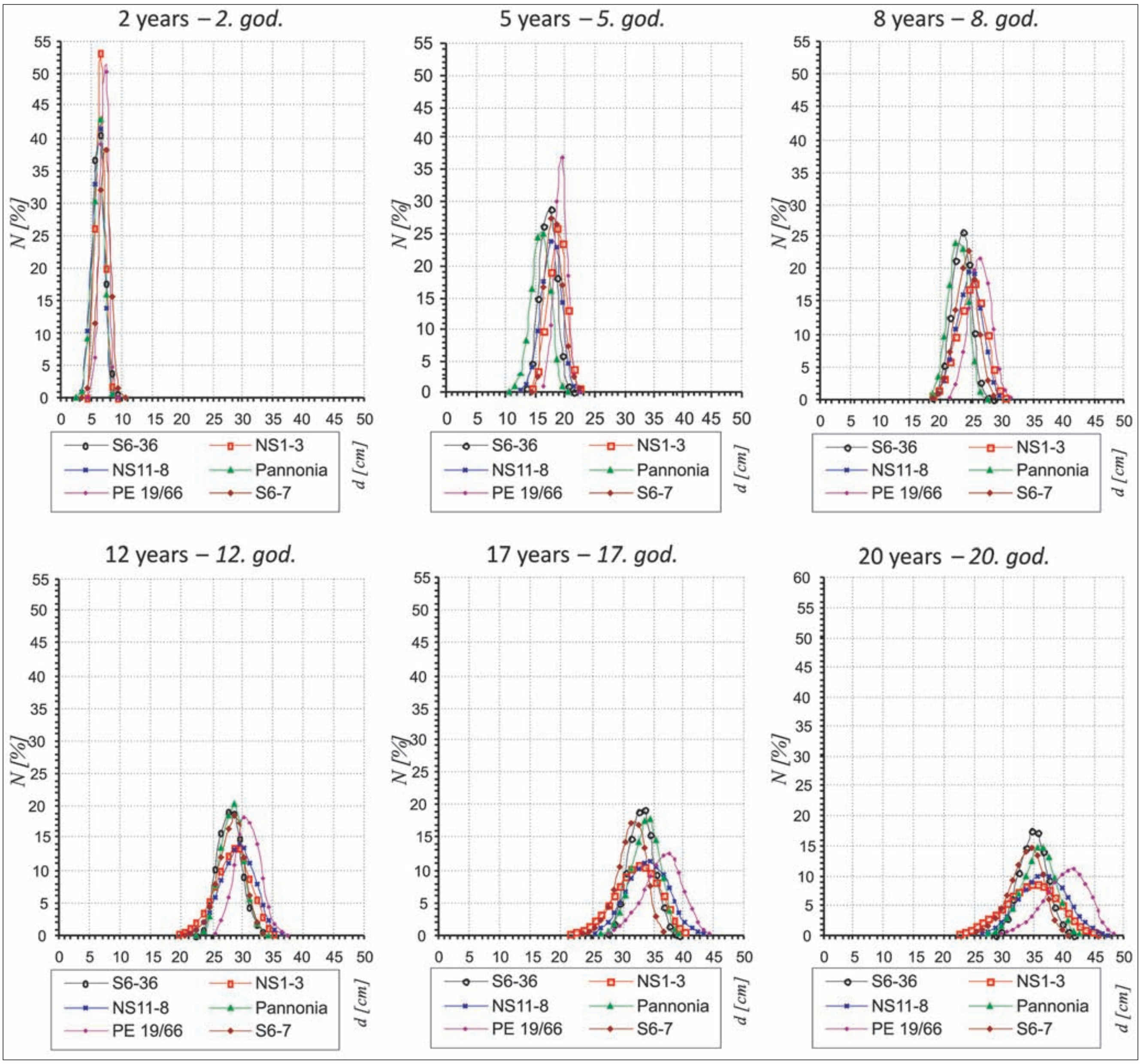

Diagram 4 Models of diameter structure of the study clones depending on plantation age.
Grafikon 4. Modeli debljinske strukture istraživanih klonova u zavisnosti od starosti nasada.

Table 10 Mean values of the percentage of the number of trees with diameters at breast height above 40 cm ($N_{d>40cm}$ [%]) and the results of the analysis of variance test and LSD test at the 5 % risk level.
Tablica 10. Srednje vrijednosti učešća broja stabala prsnih promjera većih od 40 cm ($N_{d>40cm}$ [%]) i rezultati testa analize varijance i testa NZR na razini rizika od 5 %.

Age *Starost*	Clone – *Klon*						
	S_{6-36}	NS_{1-3}	NS_{11-8}	Pannonia	PE 19/66	S_{6-7}	F[1]
	$N_{d>40cm}$ [%]						
17 years	0.0 c[2]	1.4 bc	4.4 ab	0.4 bc	13.3 a	0.0 c	5.31**
20 years	1.0 d	11.3 bc	19.1 b	4.5 cd	50.0 a	0.8 d	12.1***

[1] The comparison was preceded by the transformation arcsin *($\%N_{d>40cm}$)*$^{1/2}$ aiming at the homogenisation of the variances – *Usporedba je izvršena uz prethodnu transformaciju arcsin ($\%N_{d>40cm}$)$^{1/2}$ u cilju homogenizacije varijanci.*

[2] The same letters indicate that there is no statistically significant differences between the clones tested by least significant differences at the risk level of 0.05 – *Ista slova znače da ne postoje statistički značajne razlike između klonova po testu najmanje značajne razlike na razini rizika od 0,05.*

[ns] non significant – *nije signifikantno*; * significant at the risk level of 0,05 – *signifikantno na razini rizika od 0,05*; ** significant at the risk level of 0,01 – *signifikantno na razini rizika od 0,01*; *** significant at the risk level of 0,001 – *signifikantno na razini rizika od 0,001*.

The practical significance of the obtained models is best seen by the example of estimating the percentage of the number of trees with diameters at breast height above 40 cm. The diameter at breast height above 40 cm makes it possible to produce the best quality veneer logs (Pudar, 1986; Krznar, 1987), so the share of such trees indicates indirectly the plantation value. Table 10 presents the mean relative percentage of the number of trees with diameters at breast height above 40 cm from the diameter structure model and the results of the analysis of variance test and LSD test at the 0.05 risk level. The analysis of variance points out the significant differences between the clones, both in the 17th and in the 20th year. Significantly the highest percentage of the number of trees with diameters at breast height above 40 cm was attained by the clone PE 19/66, and the lowest percentage by the clones S_{6-7} and S_{6-36}.

5. DISCUSSION – Rasprava

The researched plantation of six newly selected clones showed different values of stand quadratic mean diameter (d_g) and total basal area per hectare (G) at the end of the study period (20 years). Based on the results of LSD test at the 5 % risk level, the clones were grouped in several production groups. Also, the periodical measurements of diameter at breast height showed different diameter growth of the clones depending on the age. In the initial period, the clones *Populus deltoides* Bartr. ex Marsh. (S_{6-7}, NS_{1-3}, PE 19/66, NS_{11-8}, S_{6-36}) developed more intensively than the clone Pannonia (*Populus × euramericana* (Dode) Guinier). In the later period, Pannonia developed more intensively and the clones of *P. deltoides* Bartr. ex Marsh. showed the differentiation. The different growth characteristics of the clones *P. deltoides* Bartr. ex Marsh. and *P. × euramericana* (Dode) Guinier, prevent the reliable productivity differentiation of the clones before the ages of 16–18 years at plantation density of 400 trees per hectare (Andrašev, 2008). Taking into account the above facts, the differentiation of study poplar clones by total basal area per hectare (G) and stand quadratic mean diameter (d_g) at the ages of 17 and 20 years showed (LSD test) that clone PE 19/66 can be classified in one group, and the other clones in the other group. The constructed Weibull models of diameter structure, and the derived percentage of the number trees with diameters at breast height above 40 cm ($N_{d>40cm}$ [%]) confirmed the grouping of the clones in two groups, as well as based on growth elements (G, d_g), which point out their implementation in productive differentiation.

The study results refer to six black poplar clones, Section *Aigeiros* (Duby), four of which were registered as cultivars in Serbia, and the other two are still undergoing the selection procedure. The registered poplar clones (S_{6-36}, NS_{1-3}, NS_{11-8} and Pannonia) attained similar plantation growth elements (d_g, G), and diameter structure, which was confirmed by statistical tests. The other two clones which were in selection procedure (S_{6-7} and PE 19/66) attained significant differences in growth elements and plantation structure. Clone S_{6-7} did not have significantly lower values of growth elements and structure compared to registered clones. However, clone PE 19/66 attained a significant advantage in the elements of growth and structure compared to the registered clones at the plantation age of 20 years, which, according to Marković et al. (1997) and Andrašev (2008), can be taken as the rotation period for the density of 400 trees per hectare, so this clone is a reliable candidate for a soon registration and putting in mass production.

The study results indicate that the Weibull diameter structure model can be successfully applied in the estimation of diameter structure of the newly selected poplar clones at different plantation ages.

The application of the model of the Weibull three-parameter distribution, especially the calculation of the location parameter (a), was made difficult and it was evaluated in different ways: using different mathematical expressions (Zarnoch and Dell, 1985), fixed values of location parameter 0 or d_{min}, the percentiles of minimal diameter, with frequent value 50 %·d_{min} (Bailey and Dell, 1973, Knoebel, et al, 1986, Lei, 2008). Our research indicates that the choice of location parameter (a) in Weibull distribution should not be uniformly defined, and that further research is necessary aiming at reliable methods of diameter structure modelling in poplar plantations.

Taking into account the so-called “biological” interpretation of the calculated parameters, it can be concluded that location parameter (a) is the minimal diameter in the plantation (but not also in the sample based on which it is predicted). In most clones, location parameters depending on the age show an increasing trend; in the initial period the trend is sharp (till the age of 5), and later on it is slower or more intensive, depending on the clone. The above can be related to the so-called “solitary growth” in the initial period before crown closure (from fifth to eighth year) and the so-called “stand growth” with the competitive impact of trees. The observed significant drop of location parameter (a) in the clone PE 19/66 is the consequence of the applied method and it shows that in periodical measurements the so-called “biological component” should be “incorporated” in its definition.

The scale parameter (b) is in high correlation (R=0.884) with the variability of diameters at breast height, represented by standard deviation (s_d). Its change depending on plantation age, with a high value of the correlation coefficient (R=0.74), points to the differentiation process of the trees in the plantation.

The parameters of the Weibull diameter structure model (a, b, c) of the study poplar clones, according to the analysis of variance F-ratio, decrease till the age of 8, and then they increase. A similar F-ratio trend was shown by the stand quadratic mean diameter (d_g) and total basal area per hectare (G), with the minimal F-ratio at the age of 12. As the parameters describe the internal plantation structure, the earlier change in parameters compared to growth elements indicates the growth changes in the trees of different categories (diameters), which enables the adequate evaluation of the plantation state and future development.

The quantification of similatities and differences in the location, scale and shape of diameter structure during the development of the plantations of different clones contributes to the advanced study of plantation development and can be applied in the construction of the growth model of selected clones, and their production differentiation.

The assessment of the effects of clone and plantation age on diameter structure enables a more reliable construction and estimation of the future structure, and also its incorporation in growth models.

6. CONCLUSIONS – Zaključci

Based on the research of 20-year old test plantation consisting of several newly selected clones of black poplar, Section *Aigeiros* (Duby), which are either registered or are in the selection procedure, we can conclude as follows:

– there are significant differences in growth elements (d_g, G) between individual clones in the test plantation at the end of the study period of 20 years, which provides the basis for their production differentiation;
– periodical measurements of diameters at breast height showed different growth of the clones depending on the age: in the initial period of development, the clones *Populus deltoides* Bartr. ex Marsh. (S_{6-7}, NS_{1-3}, PE 19/66, NS_{11-8}, S_{6-36}) developed more intensively than the clone Pannonia (*Populus × euramericana* (Dode) Guinier), and later on Pannonia had a more intensive growth, while the clones of *P. deltoides* Bartr. ex Marsh. showed the differentiation;
– the Weibull distribution model is suitable for diameter structure modelling of the study poplar clones at different plantation ages, and the applied method of predicting the location parameter (a) of the Weibull distribution model showed that in 90.6 % of the study sample, the parameter "*a*" ranged between 50 and 90 %, and in 52.4 % "*a*" ranged from 80 to 90 % of the minimal diameter;
– with higher plantation ages, location parameter (a) and scale parameter (b) also increased with small oscillations, which was confirmed by the significance of the correlation coefficient of 0.71 and 0.73 respectively. This was shown by the shift of the curve of diameter structure model to the right, towards larger diameters, and in a wider range of diameters at breast height with a lower relative frequency of the modal degree;
– in the initial period, F-ratio of all three parameters of the Weibull diameter structure model decreased and reached the minimal value at the age of eight, and the predominantly increasing trend started at the age of twelve, which points to the changes in diameter structure of the clones depending on the age;
– the constructed models of poplar clone diameter structure show the clone grouping in two groups, which was confirmed by the non-parametric Kolmogorov-Smirnov test, the analysis of variance test, and LSD test for the percentage of the number of trees with diameters at breast height above 40 cm. This emphasises the possibility and the need of their grouping in the definition of management procedures.

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SAŽETAK: Cilj rada je utvrditi pogodnost Weibull-ove distribucije za konstrukciju modela debljinske strukture više klonova topola sekcije Aigeiros *(Duby), uz primjenu tzv. "hibridnog sustava" nalaženja parametara modela iz uzorka, pri čemu se za nalaženje nepoznatog parametra lokacije (a) modela koristi više percentila minimalnog promjera u rasponu od* $0 \div d_{min}$. *Također, cilj rada je ispitati promjenu parametara modela u zavisnosti od starosti nasada i klona topole, kao i njihov odnos s elementima rasta nasada* (d_g, *G*).

Istraživanja su obavljena u pokusnom nasadu starom 20 godina, koji se sastoji od više klonova (sorti) crnih topola sekcije Aigeiros (Duby): $S_{6\text{-}36}$, $NS_{1\text{-}3}$, $NS_{11\text{-}8}$, *Pannonia, PE 19/66 i* $S_{6\text{-}7}$. *Nasad je osnovan na zemljištu tipa fluvisol, pjeskovito-ilovaste forme, pri razmaku sadnje od 5 × 5 m (400 stabala po hektaru), sa sadnicama tipa 2+0. U pokusnom nasadu svaki klon ima četiri reda (ponavljanja) i po 20–25 biljaka u svakom redu. U pokusnom nasadu su periodično mejreni prsni promjeri svih stabala (s točnošću od 1 mm), nakon prve, druge, pete, osme, dvanaeste, sedamnaeste i dvadesete godine od osnivanja. Mjereni prsni promjeri stabala u svakom redu, za svaki istraživani klon i godinu izmjere, predstavljali su uzorak stabala za konstrukciju modela debljinske strukture (ukupno 168 uzoraka). Za svaki uzorak stabala izračunata je temeljnica, kao zbroj temeljnica svih stabala, te izračunat srednji promjer po temeljnici.*

Kao model izabrana je Weibull-ova distribucija s tri parametra, čija je funkcija gustoće definirana izrazom (1), a kumulativne distribucije izrazom

(2). Za nalaženje nepoznatih parametara Weibull-ove distrbucije korišten je tzv. "hibridni sustav", odnosno metoda momenata u kombinaciji s metodom percentila (Knoebel, et al, 1986). Parametar položaja (a) dobiven je po metodi percentila, pri čemu su korišteni sljedeći percentili minimalnog promjera: 0,00; 0,01; 0,05; 0,10; 0,15; 0,20; 0,25; 0,30; 0,35; 0,40; 0,45; 0,50; 0,55; 0,60; 0,65; 0,70; 0,75; 0,80; 0,85; 0,90; 0,95; 0,99; 1,00. Parametri skaliranja (b) i oblika (c) dobiveni su po metodi momenata, pri čemu je za njihovo nalaženje izvršeno oduzimanje mjerenih veličina (prsnih promjera) od prethodno definiranog parametra "a". Ova metoda zasniva se na jednadžbama prvog ($\bar{x}$) i drugog ($\overline{x^2}$) običnog momenta Weibull-ove dvoparametarske distribucije (5, 6). Procijenjena varijanca ($\hat{s}^2$) Weibull-ove distribucije definirana je izrazom (7), a koeficijent varijacije ($\hat{c}_v$) izrazom (8). Nalaženjem prvog i drugog običnog momenta, kao i koeficijenta varijacije iz uzorka i stavljanjem u formulu 8, koeficijent varijacije je funkcija samo jednog parametra (c), te se može dobiti postupkom iteracije. U radu je korištena kombinacija metode sekante i metode polovljenja intervala uz unaprijed zadanu točnost od 10^{-6} (Conte i de Boor, 1973). Dobivena veličina parametra „c" poslužila je da se dobije veličina parametra "b" iz relacije (9). Za svaki od navedenih percentila u svakom ponavljanju dobiven je parametar „a" modela, a metodom momenata parametri "b" i "c". Zatim je izvršena usporedba empirijske debljinske strukture i modela primjenom Anderson-Darling statistike (A^2) (Anderson i Darling, 1954) po formuli (10). Izbor percentila minimalnog promjera izvršen je na temelju minimalne veličine A^2 statistike za sva 4 ponavljanja u okviru istog klona i starosti nasada. Za svaki od izabranih percentila minimalnog promjera u okviru svakog klona i starosti nasada izvršeno je ponovno nalaženje sva tri parametra Weibull-ove distribucije za svako ponavljanje. Stupanj slaganja modela debljinske strukture i empirijske distribucije izvršen je neparametarskim testom Kolmogorov-Smirnova, nalaženjem $|D|$ statistike (11). Dobiveni parametri Weibull-ove distribucije po pojedinim ponavljanjima korišteni su za utvrđivanje razlika između istraživanih klonova u pojedinim starostima (godina nakon sadnje), pri čemu je korišten statistički test analize varijance i test najmanje značajne razlike (NZR), na razini rizika od 5 %.

Istraživani klonovi ostvarili su značajne razlike u elementima rasta (d_g, G) na kraju istraživanog razdoblja od 20 godina, što pruža osnovu za njihovo proizvodno diferenciranje. Na osnovi periodičnih izmjera prsnih promjera utvrđen je različit rast istraživanih klonova u debljinu, u zavisnosti od starosti: u početnom razdoblju razvoja klonovi Populus deltoides Bartr. ex Marsh. (S_{6-7}, NS_{1-3}, PE 19/66, NS_{11-8}, S_{6-36}) rastu intenzivnije od klona Pannonia (Populus × euramericana (Dode) Guinier), a kasnije klon Pannonia ima intenzivniji rast, dok između klonova P. deltoides Bartr. ex Marsh. dolazi do međusobnog diferenciranja. Tijekom cijelog razdoblja od 20 godina klon PE 19/66 ostvario je najveće veličine, kako srednjeg promjera po temeljnici (d_g), tako i ukupne temeljnice po hektaru (G) i izdvaja se od ostalih klonova po testu NZR na razini rizika od 5 % (tablice 1, 2, grafikon 1).

Model Weibull-ove distribucije pokazao se pogodnim za modeliranje debljinske strukture istraživanih klonova topola u različitim starostima nasada, a primijenjena metoda nalaženja parametra položaja (a) modela Weibull-ove distribucije pokazala je da se u 93,1 % istaživanog uzorka parametar „a" nalazi o rasponu od 50–90 %, a u 54,2 % u rasponu od 80–90 % minimalnog promjera uzorka (grafikon 2). Usporedbom modela kumulativne distribucije i empirijske kumulativne distribucije neparametarskim testom Kolmogorov-Smirnova, povrđena je sličnost kod svih 168 uzoraka.

Uz male oscilacije s povećanjem starosti nasada povećavaju se parametri položaja (a) i skaliranja (b), što je potvrđeno koeficijentom korelacije od 0,71 i 0,73 (grafikon 3). To se manifestira u pomicanju krivulje modela debljinske

strukture udesno k većim promjerima i u širem rasponu prsnih promjera s manjom relativnom frekvencijom modalnog stupnja (grafikon 4). Promjene parametra oblika raspodjele (c) manje su izražene, što potvrđuje iznos koeficijenta korelacije od 0,36 (grafikon 3). Međutim, njegovo značenje na razini rizika od 0.001 ukazuje na trend povećanja sa starošću nasada, odnosno na promjenu oblika debljinske strukture.

U početnom razdoblju koda sva tri parametra modela debljinske strukture po Weibull-u F-količnik ima trend opadanja i dostizanja minimalne vrijednosti u osmoj godini, a u dvanaestoj godini pokazuje porast, odnosno pretežito trend povećanja, što ukazuje na promjene u debljinskoj strukturi istraživanih klonova u zavisnosti od starosti.

Konstruirani modeli debljinske strukture istraživanih klonova topola pokazuju grupiranje klonova u dvije grupe, što je potvrđeno neparametarskim testom Kolmogorov-Smirnova, kao i testom analize varijance i testom NZR za učešće broja stabala prsnih promjera debljih od 40 cm, te ukazuje na mogućnost i potrebu njihovog grupiranja pri definiranju odgovarajućih gospodarskih postupaka

Ključne riječi: crna topola, klonovi, debljinska struktura, Weibulova funkcija gustoće