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Multi-stage parallel model in determining the quality of structural timber by the penetration method

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Abstract: *Multi-stage parallel model in determining the quality of structural timber by the penetration method*. Various devices are used in situ to diagnose the quality of structural timber. A semi-destructive method is used for the approximate determination of wood density. The Pilodyn 6J uses a depth of cut that correlates with wood density. The experiments were performed on spruce wood (*Picea excelsa*, Karst. L.). Boards 40 × 200 × 2500 mm^3, were tested, n = 5 pcs. The density of wood was determined by the gravimetric method according to EN 408 (2013). The penetration depth (h_p), number and width of annual rings (RoG) were determined on the boards. Based on the density of the wood, the quality of the structural timber was specified by strength classes according to EN 338 (2016). The dependences between the measured characteristics were expressed in a model with a multi-stage parallel scale (penetration depth ~ number of annual rings ~ rate of growth ~ strength class and density wood). It is possible to predict visual strength class of board and indicative density of wood (EN 338) by the proposed model in situ. Methods of model are easy to use, reliable and economically undemanding.

Keywords: spruce structural timber, board, density wood, penetration depth, rate of growth, visual strength class

INTRODUCTION

Structural timber is specific because its quality has to be set by visual or mechanical grading. Quality of structural timber is set by followed parameters: modulus of rupture (MOR) modulus of elasticity (MOE) and density of wood. They can be detected by destructive (EN 408) or non-destructive method based on various principles (Krzosek *et al.* 2015, Fridrich and Denzler 2010, Krzosek and Bacher 2011). Widely used key parameter for wood characteristics is wood density. Currently developed semi-destructive methods to estimate wood density and strength damage wood only partially without weakening the material. All of these methods are marked as semi-destruction in situ. They are primarily used when visual assessment of timber in situ is limited. Widely used are methods of drilling resistance e. g. conventional drill (Bobadill *et al.* 2013) or core drill (Kasal 2003), resistograph or dynamical pin shooting as Pilodyn 6J (Teder *et al*. 2011; Rohanová 2008; Rohanová and Bajza 2017). Assessment shall take into account the wood species, its structure (width of growth rings) timber health (affected wood) and environmental conditions (temperature, humidity etc).

They also use PILODYN 6J or incremental drill to identify affected wood elements. Teder *et al.* (2011) assessment of timber health by PILODYN 6J device show good correlation between depth of penetration and wood density $r^2 = 0.49$. Shooting of pin or drilling give only relative information about wood density. However, these indirect methods give a good estimate of properties over the entire length or depth of the element, which is especially valuable if there is no direct access to the wood elements. Authors report only observed dependence between wood density and depth of penetration /drilling resistance. Interaction with other parameters as wood structure or quality ware not assessed.

Hansen (2000), Mäkipää and Linkosalo (2011) state the universal use of the PILODYN 6J. For first, more than 20 years ago the technical manual (Technical Note NO.55 – July 2000 by Ch. P. Hansen) defined PILODYN 6J as a device designed for living trees or electric poles applications. Görlacher (1987) was the pioneer in the non-destructive testing of timber.

Depth of penetration depends on wood structure (spring and summer wood), its quality (healthy, old, reaction or degraded wood) (Reinprecht 2016). Depth of penetration is also affected by moisture content of wood according to Görlacher (1987); Hansen (2000); Dubovský and Rohanová (2007), Rohanová (2013).

Application of depth of penetration on timber declares TRIOMATIC industrially used equipment in machine-controlled systems. Local wood density and moisture content of wood are tested by shooting of two pins into wood as non-destructive method. The compression load is measured in order to evaluate the wood's density. The measured results are taken into account in machine sorting methods (Sandoz and Benoit 2007, Triomatic CBS-CBT).

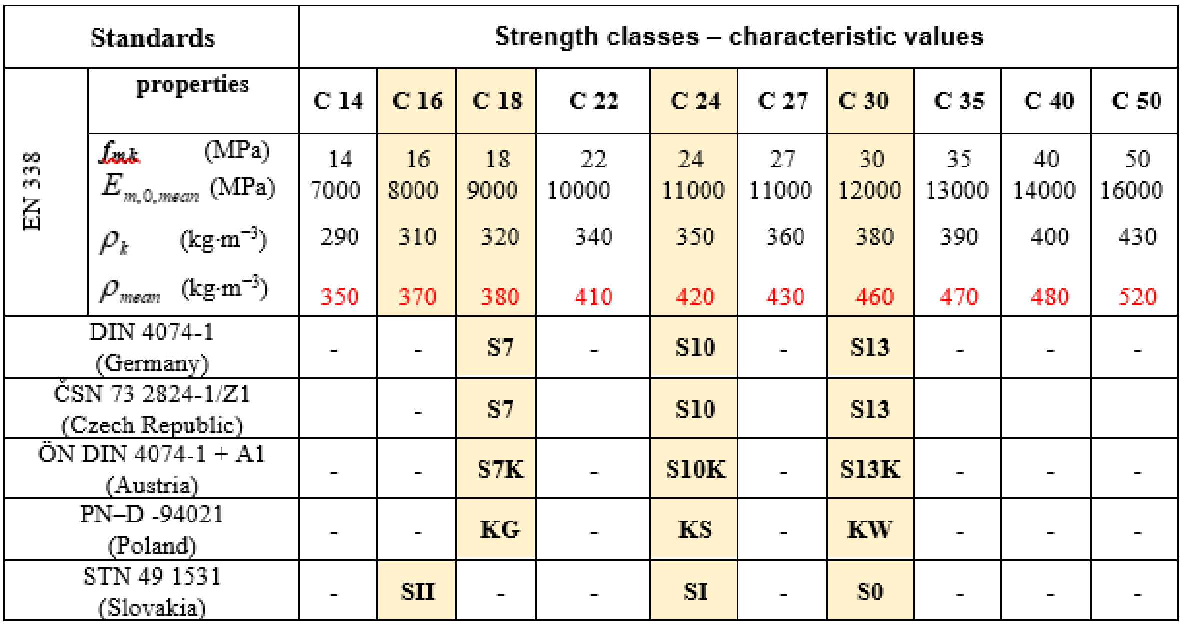
Concentric layers – growth rings are located on cross cut surface of tree. They reflect time of grow during vegetation seasons. The significance of growth ring of coniferous wood is considerably higher than deciduous trees. Multiplicity of growth rings and their width influence the physical and mechanical properties of wood (Požgaj *et al.* 1993). Their dominant importance is in detecting wood density. Width of growth rings is determined by cross-oriented line length and number of annual growth rings. Methods of testing and their limit values are stated by DIN 4074, ČSN 73 2824-1/Z1 and STN 49 1531. They are considered an indicative criterion for visual quality assessment of timber.

This paper was focused on testing the quality of spruce structural timber by non-destructive penetration method. The wood structure characteristics (width and number of annual rings) were determined by visual method. The aim of the study is to design a multi-stage parallel scale model. The model allows the in - situ mapping of the visual class of strength and orientation density of the wood through the measured characteristics in situ (EN 338 - ρ_{mean}). The quality of the structural timber is represented by the elasticity and strength properties but also by density of wood. European standard EN 338 specifies their characteristic values applied in both, visual and machine grading methods. Selected characteristic values and strength classes according to EN 338 are listed in Table 1.

Device PILODYN 6J is used for indicative testing of wood density. The starting point is the dependence between depth of penetration and wood density according to wood species and moisture content of wood. Advantage of device is easy manipulation and possibility of using in situ. Two types of PILODYN 6J are used, one for structural timber and PILODYN 6J Forest for measurements of living trees or electric poles. Device uses the principle of shooting steel pin into the wood by differentiated energy. Shooting of pin is perpendicular to annual growth rings.

For structural timber the width of growth rings is expressed by the rate of growth (*RoG*) according to EN 14 081-1 about methodology of measurements. *RoG* limits for softwoods and temperate hardwoods are 15 mm, 10 mm, 8 mm, 6 mm, 4 mm and 3 mm. Similarly, to strength classes, the *RoG* commonly uses three limits in practice, 4 mm, 6 mm and less (DIN 4074-1, ČSN 73 2824-1/Z1 and STN 49 1531).

Table 1. Characteristic values and strength classes – standards in the selected European countries



Standards		Strength classes – characteristic values									
EN 338	properties	C 14	C 16	C 18	C 22	C 24	C 27	C 30	C 35	C 40	C 50
	$f_{m,k}$ (MPa)	14	16	18	22	24	27	30	35	40	50
	$E_{m,0,mean}$ (MPa)	7000	8000	9000	10000	11000	11000	12000	13000	14000	16000
	ρ_k (kg·m^{-3})	290	310	320	340	350	360	380	390	400	430
	ρ_{mean} (kg·m^{-3})	350	370	380	410	420	430	460	470	480	520
DIN 4074-1 (Germany)		-	-	**S7**	-	**S10**	-	**S13**	-	-	-
ČSN 73 2824-1/Z1 (Czech Republic)			-	**S7**		**S10**		**S13**			
ÖN DIN 4074-1 + A1 (Austria)		-	-	**S7K**	-	**S10K**	-	**S13K**	-	-	-
PN–D -94021 (Poland)		-	-	**KG**	-	**KS**	-	**KW**	-	-	-
STN 49 1531 (Slovakia)		-	**SII**	-	-	**SI**	-	**S0**	-	-	-

$f_{m,k}$ – 5-percentile characteristic value of bending strength, $E_{m,0,mean}$ - mean characteristic value of modulus of elasticity in bending parallel to grain, ρ_k – 5-percentile characteristic value of density, ρ_{mean} - mean characteristic value of density

Characteristic values of average wood density and *RoG* for three chosen strength classes according to DIN 4074-1and equivalents according to EN 338 are specified in Table 2.

Table 2. Characteristics of wood density and rate of growth in strength classes

Strength classes according rules - characteristics			
Strength classes		Density of wood ρ_{mean} (kg.m^{-3})	Rate of growth *RoG* (mm)
EN 338	DIN 4074-1		
C30	S13, S13K	460	less 4
C24	S10, S10K	420	4 - 6
C18	S7, S7K	380	unlimited

MATERIALS AND METHODS

Material of specimens used in this research comes from the central part of Slovakia (region Žarnovica). Timber boards were cut out of spruce wood (*Picea abies*, Karst. L.) by random selection. Dimensions of boards: 40 × 200 × 2500 mm - 5 pcs. Boards were divided into 3 segments and 9 test specimens (Figure 1). Test specimens were conditioned under standard conditions, at a temperature of 20 ± 2 ° C and a relative air humidity of 65 ± 5%, at equilibrium moisture content of 12% (reference moisture content).

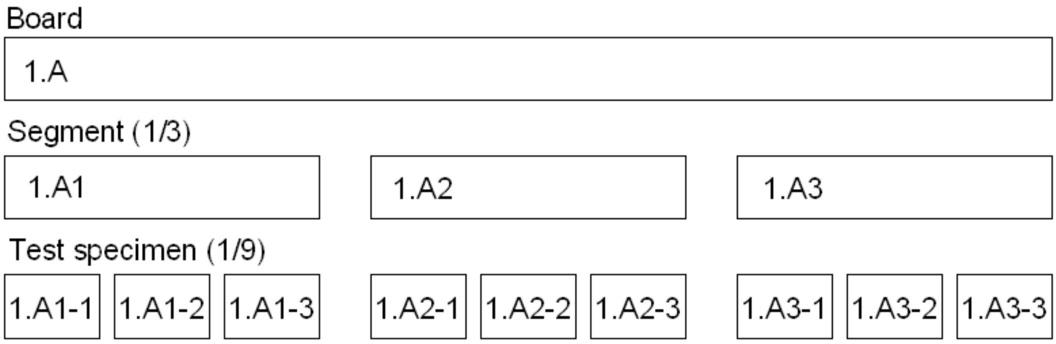


Figure 1. Scheme of dividing the board into segments (1/3) and specimens (1/9)

Density of wood ρ_{12} was set according to EN 408. Number of measurements per board n = 18. The distribution of the density of wood along the board length was monitored on each board.

Depth of penetration h_p was measured by device PILODYN 6J (pin diameter ϕ = 2.5 mm). Number of measurements per board n = 36.

Number of annual growth rings (R_n) was measured on abscissa of penetration depth (h_p). Width of growth rings *RoG* was calculated from measured data (Figure 2).

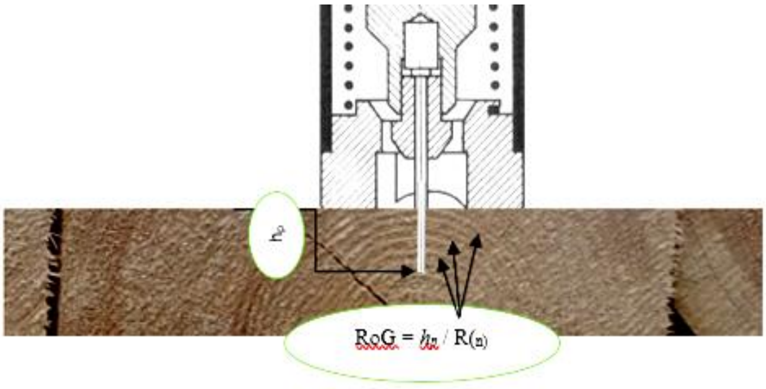


Figure 2. Measurement and calculation of *RoG*

Model – interaction of characteristics

Strength classes are expressed by class lines of C30 and C24. Class lines are set according to formula (1),

$$RoG = h_p / R_n$$

where h_p is depth of penetration in mm, R_n is number of growth rings in pcs.

For example C30 ~ *RoG* = 4 mm (e.g. 8/2, 12/3, 16/4),
C24 ~ *RoG* = 6 mm (e.g. 12/2, 18/3).

Procedure: PILODYN 6J measures the depth of penetration h_p (mm). R_n is set on abscissa of h_p. Class line C30 or C24 is set according to *RoG* value. Reliability of the model is verified trough the measured values ρ_{12} and by visual grading of board into strength class (number of knots and *RoG).*

RESULTS AND DISCUSSION

Results of experiments and basic statistical characteristics are summarized in Table 3 (average values 5 boards).

Table 3. The basic statistical characteristics of tested properties –wood density ρ_{12} (w = 12%), depth of penetration h_p and rate of growth *RoG* (n - number of measurements, - mean value, x_{max} - maximum value, x_{min} – minimum value, V - coefficient of variation)

Parameters	Statistical characteristics				
	n	$\bar{x}$	x_{max}	x_{min}	V (%)
Density of wood ρ_{12} (kg.m^{-3})	90	392	438	341	7
Depth of penetration h_p (mm)	170	15.6	23	7	23
Rate of growth *RoG* (mm)	170	5.5	8	2.5	23

Selection of spruce boards was random; characteristics were analyzed separately for every single board (Table 4).

Table 4. Average values of board 1–5 and their characteristics (wood density ρ_{12}, depth of penetration h_p and rate of growth (*RoG*) and visual strength class (EN 338, DIN 4074-1)

Number board	**Characteristics**						
	Density of wood		**Depth of penetration + width of growth rings**			**Visual strength class**	
	n	ρ_{12} (kg.m^{-3})	n	h_p (mm)	*RoG* (mm)	EN 338	DIN 4074 -1
1	18	363	36	18.6	6.2	C18	S 7
2	18	369	36	18.3	6.1	C18	S 7
3	18	400	36	12.9	5.9	C24	S 10
4	18	400	36	14.4	5.5	C24	S 10
5	18	426	36	14.1	3.7	C30	S 13

Figure 5 shows variability of wood density in testes boards. No significant differences were found out between segments and test specimens (test ANOVA, p = 0,001). The following results were found:

1. Distrubution of wood density – Wiebull's distribution, skeweness -0.05, and kurtosis -0.65, symerical distribution but flatter than normal;
2. Distribution of depth of penetration – log normal distribution (positive asymmetry skeweness +0.38, kurtosis -0.57, flatter than normal distribution, left-side distribution). More than half of the values are lower than arithmetic mean, higher values show more significant and rare differences;
3. Distribution of rate of growth – Wiebull's distribution, skeweness -0.35, kurtosis -0.38, flatter than normal distribution, right-side distribution, more than half is higher than average.

Location of segments and test specimens in board do not affect measured values of wood density. Significant differences were determined in wood density values (Fig. 5).

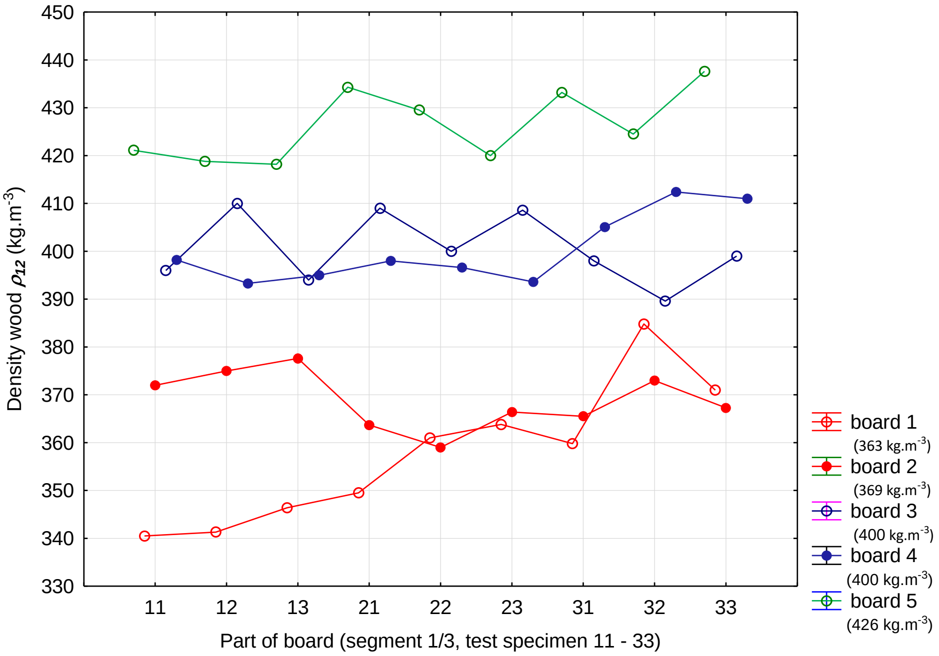


Figure 5. Variability of wood density in boards (segment 1/3, test specimen 11 – 33)

Model and its application

Interaction of model characteristics is shown in Figure 6.

- *measured:* depth of penetration (*hp*) ~ the number of growth rings,
- *standard characteristics:* rate of growth (*RoG*) ~ density of wood ($\boldsymbol{\rho_{12}}$) ~ strength class (C)

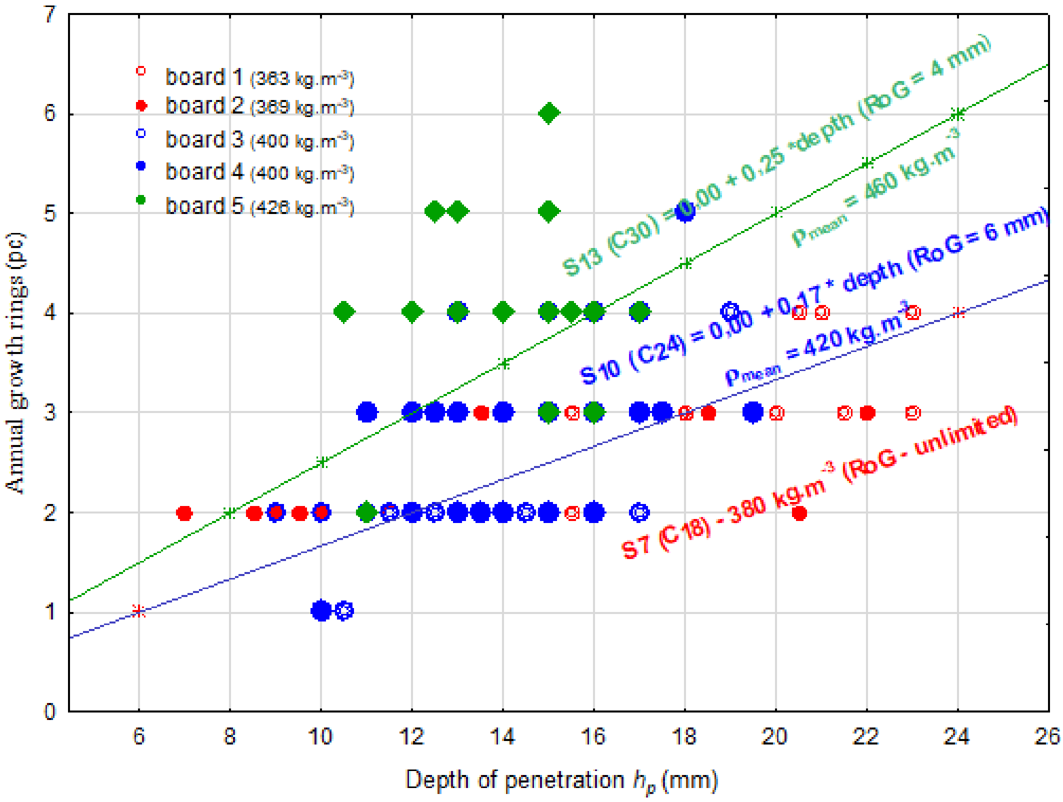


Figure 6. Model interactions of characteristics: depth of penetration ~ number of growth rings ρ_{mean} ~ rate of growth ~ strength class S13 (C30), S10 (C24) and S7 (C18) and wood density

Description of results (Figure 6):

- Boards 1 and 2 – red colour are mostly in the zone S7. With low depths ($h_p < 10$ mm) and low number of growth rings, segment parts are in a higher zone (S10 – blue colour). Boards 3 and 4 – blue colour – the wood density in segments and along the board is uniform and the density values are located around the S10 (C24) line.
- Board 5 – green colour. The segments are dominated by high wood density S13 (C30). Segments 1/1 – 1/3 show lower values of wood density and these values are located in S10 zone.

Board was visually graded according to defects of wood (knots, cracks, warping). A match between the proposed model and visual grading was confirmed. The results confirmed that it is not sufficient to evaluate only the $\rho - h_p$ dependence for the determination of wood density. Dependence between depth of penetration h_p and wood density was not confirmed. By expending research with parameters of number and width of growth rings, the level of reliability of methods in the model increases e.g. the same number of growth rings may vary, so the *RoG* value is different (even the strength class). Model can predict the quality of structural timber based on interaction of measured and modeled parameters in situ. In practice, it is not important to define wood density precisely, but to determine the strength class related to other characteristics (strength, flexibility) as accurately as possible. Measuring is carried out using 1–2 boards of timber stack, measured data being than representative for all the boards in stack. Subsequently, the dynamic modulus of elasticity is determined by the vibration method and assigned to strength class. E. g. industrial machine called Triomatic applied extra measurement module (two pins screwed). The compression load is measured in order to evaluate the wood's density (Sandoz and Benoit 2007). Wood density is a determining parameter of grading timber into strength classes. They are taken into account during design of timber elements according to EUROCODE 5.

CONCLUSION

Distribution of all three parameters shows significant deviation from normality (density of wood - Weibull's distributions, depth of penetration - log normal, rate of growth - Weibull's distributions).Proposed multi-stage parallel scale model (penetration depth ~ number of annual rings ~ rate of growth ~ strength class and wood density) can assign to the board visual class of strength and orientation density of wood (EN 338) in situ. The wood structure characteristics can be detected both visually and optically. The reliability of the model was verified by the measured densities of wood ρ_{12} along the board and visual grading over knots, cracks, warping and a match was confirmed. DIN 4074-1 has a larger use in Europe. The criteria for assessment of visual classes S13, S10 and S7 are in accordance with ČSN 73 2824-1 and STN 49 1531. The pioneers in this field are Görlacher, 1987 and Hansen, 2000. Wood density distribution in segments along the board was studied (Fig. 5), what is ρboard. During the visual assessment, the entire board is assessed (e. g. S13, S10, S7) – equivalents being C30, C24 and C18 and are assigned ρmean. In practice this method is used in visual grading in situ, as well as in designing according to the Eurocode 5. The presented results cannot be compared to related studies since this issue was studied only by the two authors mentioned above (Görlacher, 1987 and Hansen, 2000). This method is original and it uses the measured depth and growth ring number to determine the strength class and corresponding wood density.

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Streszczenie: *Wielostopniowy model równoległy w określaniu jakości drewna konstrukcyjnego metodą penetracji.* Do diagnozowania jakości drewna konstrukcyjnego wykorzystywane są różne urządzenia. Do przybliżonego oznaczania gęstości drewna stosuje się metodę półniszczącą. Pilodyn 6J wykorzystuje głębokość cięcia, która koreluje z gęstością drewna. Doświadczenia przeprowadzono na drewnie świerkowym (*Picea excelsa*, Karst. L.). Badano próbki o wymiarach 40 × 200 × 2500 mm3, n = 5 szt. Gęstość drewna wyznaczono metodą grawimetryczną zgodnie z normą EN 408 (2013). Dla badanych próbek drewna określono głębokość penetracji (hp), liczbę i szerokość słojów rocznych (RoG). Klasy wytrzymałości badanego drewna konstrukcyjnego zostały określone na podstawie gęstości drewna oraz jego jakości w oparciu o normę EN 338 (2016). Zależności pomiędzy mierzonymi cechami wyrażono w modelu z wielostopniową skalą równoległą (głębokość penetracji ~ liczba słojów ~ tempo przyrostu ~ klasa wytrzymałości i gęstość drewna). Za pomocą zaproponowanego modelu można przewidzieć wizualną klasę wytrzymałości deski i orientacyjną gęstość drewna (EN 338). Metody modelowania są łatwe w użyciu, niezawodne i mało wymagające ekonomicznie.

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