The Influence of Pine Logs (*Pinus sylvestris* L.) Quality Class on the Mechanical Properties of Timber

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This study analyzed how the quality class (A, B, C) of pine logs (*Pinus sylvestris* L.) from the Silesian Forestry Region influences the mechanical properties of timber produced from those logs. The study utilized 210 pieces of timber with nominal cross section dimensions of 40 × 138 mm that were 3500 mm long and made of logs from a specific quality class. From these timber pieces, the density (with the stereometric method), the dynamic modulus of elasticity (using the Mobile Timber Grader device), the global modulus of elasticity, and static bending strength (EN-408 2012) was determined. On the basis of the conducted analyses, the log quality class influenced the physical and mechanical parameters of structural timber to a limited degree. However, statistically significant differences were not found for the density, dynamic and global modulus of elasticity, and bending strength between timber elements made of logs from A and B quality classes (Anova analysis with significance level $p < 0.05$).

Keywords: Quality class; Pine timber; Dynamic modulus of elasticity; Global modulus of elasticity; Static bending strength

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INTRODUCTION

Every year, the demand for wooden logs grows, and the demand is satisfied by continuously increasing its production. The global production of wooden logs in 2017 reached 3,797 million m^3, which constituted a growth by 1% in comparison to 2016 and by 10% in comparison to 2000 (FAO 2019). At the same time, in 2017, the production of logs in the EU-28 countries amounted to 470.3 million m^3, which equals about 12% of the global production (Eurostat 2019). Efficient and effective production of timber depends on the possibility to supply adequate amounts of wood to each market, in order to optimize wood value and ensure market competitiveness. In the case of a typical value chain, the supply of adequate amounts of wood is a big challenge, due to very different customer expectations concerning the quality properties of wood. It is crucial to know wood quality parameters very well, in order to guarantee an optimum value chain.

The classification of logs in the forest is the first stage in the evaluation of wood's technical quality and serves as the point of departure for subsequent tasks needed to trade and evaluate wood. For ages, wood quality was assessed without the use of advanced technologies, and only by visual inspection (Berglund *et al.* 2015). In reality, many properties of wood are mutually correlated, which makes it possible to perform quite simple field tests to select the logs with desired quality properties, which will later translate into a high efficiency of sawn timber (Tsehaye *et al.* 2000a,b; Roos *et al.* 2001). For example, actions aimed at reducing the number of branches during tree growth can influence the possibility of achieving wood logs with a much higher quality class (Meadows and Goelz 1998). Research has shown that adequate forestry management can increase the production of logs in the A quality class by 97%, and in the B quality class by 68%, which means there will be less low quality, C class logs (Carvalho *et al.* 2009; Diaconu *et al.* 2015; Reventlow *et al.* 2019).

The analytical approach to wood classification ensures a more effective, transparent, and rational use of forestry resources. The visual method used in the quality assessment of large logs consists of analyzing such characteristics as log length and volume, as well as other components such as top or bottom log diameter, or indicating what percentage of the log volume should be dedicated for wood appropriate for further processing into timber of specific quality. Log quality is described through a set of properties related to selected attributes that will influence further use of the material, that is: trunk diameter, its length, tapering, knot free area, or wood defects. The rule for accepting defects is the following: the higher the quality of the class, the less acceptable such defects as knots, twisted fibres (grain deviation), or stains become.

Large dimension coniferous logs are those whose diameter at the narrower end, measured without bark, equals or exceeds 14 cm. The classification of round logs in Poland is carried out on the basis of the PN-92/D-95017 standard. Recently, the Polish Committee for Standardization (PKN) deemed that the standard was no longer binding. However, it is still being used in the trade of wooden logs, together with the related ordinances issued by the General Director of National Forests concerning the technical conditions of sales of this raw material. According to the standard, large dimension coniferous wood can be classified into 4 quality classes: A, B, C, and D. The A class is the best quality, while D corresponds to the lowest quality. In the D class, at least 40% of the volume of each piece should be adequate for further processing and use. The standard specifies that the smallest diameter, without bark, at the narrower end should be 22 cm for class A, and 14 cm for the remaining classes. The smallest diameter at the distance of 1 m from the thicker end (the nominal diameter) is 35 cm for class A, and 25 cm for class B. The nominal diameter has not been indicated for classes C and D, according to this standard. The smallest length of the lower end, without defects, or with defects acceptable in classes A and B, amounts to 4 m. This value has not been limited for classes C and D. Class D is practically useless for industrial processing and is never ordered by lumber mills in Poland. Most logs from Polish forests fall into the C quality class and this is the class that is most frequently bought by lumber mills.

In other European countries, the requirements concerning classes based on the quality and dimensions of large logs are slightly different. For example, in Switzerland, there is less tolerance for wood defects in each class (A, B, C, and D) (Riegger 2010). After mutual agreement, it is possible to mark coniferous wood with more than one quality class (*e.g.* AB, BC). Class A requirements refer to pine wood whose minimum diameter in the middle of the log length, for L1 and L2, amounts to 40 cm. No knots are acceptable on the length, it is only possible to have defects that do not significantly affect the possibility of wood usage. Swiss guidelines also refer to the average width of annual growth rings (less than 6 mm for wood to be used in construction), and also pith eccentricity, which has not been taken into account in the Polish standard. Requirements for class C are more detailed in the Polish standard that accepts most wood parameters and defects in this class or does not limit them (except for cracks on the front and the sides, curvature limitations and wood defects caused by biological corrosion). The requirements concerning wood quality and dimensions in Germany are set out in the Framework Agreement on Wood Trade

(Rahmenvereinbarung für den Rohholzhandel in Deutschland – RVR). The document (Deutscher Forstwirtschaftsrat e.V. and Deutscher Holzwirtschaftsrat e.V. 2015) includes tables used for quality classification of coniferous wood: for spruce/fir, pine, Douglas fir, and larch. German quality classification also divides wood into 4 quality classes: A, B, C, and D. In reference to the main wood defect of knots, RVR allows the presence of non-ingrown knots in the B class (1 knot per 4 m of log length), while the Polish standard says that open knots in pine wood are unacceptable in classes A and B. The German requirements for unidirectional curvature, as well as shallow and deep insect tunnels, are more stringent in comparison to the Polish standard.

EXPERIMENTAL

Material

The research material consisted of pine timber from the Silesian Forestry Region in Poland. The sawn timber was made of log quality classes of A, B, and C, from raw materials with the age of around 124 years and 25 m of height. The trees grew in a young, mixed forest within the Regional National Forest Directorate of Katowice (Olesno Forest District, Sternalice Forest Division, unit 14d, geographic coordinates: 50.898629, 18.423915). The timber was dried in industrial conditions in a chamber drier, down to a moisture content of *ca*. 12%, and planed. The nominal dimensions of the timber after drying and planing were: 40 x 138 x 3,500 mm. There were 210 pieces of timber in the batch under research. Table 1 presents the number of timber elements obtained from logs from each class: A, B, and C.

Methods

Determination of timber density and water content

The water content of the timber batch was measured with the use of a HIT5 resistance wood moisture meter (TANEL, Gliwice, Poland), with measurement precision of 0.1%. During the moisture measurements, the nominal density of the wood being researched was taken into account under ambient temperature (room temperature 20 °C and relative humidity 65%). Timber density was determined through the stereometric method, in accordance with the PN-D-04101 (1977) standard. Test results are presented in Table 1.

Non-destructive tests of timber

The non-destructive tests included measurements of the dynamic modulus of elasticity with the use of a portable grading device called the Mobile Timber Grader (MTG) by the Brookhuis MicroElectronics Company (Brookhuis Applied Technologies, Enschede, The Netherlands). The dynamic modulus of elasticity is measured by the vibration method that measures the natural frequency of vibration after a short impact (Fig. 1). Together with length and density, the dynamic modulus of elasticity was calculated according to the Eq. 1 (de Vries and Gard 2008),

$$MOE\ dyn = \rho(2lf)^2 \tag{1}$$

where ρ is the wood density (kg/m^3), l is the length of the sawn timber piece (m), and f is the frequency of the induced vibrations (Hz). The test results are presented in Table 2.

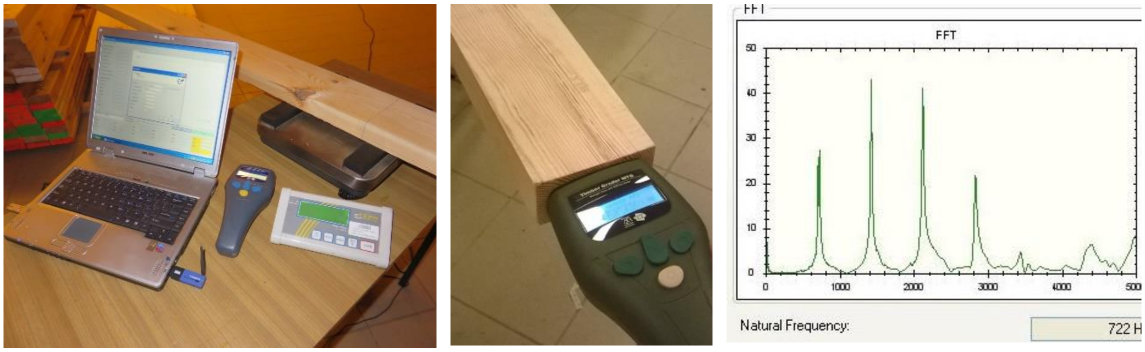

Fig. 1. An overview of the non-destructive test station with the MTG device (on the left), MTG during the determination of the MOEdyn and class C wood durability (in the centre), and a screenshot from the computer software presenting an example of the registered vibrations induced by the MTG device (on the right)

Destructive tests of timber

The destructive tests of research material included: determination of the global modulus of elasticity for timber during static bending (MOE EN-408) and determination of static bending strength (Modulus of Rupture – MOR), according to EN 408:2010+A1 (2012), with the use of the 10-tonnes resistance machine TIRA Test 2300 (TIRA GmbH, Schalkau, Germany). The static diagram of the test is presented in Fig. 2. The tests were performed with a displacement control. The speed of the load head was 3 mm/min. During the test, we registered the value of the load and the bend. The bend value was measured with the help of additional equipment, and namely the movement sensors (Novotechnik, type TRS 75, Southborough, MA, USA) with a precision of 0.01 mm.

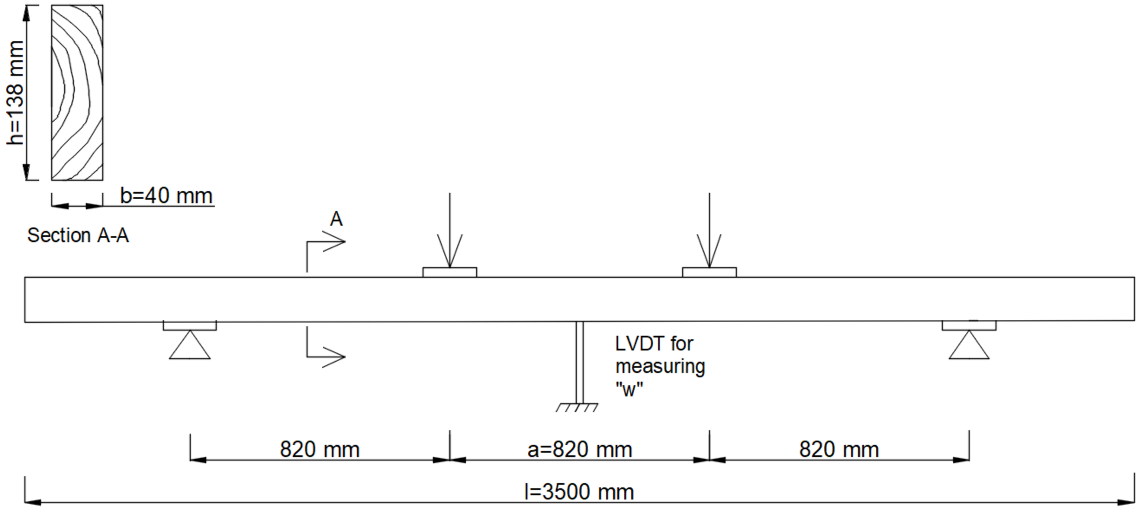

Fig. 2. Static diagram of a four-point structural timber bending test to determine MOE EN-408 and MOR

Statistical analysis

The statistical analysis of test results was carried out using Statistica v.13.3 software (StatSoft, Inc., Tulsa, OK, USA). The data was analyzed and provided as the mean ± standard deviation and the coefficient of variation. Additionally, Student’s T test was performed, with a confidence level of 95%, to determine the significant differences between the mean values of the tested parameters in each of the analyzed groups. Additionally, in order to determine whether the quality class of the given log used to make timber influenced its physical and mechanical parameters, a one-way Anova analysis was performed. One of the basic assumptions for this analysis consists of a normal distribution of the variable under analysis (timber density, dynamic modulus of elasticity, global modulus of elasticity during bending, and static bending strength). For all the analyzed cases, in each log quality class (A, B, C), the normal distribution of results was verified with the Kolmogorov-Smirnov test, with a minimum level of significance of p=0.05. The second basic assumption of the test is a homogeneous variance of the tested parameter, which was verified with the Levene’s test. If the test confirmed the fulfillment of the zero hypothesis, a Turkey’s post-hoc test was carried out. If the Levene's test revealed a lack of variance homogeneity for a given parameter, a corrective coefficient was used and an adequate method of post-hoc testing, the Duncan test, was completed. The test results have been presented in Table 3.

RESULTS AND DISCUSSION

Tables 1 and 2 present the obtained research results for selected physical and mechanical parameters of the pine timber under research, made of logs from A, B, and C quality classes.

Table 1. Selected Physical Parameters of the Timber

Log quality class	Density (kg/m^3)			Moisture (%)			Number of timber elements
	Mean	SD	COV	Mean	SD	COV	
A	574	67	12	12.1	1.3	11.1	17
B	570	60	11	12.2	1.2	9.8	87
C	524	53	10	11.0	1.3	11.6	106
The entire timber batch	547	62	11	11.6	1.4	12.0	210

Table 2. Selected Mechanical Parameters of the Timber

Log quality class	MOE dyn [MPa]			MOE EN-408 [MPa]			MOR [MPa]			Number of timber elements
	Mean	SD	COV	Mean	SD	COV	Mean	SD	COV	
A	14275	3496	24	13283	2800	21	60.54	22.12	36.53	17
B	14190	2465	17	12943	2255	17	54.47	18.23	33.48	87
C	12037	2174	18	10882	2061	19	37.88	12.30	34.46	106
The entire timber batch	13105	2645	20	11915	2440	20	46.47	18.14	39.04	210

The high correlation ($R^2 = 0.86$) between the global modulus of elasticity and the dynamic modulus of elasticity was already confirmed for timber at a laboratory scale in 1984 (Görlacher 1984). Similarly, a high correlation between those two parameters was also observed, among others, for the wood of Dutch larch ($R^2 = 0.75$) (de Vries and Gard 2008). On the basis of the performed tests, it can be concluded that the observed correlation between the global modulus of elasticity, determined in accordance with the EN 408 standard, and the dynamic modulus of elasticity, determined with the MTG device, is very high (Fig. 3).

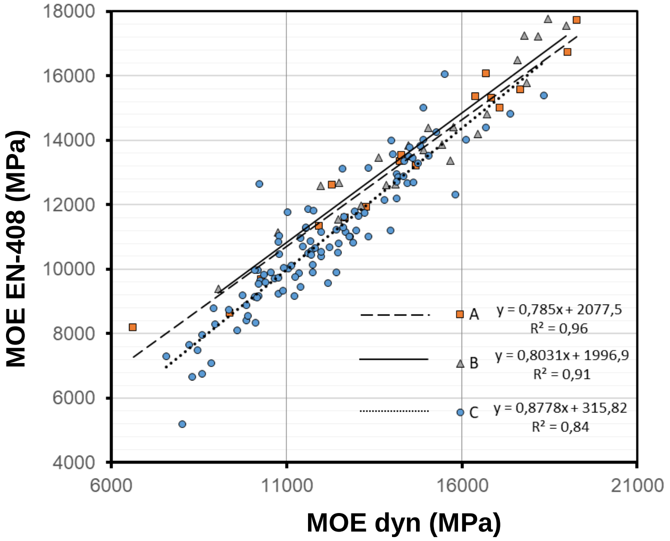

Fig. 3. Correlation between the global (MOE EN-408) and dynamic (MOE dyn) modulus of elasticity for timber made of logs from different quality classes (A, B, and C)

At the same time, taking into account the origin of timber, and specifically the quality class of the logs it was made of, it can be observed that the timber made of higher quality logs demonstrates a higher correlation between those characteristics ($R^2 = 0.96$) in comparison with timber made of B ($R^2 = 0.91$) or C ($R^2 = 0.84$) quality logs. On the basis of analysis of data from Table 2, it can be concluded that A class logs produced timber with the highest mean value of both moduli (and, at the same time, with the highest coefficient of variation), while the lowest mean value was observed for timber made of C quality logs. What is more, reference literature points out that the dynamic modulus of elasticity depends greatly on wood density, and not so much on the acoustic velocity or resonance frequency. Acoustic velocity and wood density were found to be independent parameters (Zhang *et al.* 2011; Ponneth *et al.* 2014). On the basis of analysis of data from Table 2, one can observe that the mean value of the dynamic modulus of elasticity of timber is always higher than the mean value of the global modulus of elasticity for a given quality class (by *ca.* 7% for A quality logs, *ca.* 9% for B quality logs and *ca.* 10% for C quality logs). This can mean that the global modulus of elasticity parameter is more susceptible to the presence of wood defects, especially that of knots and twisted fibres, which lowers the natural stiffness of the tested element. Reference literature points out that an analogous situation (lower correlation coefficient between the global and dynamic modulus of elasticity) happens in the case of applying the vibration method under industrial conditions (Görlacher 1984; Blass and Gard 1994; Guan *et al.* 2015; Chauhan and Sethy 2016).

The coefficient of determination between the global modulus of elasticity and density (Fig. 4) was the highest in the case of timber elements made of A quality logs ($R^2 = 0.63$), and the lowest for C quality logs ($R^2 = 0.38$). The mean density of timber pieces made of A and B quality class logs did not differ significantly (574 kg/m^3 and 570 kg/m^3, accordingly), just like the mean values of the global modulus of elasticity. Although, in general, the correlation between these parameters (density and global modulus of elasticity) was stronger in case of timber made of better-quality logs. The obtained coefficient of determination values were in line with reference literature data concerning the relation between the above-mentioned characteristics for a timber batch (without indicating the quality of the logs they were made of). In the case of Finnish pine timber (Hanhijarvi *et al.* 2005), the coefficient of determination between the global modulus of elasticity and timber density amounted to 0.65. For Polish pine timber, the analogous coefficient of determination (for 764 timber pieces) amounted to 0.58 (Krzosek 2009).

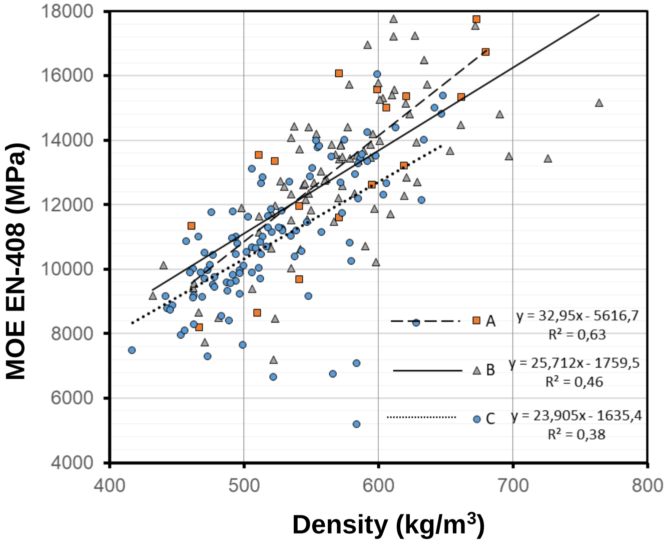

Fig. 4. Correlation between the global modulus of elasticity (MOE EN-408) and timber density for timber made of logs from different quality classes (A, B, and C)

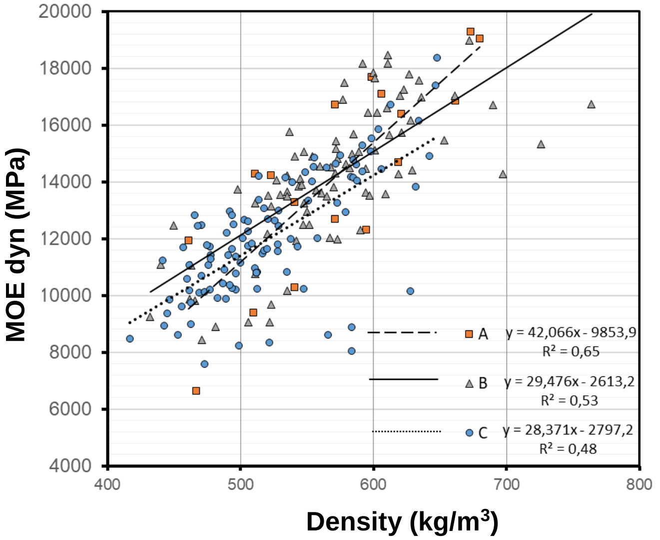

Fig. 5. Correlation between the dynamic modulus of elasticity (MOE dyn) and timber density for timber made of logs from different quality classes (A, B, and C)

The correlation between the dynamic modulus of elasticity and timber density, taking into account the influence of the quality class of logs used to make the test material (Fig. 5), was analogous to the correlation observed between the global modulus of elasticity and density. Timber made of higher quality class logs showed a higher coefficient of determination between the dynamic modulus of elasticity and the density (for timber made of A quality class logs: $R^2 = 0.65$; C class: $R^2 = 0.48$). According to reference literature, the coefficient of determination between the dynamic modulus of elasticity and timber density, for wood without defects, amounts to 0.64 (Bengtsson 2006). At the same time, it can be observed that these coefficients were lower than analogous correlations observed between the modulus of elasticity determined in line with EN-408 (2012) and the density. In the case of timber made of higher quality logs with higher mean density and relatively few, randomly distributed natural structural defects, there was a correlation between mechanical properties and density.

For the sake of a deeper analysis of properties of timber made of logs from different quality classes, the correlation between the global modulus of elasticity (MOE EN-408) and modulus of rupture (MOR, static bending strength) was determined. The coefficient of determination between the static bending strength (MOR) and modulus of elasticity determined for a batch of 764 timber pieces, amounted to 0.68 (Krzosek 2009). There is data in the reference literature suggesting that this coefficient can differ a lot depending on the origin of timber. For pine wood from the Greater Poland-Pomerania Region, this coefficient amounted to 0.59 (Szukala and Szuminski 2003). At the same time, it is pointed out that the relation between bending strength and the global modulus of elasticity is the highest. Thus, it is taken into account when creating various kinds of models, allowing to predict the characteristic values of resistance parameters (de Vries and Gard 2008). On the basis of analysis of Fig. 6, one may conclude that also in this case there was a direct correlation between the quality of logs used to make the timber under research and the coefficient of determination. The highest coefficient of determination between the modulus of elasticity and the static bending strength was found for timber made of A quality logs (0.63), while in the case of B and C quality logs, it was only 0.45. At the same time, the coefficient of variation for bending strength was quite high and independent from both the log quality class and number of samples. The coefficient amounted to 33% to 36%.

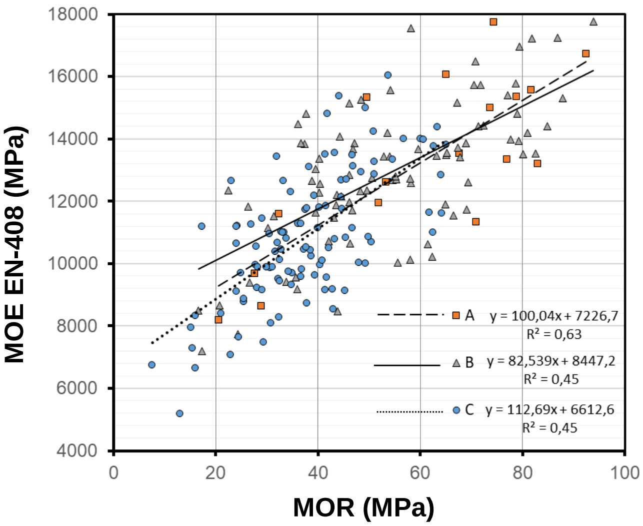

Fig. 6. Correlation between the global modulus of elasticity (MOE EN-408) and modulus of rupture (MOR, static bending strength) for timber made of logs from different quality classes (A, B, and C)

The Anova analysis (Table 3) revealed that the quality classes of logs from the Silesian Forestry Region influenced the physical and mechanical parameters of pine timber made of those logs. At the same time, the analysis revealed that there were no significant differences in the values of timber density, its dynamic and global modulus of elasticity, and static bending strength in the case of timber made of A and B quality logs. Only the lowest of the classes under analysis (C) showed statistically significant differences in the values of timber resistance parameters, both comparing to timber made of A and B quality logs.

The plans to continue this research include additional analyses of wood from other Polish forestry regions, which will make it possible to verify the results obtained until now, and to find out whether in other regions there are analogous correlations between the quality class of pine logs (*Pinus sylvestris* L.) and the mechanical properties of timber made of it. If it turns out that also in this case the differences between resistance parameters of timber made of A and B quality class logs will not be statistically significant, then it will prove recommendable to verify and correct the assumptions and guidelines of the PN-92/D-95017 standard.

Table 3. Probability of Post Hoc Tests for Log Quality Classes as a Source of Variance in ANOVA Analysis

Parameter	Log Quality Class	Log Quality Class		
		A	B	C
Density	A	-	0.985408	**0.029233**
	B	0.985408	-	**0.000022**
	C	**0.029233**	**0.000022**	-
MOE dyn	A	-	0.879472	**0.000103**
	B	0.879472	-	**0.000127**
	C	**0.000103**	**0.000127**	-
MOE EN-408	A	-	0.894506	**0.004301**
	B	0.894506	-	**0.000022**
	C	**0.004301**	**0.000022**	-
MOR	A	-	0.097087	**0.000011**
	B	0.097087	-	**0.000014**
	C	**0.000011**	**0.000014**	-

CONCLUSIONS

1. The quality class of pine logs (*Pinus sylvestris* L.) has only a limited degree of influence on the physical and mechanical properties of timber produced from those logs. Timber elements made of A and B, high quality class logs do not present any statistically significant differences as far as their physical and mechanical parameters are concerned.
2. In the case of timber made of logs from higher quality classes, higher values were obtained for coefficient of determination characterizing the interdependence between given physical and mechanical parameters: timber density, dynamic modulus of elasticity, global modulus of elasticity, and static bending strength. In the case of timber obtained from low quality logs, the coefficient of determination was proportionally lower.
3. Numerical and analytical models used to predict the resistance class of timber are more reliable for logs from higher quality classes.

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