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NON-DESTRUCTIVE PENETRATION METHOD FOR DETERMINING THE QUALITY OF STRUCTURAL SPRUCE WOOD (*Picea Abies* KARST. L.) IN SITU

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ABSTRACT

Structural timber is specific, because its quality is set by visual or mechanical grading. Visual grading method by PILODYN 6J device is examined in the paper. Experiments were carried out using 5 spruce boards (*Picea abies* Karst. L) from Slovakia. Dimensions of boards were 40 × 200 × 2500 mm. Density of wood was set by gravimetric method according to EN 408 (2013). Depth of penetrations was measured using the device PILODYN 6J (h_p). Wood structure was described by the rate of growth (*RoG*) according to DIN 1052 (2004). Three most used visual grading strength classes C30, C24 and C18 according to EN 338 (2016) were specified. Dependencies between measured characteristics were expressed by multistage parallel scale model (penetration depth ~ number of growth rings ~ rate of growth ~ strength class and wood density). 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.

Key words: Spruce structural timber, board, density of wood, depth of penetration, rate of growth, visual strength class.

INTRODUCTION

The wood is one of the basic construction materials, widely used as structural or additional elements. Efficiency and reliability of timber constructions is conditional by compliance at all levels of regulations. Quality of the structural timber and its diagnostics has an important position in the whole process. Quality of the structural timber is set by followed parameters: the modulus of rupture (MOR), the modulus of elasticity (MOE) and the 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 the wood density. Currently used non-destructive methods to estimate the wood density are expensive, unavailable and statistically less significant (Bobadill *et al.* 2013). Currently developed semi-destructive methods to estimate the wood density and the strength damage the wood only partially without weakening the material. All of these methods are marked as semi-destruction in situ. They are primarily used when the visual assessment of timber in situ is limited. Methods of drilling resistance are widely used e.g. conventional drill (Acuna *et al.* 2013, 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 tree 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 the timber health by PILODYN 6J device showed good correlation between the depth of penetration and the wood density $r^2 = 0.49$. Shooting of pin or drilling gives only relative information about the 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. For the wood density prediction can by also use non-destructive method by resitograph drilling. The drilling resistance testing is described in RINN *et al.* (1996), ACUNA *et al.* (2011), RIGGIO *et al.* (2014). The drilling resistance can detect also scale and location of inner wood defects, cracks or wood degradation. Authors report only observed dependence between the wood density and the depth of penetration/drilling resistance. The interaction with other parameters as the wood structure or the quality was not assessed.

HANSEN (2000), MÄKIPÄÄ and LINKOSALO (2011) state the universal use of the PILODYN 6J. At 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. The depth of penetration and the wood density detection as non-destructive testing of structural timber is considered as a very promising method. HANSEN (2000) describes the interaction between the depth of penetration and the angle of shooting. He confirmed no significant influence. The depth of penetration depends on the wood structure (spring and summer wood), its quality (healthy, old, reaction or degraded wood) (REINPRECHT 2016). The depth of penetration is also affected by the moisture content of wood according to GÖRLACHER (1987), HANSEN (2000), DUBOVSKÝ and ROHANOVÁ (2007), ROHANOVÁ (2013).

Application of the depth of penetration on timber declares TRIOMATIC industrially used equipment in machine-controlled systems. Local wood density and the moisture content of wood are determined by shooting two pins into the wood as non-destructive method. The compression load is measured in order to evaluate the wood 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 the cross cut surface of tree. They reflect the time of grow during vegetation season. The significance of growth ring of coniferous wood is considerably higher than deciduous wood. 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 of the wood density. The 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 1052:2004, ČSN 73 2824-1/Z1 and STN 49 1531. They are considered an indicative criterion for visual quality assessment of the timber.

Wood characteristics determined by visual methods are criteria for the wood quality in strength classes. They can identify wood defects (nots, slope of grain, pith), biological degradation (decay, insect) and defects of wood growth (warping). They must be identified during machining of the wood. For example, cracks in structural timber (within, outer) could be repaired by gluing, what increases the wood quality. Limit values for each strength class are set in national regulations. Although the visual grading is less accurate, it is still used in practice. The results of the spruce timber experiments are stated by VEGA *et al.* (2011), STAPEL and DENZLER (2011), ROHANOVÁ *et al.* (2010), FRIEDRICH and DENZLER (2010).

KRZOSEK *et al.* (2008), HERMOSO *et al.* (2016) assessed visually the pine (*Pinus sylvestris* L.) timber. They set a criterion for reducing the wood quality as rejects, knots, slope of grain and twist. Authors did not found out the rate of growth (*RoG*) significantly influenced the wood density and its quality.

This paper was focused on testing the quality of spruce structural timber by non-destructive penetration method. The wood structure characteristics (the width and number of annual rings) were determined by a visual method. The aim of the study is to design a multi-stage parallel scale model. The model allows mapping the visual class of strength and orientation density of the wood through the measured characteristics in situ (EN 338 - ρ_{mean}).

Quality of structural timber

The quality of the structural timber is represented by the elasticity and strength properties but also by the density of wood. Euro standard EN 338 specifies their characteristic its values applied in both, visual and machine grading methods. Selected characteristic values and strength classes according to EN 338 are listed in Table 1. The classification of visual classes and species of the wood are stated by EN 1912. Only 3 classes of the strength are used in practice (yellow highlighted classes). They are listed in national regulations.

Tab. 1 Characteristic values and strength classes – standards in the countries.

Standards		Strength classes – characteristic values									
	properties	C 14	C 16	C 18	C 22	C 24	C 27	C 30	C 35	C 40	C 50
EN 338	$f_{m,k}$ (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

PILODYN 6J

The device is used for indicative testing of the wood density. The starting point is the dependence between the depth of penetration and the wood density according to tree species and the moisture content of wood. Operation and possibility of using are advantages of the device 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.

The device follows principles of shooting steel pin into the wood by differentiated energy. Shooting of pin is perpendicular to annual growth rings Fig. 1, Fig. 2).

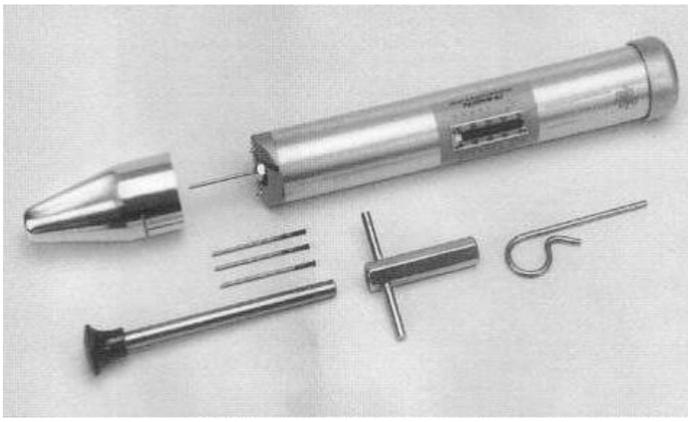

Fig. 1 PILODYN 6J - impact device with the scale and pin, loading rod, protective cap.

Fig. 2 System of penetration of working pin into wood in PILODYN

Rate of growth – RoG

For structural timber the width of growth rings is expressed by the rate of growth (*RoG*) according to EN 14081-1 concerning 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, 6 mm, 4 mm, and less (DIN 4074-1, ČSN 73 2824-1/Z1 and STN 49 1531).

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.

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

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

MATERIALS AND METHODS

Material of specimens in this research came from the central part of Slovakia (region Žarnovica, altitude 230 m a.s.l., soil – cambisol). The board was 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 3). MÄKIPÄÄ - LINKOSALO (2011) described a similar process for both, dry and wet wood. Test specimens were conditioned under standard conditions, at the temperature of 20 ± 2 ° C and the relative air humidity of 65 ± 5%, at equilibrium humidity of 12% (reference humidity).

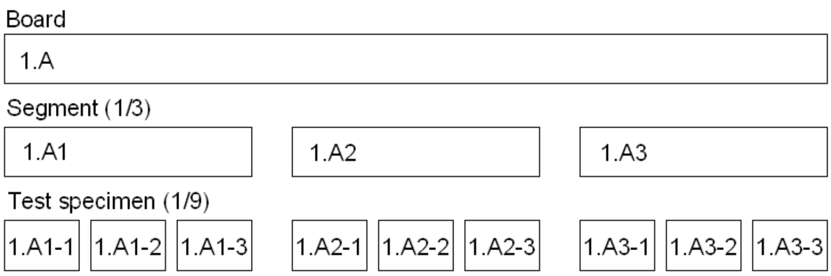

Fig. 3 Scheme of dividing the board into segments (1/3) and specimens (1/9).

Density of wood ρ_{12} was determined 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 the abscissa of penetration depth (h_p). The rate of growth *RoG* was calculated from measured data (Figure 4).

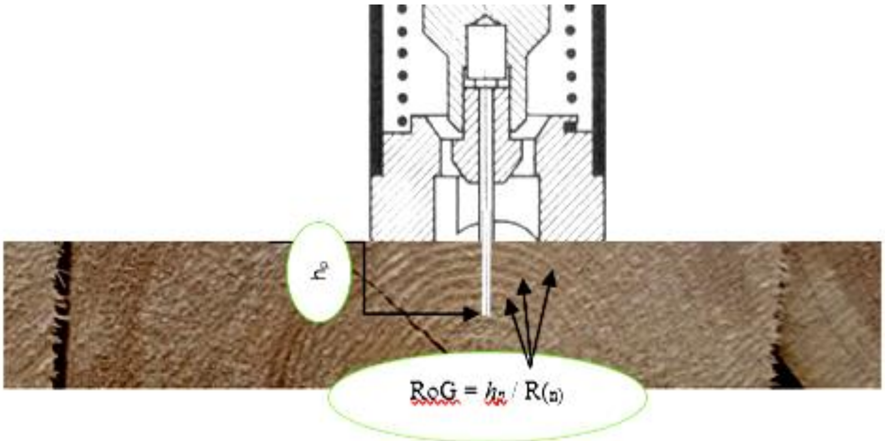

Fig. 4 Measurement and calculation of *RoG*.

Model – interaction of characteristics

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

$$RoG = h_p / R_n \quad (1)$$

Where h_p is the depth of penetration in mm, R_n is the 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 the abscissa of h_p. Class line C30 or C24 is determined according to *RoG* value. Reliability of the model is verified trough the measured values ρ_{12} and by visual grading of the 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).

Tab. 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_x - coefficient of variation).

Parameters	Statistical characteristics				
	n	$\bar{x}$	x_{max}	x_{min}	V_x (%)
Density of wood ρ_{12} (kg·m^{-3})	90	392	438	341	7
Depth of penetration h_p (mm)	180	15.6	23	7	23
Rate of growth *RoG* (mm)	180	5.5	8	2.5	23

Selection of spruce boards was carried out randomly. Characteristics were analyzed separately for every single board (Table 4).

Tab. 4 Average values of characteristics for the board 1–5 (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 in the wood density in the board. No significant differences were found out between segments and test specimens (test ANOVA, p = 0,001). Location of segments and test specimens in the board do not affect measured values of the wood density. Significant differences were determined in wood density values.

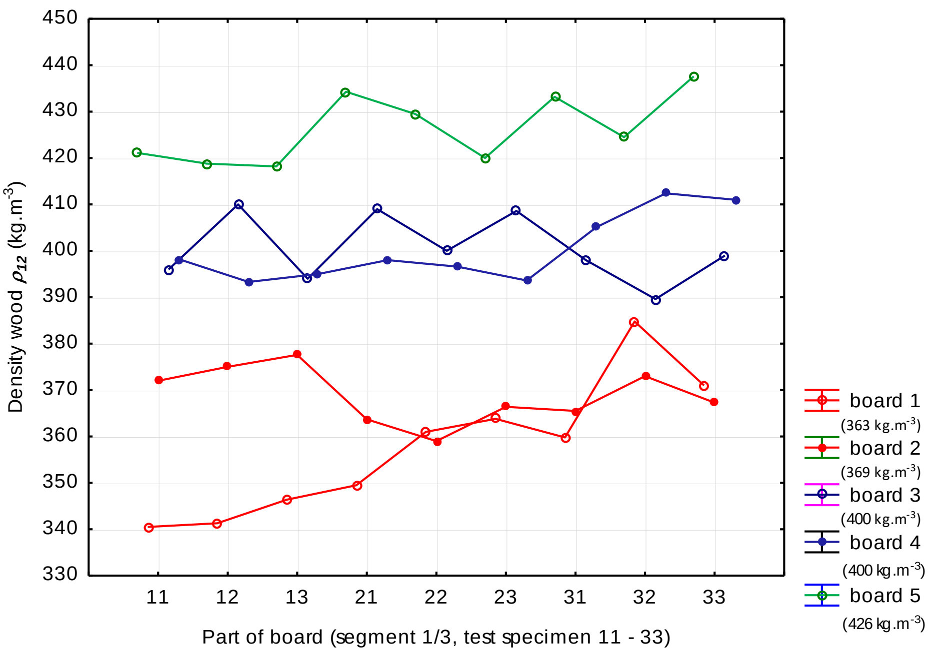

Fig. 5 Variability of wood density in boards (segment 1/3, test specimen 11–33).

The dependence between the wood density and the depth of penetration (Figure 6) is only 12% (p = 0,001). If we compare our results with GÖRLACHER (1987) and HANSEN (2000), our results shows weaker dependence. The factors that could affect obtained dependence are for example various wood structures in the boards, not exact perpendicularity of shooting, location of the board in the prism and others. The same finding was also found between the wood density and *RoG* (Fig. 7).

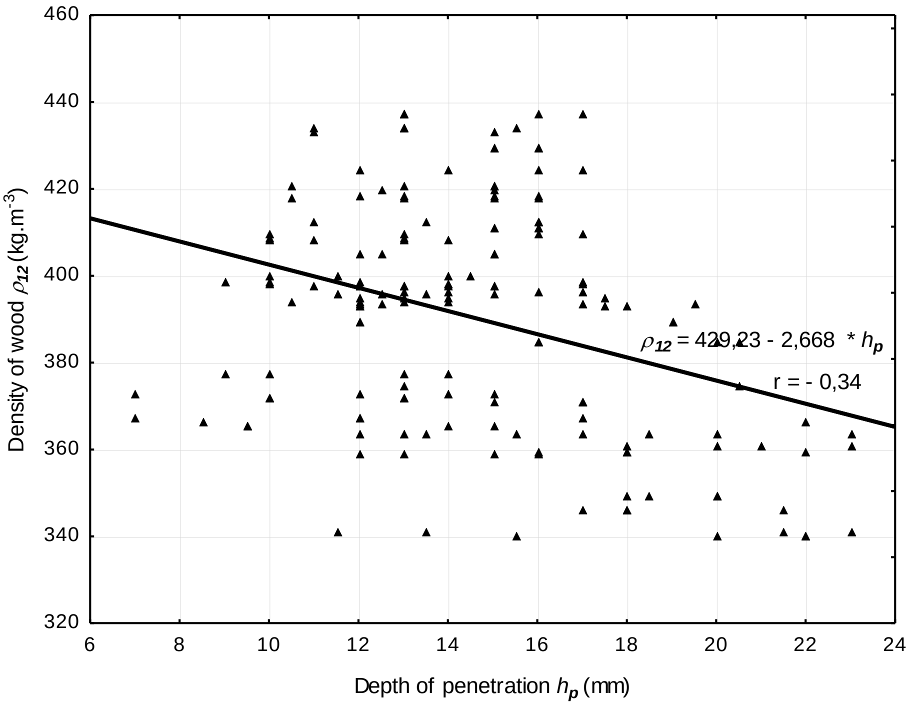

Fig. 6 Relationship between density of wood (ρ_{12}) and depth of penetration (h_p).

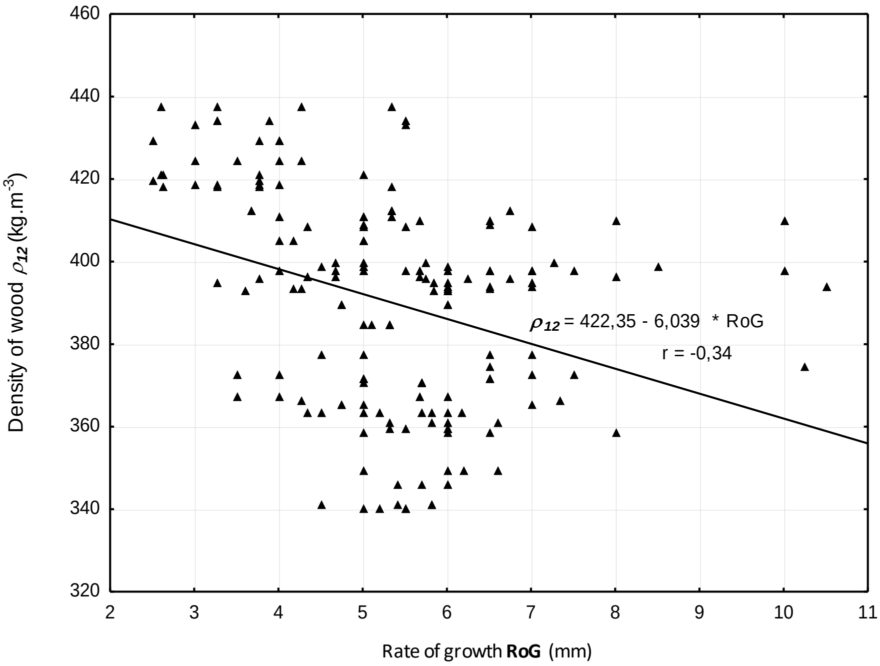

Fig. 7 Relationship between density of wood (ρ_{12}) and rate of growth (*RoG*).

Model and its application

Interaction of model characteristics is shown in Figure 8.

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

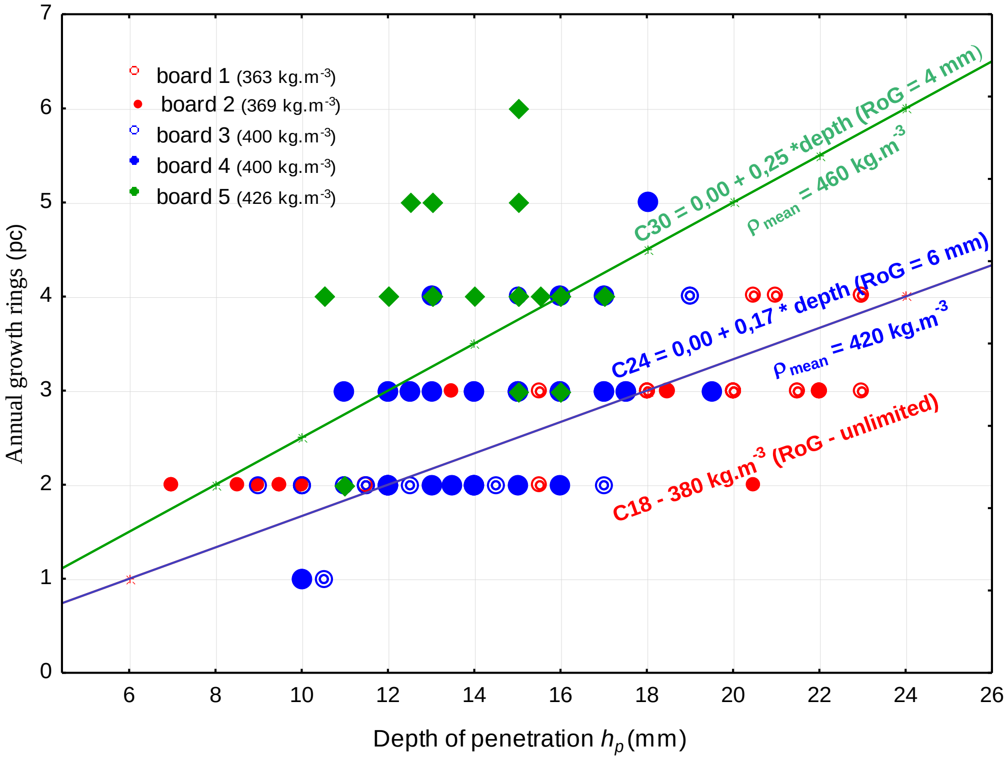

Fig. 8 Model interactions of characteristics: depth of penetration ~ number of growth rings ρ_{mean} ~ rate of growth ~ strength class C30, C24 and C18 and wood density.

Description of results (Fig. 8):

- The boards with low densities (board 1 and board 2 - red color) are added to zone of C18 eventually C24**.** The wood density variability along the board length means that a part of board has higher density than average C18 - 380 kg·m^{-3}. It is assumed that these values are ranked in the higher class (C24).
- The boards with the middle density (board 3 and board 4 - blue color) have balanced the wood density along the length of board and are located around the line zone of C24.
- The boards with the high density (board 5–green colour). Although there is a slight fluctuation in the density of the wood along the length of board, values are in the zone around the line C30 and above.

The boards were visually graded according to defects of the wood (knots, cracks, warping). A match between the proposed model and the visual grading was confirmed. The results confirmed that it is not sufficient to evaluate only the $\rho - h_p$ dependence for the determination of the wood density. The dependence between the depth of penetration h_p and the wood density was not confirmed. By expending research with parameters of the number and the 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 the interaction of measured and modeled parameters in situ (visually, optically).

In practice, it is not important to define the wood density precisely, but to determine the strength class related to other characteristics (strength, flexibility) as accurately as possible. The device MTG Timber Grader, for example, determines the wood density by the weighting method on the whole board as well as timber defects. Measuring is carried out using 1–2 boards of the timber stack, measured data are than representative for all boards in the stack.

Subsequently, the dynamic modulus of elasticity is determined by the vibration method and assigned to "C" strength class. E.g. the industrial machine Triomatic applies extra measurement module (two pins screwed). The compression load is measured in order to evaluate the wood's density (SANDOZ and BENOIT, 2007). The 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.

CONCLUSIONS

1. The wood density along the board length does not have any significant differences (ANOVA, $p = 0.001$). Different densities of the wood were measured between single boards.
2. Weak linear correlation was found between the depth of penetration and the density of wood.
3. Calculation method of the width of growth rings according to the depth of penetration and number of growth rings is reliable and fast.
4. Linear correlations between the wood density and the width of growth rings were confirmed with all boards.
5. The linear dependence between the wood density ρ_{12} and the strength class "C" (EN 338) was confirmed experimentally.
6. 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 the visual class of strength and the orientation density of the wood (EN 338) in situ. The wood structure characteristics can be detected both visually and optically.
7. The reliability of the model was verified by the measured densities of wood ρ_{12} along the board and the visual grading over knots, cracks, warping and a match was confirmed.
8. Methods for determination of parameters in the model are easy, reliable and economically undemanding.

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