forests

Article

Mechanical Properties of Machine Stress Graded Sawn Timber Depending on the Log Type

Izabela Burawska-Kupniewska *, Piotr Mańkowski and Sławomir Krzosek

Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences-SGGW, Nowoursynowska 159, 02-776 Warsaw, Poland; piotr_mankowski@sggw.edu.pl (P.M.); slawomir_krzosek@sggw.edu.pl (S.K.)
* Correspondence: izabela_burawska@sggw.edu.pl

Abstract: This article presents the results of tests conducted on Scots pine timber from three different kinds of logs: butt, middle and top. A planed pine timber batch composed of 510 pieces, dried to ca. 12% humidity, was machine-graded using a portable MTG device, and classified into the following classes: C18, C24, C30, C35 and C40 (according to EN 338:2016). During the second stage of the study, the timber was tested to determine its density, MOE and MOR, in accordance with EN 408:2012. We analyzed the impact of the timber's log of origin on the results of machine strength grading and on the values of correlation coefficients between the tested properties. The results show, among others, that there is a correlation between the C classes and MOR of the tested timber, as well as its origin from butt, middle or top logs.

Keywords: Scots pine; strength grading; non-destructive testing

Citation: Burawska-Kupniewska, I.; Mańkowski, P.; Krzosek, S. Mechanical Properties of Machine Stress Graded Sawn Timber Depending on the Log Type. *Forests* **2021**, *12*, 532. https://doi.org/10.3390/f12050532

Academic Editor: Grzegorz Trzciński

Received: 1 April 2021
Accepted: 22 April 2021
Published: 25 April 2021

1. Introduction

In recent years, the use of structural timber has significantly increased. The total global production of coniferous sawn wood in 2019 amounted to over 488.9 million m^3 (in 2009, it was almost 30% less: 344.4 million m^3). This trend looks similar both globally and in the European market [1], which is related to, among other things, the development of standardization in Europe, which guarantees higher quality and increased safety of wooden structures. The potential of wood as an engineering material is unlimited, provided that there are means to guarantee precisely defined properties, determined by obligatory machine strength grading of sawn structural timber. The degree of variation of the physical and mechanical properties of wood has been the focus of many research projects in recent years, both concerning the quality classification of wood [2] and possibilities for improving the quality of wooden resources by adequate tree cultivation, forest management and division of resources [3–5]. As we know, the high variance of wood properties is due to geographic variations (place of origin/climate/forest cultivation techniques), but also appears within one single tree (due to the tree growth biomechanics) [6]. Moreover, timber properties differ depending on log location within the trunk: butt, middle or top [7]. The strength properties of wood depend, to a large extent, on the presence of wood defects, especially knots, and twisted fibers that often go together with them. As a result, many strength grading machines and devices take these features into account during the strength grading process. There are multiple publications describing the development of industrial machines used for the strength grading of timber [8–17]. Strength grading machines measure one or several wood properties that can be verified in a non-destructive way, and whose correlation with the wood's bending strength is known. The more indicating properties are simultaneously taken into account to predict timber strength, the higher the coefficient of correlation and the certainty level of the grading results. Modern scanners and grading machines make use of multiple methods (X-ray photographs, photographs of surfaces, laser scans using the tracheid effect) to acquire in-depth data, which, combined with mechanical or dynamic stiffness with density, provide high precision strength grading [18–28].

Other wood characteristics, such as its origin, but also within a tree (butt, middle, top logs), should be taken into account in the grading process; though, due to their high variability, their correlation with strength is low. Studies aimed at verifying the influence of log type on the mechanical properties of structural timber obtained from them were carried out in various countries [6,22,23]. German studies revealed that spruce timber from butt logs was more often classified as high quality than from middle or top logs [29]. Moreover, Austrian research performed within the framework of the XXL-Wood Project shows that the mechanical properties of spruce timber from three log types (butt, middle and top) remain stable until ca. 12–15 m from the lower end [6]. This conclusion was drawn on the basis of comparisons between wood properties such as density, dynamic modulus of elasticity, modulus of elasticity in bending, average width of annual growth rings and fiber angle deviation. Nonetheless, a commonly applied rule states that, for wood species with increasing density from pith to bark, density decreases from butt to top, similarly to other density-correlated wood properties, i.e., MOE and MOR [30–33]. A variance of wood properties depending on the type of log is a common observation. For Scots pine, independently of the geographic region of origin, the highest average values of density, MOE and MOR are observed for timber made of butt logs, and the lowest values are apparent in top logs [34]. However, additionally, it is scientifically interesting to scrutinize the efficiency of the machine strength grading process for timber from butt, middle and top logs, and to determine timber grading efficiency depending on its origin. Another goal of this research was to verify the C classes appointed by machine strength grading, in view of the actual mechanical properties of timber from different log types, measured with a destructive method.

2. Experimental Tests

2.1. Material

Tests were conducted on a batch of Scots pine (*Pinus sylvestris* L.), including 510 pieces obtained from a middle-sized sawmill in Poland in the Mazovian Region. The timber was acquired from raw wood that was approximately 120 years old, from logs classified as C quality classes [35]. Roundwood came from trees growing in fresh mixed and moist-mixed forest, from the soils typical of Polish pine forests: post-glacial, mostly sands and clays (technical quality of forest 2).

The timber pieces were sawn from logs of 3 different types: butt, middle and top, with exactly 170 pieces in each group. Tree trunks were cut into 3 logs, each 3.5 m long: first, 1 m adjacent to the ground was cut off to remove root deformations. Later, the butt log was obtained. A section for small samples, 0.5 m long, was cut between the butt log and the middle log. Later, the middle log was cut. The top log was obtained as follows: the diameter of d = 14 cm was found in the top part of the trunk (diameter on the thinner end, according to [36]) and 3.5 m was measured from that point (Figure 1).

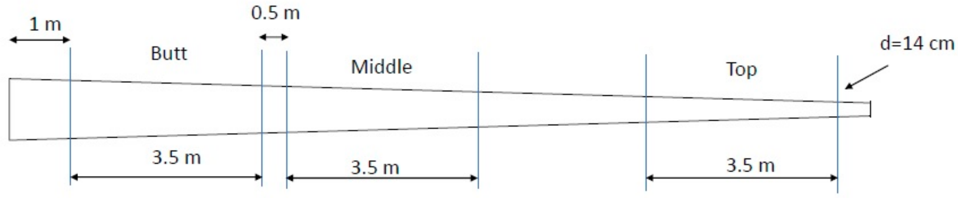

Figure 1. Diagram presenting divisions of the trunk into logs.

The sawn timber was kiln-dried to an average final moisture content of 12% (+/−1.7%). After drying, timber was machined to the final dimensions of 40 × 138 × 3500 mm.

2.2. Methods

2.2.1. 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 used a contact accelerometer to measure the natural frequency of longitudinal vibration after a short impact. Together with length and density (determined by the stereometric method), the dynamic modulus of elasticity was calculated according to Equation (1) [15].

$$MOE\ dyn = \rho(2lf)^2 \quad (1)$$

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).

In the first stage of the study, timber was machine strength graded into C classes [37] using the machine stress grading method with an MTG device with balance.

2.2.2. Destructive Tests of Timber

The destructive tests included: determination of the modulus of elasticity for timber during static bending (MOE) and determination of static bending strength (MOR) [38]. Four-point bending tests (Figure 2) were conducted with the use of a 10-tonne strength test machine-TIRA Test 2300 (TIRA GmbH, Schalkau, Germany). The tests were performed with displacement control. The speed of the load head was 3 mm/min. The weakest section of each piece was determined by visual inspection [39] and placed in the mid-test span. During the test, load and displacement were registered.

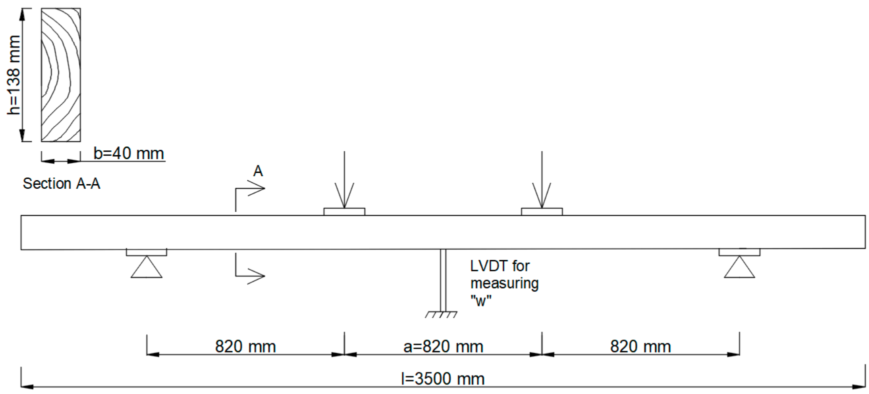

Figure 2. Static diagram of a four-point structural timber bending test to determine MOE and MOR, where LVDT—linear variable differential transformer, w—deflection.

Later, a sample was taken from the rupture area to test its density with a gravimetric method [36] and moisture [40]. Finally, according to the guidelines of [41], moisture content adjustment was carried out for density and MOE, and size adjustment for bending strength.

2.3. Statistical Analysis

The results were analyzed using the program STATISTICA 13.3 PL (TIBCO Software Inc., Palo Alto, CA, USA), descriptive statistics. The data was analyzed and provided as the mean ± standard deviation. Then, the two-factor variance analysis ANOVA was performed for the physical and mechanical properties of Scots pine, depending on type of log (butt, middle, top) and strength class C (C40, C35, C30, C24, C18, Reject). All the tests were carried out for a significance level of $p < 0.05$.

3. Results and Discussion

Table 1 shows the characteristics of timber, taking into account its log type of origin, classified to C classes by machine strength grading. There were a few pieces that could not be machine strength graded, as the MTG device displayed the "Error" message. These pieces were not taken into account in further analysis.

Table 1. Average values of physical and mechanical parameters (standard deviation is given in parentheses), percentage of fulfillment of the EN 338 values are given in square brackets, DEN—density, MOE—modulus of elasticity, MOE dyn—dynamic modulus of elasticity, MOR—bending strength.

Class	Log Type	N		DEN	MOE	MOE_dyn	MOR
		(-)		(kg/m^3)	(MPa)	(MPa)	(MPa)
All	B	170	510	583 (54)	14,063 (2851)	13,580 (2397) *	54 (19)
	M	170		537 (49)	12,309 (2327)	11,947 (1922) *	42 (14)
	T	170		504 (37)	10,493 (1893)	10,390 (1658) *	36 (12)
C40	B	23	29 {6%}	654 (52) [136%]	18,046 (1652) [136%]	17,561 (936)	72 (14) [180%]
	M	6		636 (25) [133%]	16,936 (512) [127%]	17,604 (483)	50 (15) [125%]
	T	0		-	-	-	-
C35	B	60	91 {18%}	611 (43) [130%]	15,472 (1089) [125%]	15,492 (947)	64 (14) [183%]
	M	28		584 (37) [124%]	14,701 (1351) [119%]	15,018 (1018)	50 (13) [143%]
	T	3		561 (26) [119%]	14,011 (678) [113%]	14,537 (206)	53 (3) [151%]
C30	B	46	130 {26%}	560 (52) [122%]	13,221 (998) [116%]	13,316 (896)	52 (14) [173%]
	M	55		525 (27) [114%]	12,841 (922) [113%]	13,261 (790)	47 (12) [157%]
	T	29		532 (35) [116%]	12,903 (1347) [113%]	12,996 (617)	47 (14) [157%]
C24	B	23	200 {40%}	506 (47) [120%]	10,706 (877) [102%]	10,994 (684)	41 (13) [171%]
	M	69		486 (34) [116%]	10,734 (1085) [103%]	10,972 (783)	39 (12) [163%]
	T	108		477 (34) [114%]	10,276 (1046) [98%]	10,847 (858)	36 (11) [150%]
C18	B	9	43 {8%}	479 (20) [126%]	8867 (1130) [104%]	8793 (543)	23 (5) [128%]
	M	10		452 (41) [119%]	8615 (886) [101%]	8900 (321)	26 (9) [144%]
	T	24		461 (32) [121%]	8219 (1271) [96%]	8914 (425)	28 (8) [156%]
Reject	B	1	9 {2%}	470 (-)	8072 (-)	6625 (-)	21 (-)
	M	2		458 (-)	7490 (-)	7790 (-)	21 (-)
	T	6		434 (19)	7036 (1010)	7478 (749)	30 (9)

* for 502 sawn timber elements, in curly brackets is the percentage of timber of a given class, determined using MTG.

Table 1 shows that, as a result of strength grading, most timber pieces were classified as medium quality (C24–39.2% of the tested batch, C30–25.5%), and the least as the highest strength class (C35–17.8%, C40–5.7%) and the lowest class (C18–8.4%, Reject–1.8%). Other studies of pine timber produced the following efficiency for each class: C40–0.5%, C35–5.8%, C30–16.7%, C24–36.8%, C18–22.7%, Reject–17.5% [42].

Considering log types (butt, middle, top), a larger share of high strength classes was obtained from butt logs, while top logs produced a higher share of lower strength classes. This is due to the fact that butt logs have fewer or no knots, which usually translates into better quality parameters of the timber obtained from them. On the other hand, typical top logs have large open knots, as well as high amounts of small knots which cause worse quality parameters of timber from those logs. In turn, the size and number of knots in the butt logs is the smallest in relation to other types of logs.

Density decreased from the butt log section to the top log section. The average density of timber sawn from butt logs was 583 kg/m^3, while the average density of timber made of top logs was 79 kg/m^3 lower. An analogous relation was observed for pine timber from Sweden. Density decreased within the trees of that study from butt to top, with the difference between the lowermost and the uppermost stem parts being approximately 57 kg/m^3 [43]. Repola (2006) noted an even larger difference, approximately 100 kg/m^3, between the butt and the top of Scots pine trees [44].

On the basis of the obtained results (Table 1 and Figure 3), it was concluded that lowest average density characterizes timber classified as Reject (439 kg/m^3), and highest density characterizes timber from class C40 (645 kg/m^3). Within each class from C18 to C40, the highest density was observed for timber from butt logs. The lowest density for individual strength classes (C) was observed for timber from either top logs (C24, C35) or middle logs (C18, C30). There were no C40 pieces sorted from top logs. The value of standard deviation from the average in case of timber density depended on its C class. There were large values of standard deviation from the average density observed in the highest class achieved by the timber (C40 for butt logs and middle logs, and C35 for top logs) and for the lowest strength class (Reject, C18).

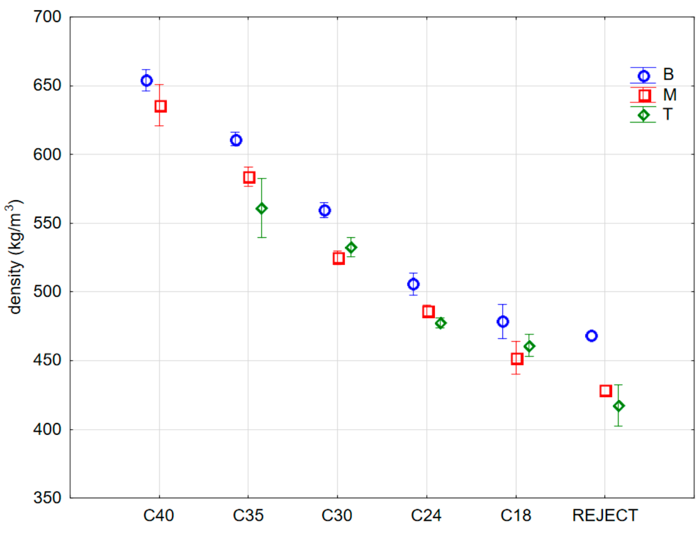

Figure 3. Density distribution within timber strength classes.

The ANOVA (Table 2) confirmed the impacts of strength class and type of log on density values. Density is one of the basic physical parameters of wood taken into account during the strength grading of timber with a machine method. The C strength classes were assigned on the basis of timber density, which had a direct impact on the value of the dynamic modulus of elasticity, which directly influenced the classification into C strength classes. Based on previous studies, the type of log [45,46] affects the density of wood in a significant way, which further impacts the strength class of timber.

Table 2. Values of ANOVA for density, MOE and MOR, depending on the type of log and assigned strength class.

Feature	Factor	SS	DF	MS	F	p
DEN	Type of log (1)	13,273.7	1	13,273.69	9.63965	0.002017 *
	Strength class (2)	387,189.8	4	96,797.44	70.29649	0.000000 *
	1 *2	7698.1	9	855.34	0.62117	0.779319 NS
	Error	660,954.4	480	1376.99	-	-
MOE	Type of log (1)	4,061,502	1	4,061,502	3.3307	0.068619 NS
	Strength class (2)	1,014,500,000	4	253,624,881	207.9879	0.000000 *
	1 *2	11,871,920	9	1,319,103	1.0817	0.374606 NS
	Error	586,541,600	480	1,219,421	-	-
MOR	Type of log (1)	708.70	1	708.699	4.78563	0.029177 *
	Strength class (2)	22,544.32	4	5636.079	38.05876	0.000000 *
	1 *2	3998.60	9	444.289	3.00015	0.001715 *
	Error	71,526.93	480	148.089	-	-

SS—the sum of squares; DF—degrees of freedom; MS—mean sum of squares; F—Fisher's F-test; *p*—significance level; *—significant at the 0.05 level; NS—not significant.

On the basis of Table 2 and Figure 4, it can be observed that the lowest average modulus of elasticity value was measured for timber classified as Reject (7252 MPa). The highest average value of modulus of elasticity was observed for timber in the C40 class (16,918 MPa). The ANOVA statistical analysis confirmed a significant influence of the strength class on the value of modulus of elasticity, while the log of origin of the timber turned out to be statistically insignificant ($p < 0.05$). Nonetheless, the reference literature contains publications that indicate a relation between MOE and log type. Mirski et al. [45] observed that the highest value of MOE for sawn timber (12,400 MPa) was measured for timber from a butt log, while the lowest value was measured for a timber piece sawn from a top log (9100 MPa). Similar relations were observed by Antony et al. [47].

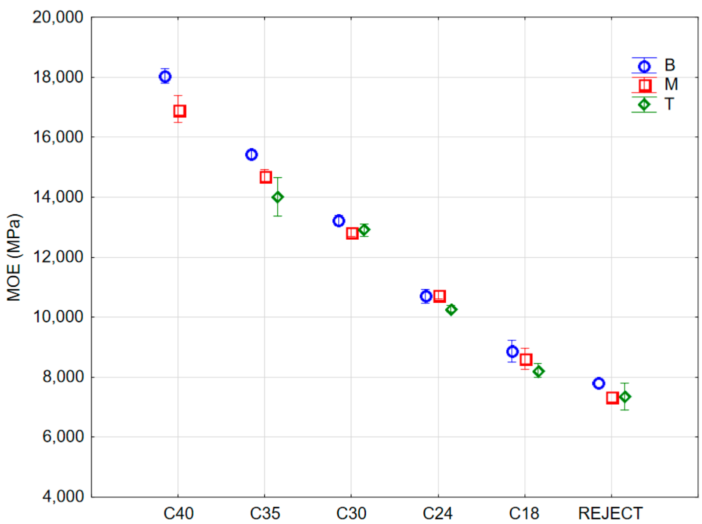

Figure 4. Modulus of elasticity distribution within timber strength classes.

Comparing the results of the static bending test (MOE) with the results of dynamic testing (MOE_dyn) presented in Table 1, it can be seen that MOE_dyn indicates higher values than static ones, which is also reported by other authors [48–52]. The relation between MOE and MOE_dyn was also studied by Bučar and Bučar [53]. The coefficient of determination R^2 between these two properties amounted to 0.84 and 0.82, depending on the tested timber batch. Krzosek [42] also studied this property and obtained a coefficient of determination R^2 equal to 0.85.

The value of standard deviation from the average in case of MOE depended on the timber's C class. Similarly, as in the case of density, there were high values of standard deviation from the average MOE observed in the highest class achieved by the timber (C40 for butt logs and middle logs, and C35 for top logs), and for the lowest strength class (Reject, C18).

On the basis of Figure 5 and Table 1, it can be observed that MOR decreased from the butt log section to the top log section. The average MOR value of timber sawn from butt logs was 55 MPa, while the average MOR of timber made of top logs was lower by 18 MPa. Furthermore, according to Šilinskas et al. [54], a higher vertical position in the tree had a negative effect on the MOE and MOR of Norwegian spruce timber. In maritime pine (*Pinus pinaster* Ait.), for instance, a decrease greater than 20% in MOR and MOE was observed between stem height levels of 35% and 65% [55]. In the case of spruce wood, the MOR values also depended on log type. Timber made of butt logs achieved an average MOR value of 56 MPa, while, for top logs, the average was 31 MPa [29]. There were no C40 pieces sorted from top logs. In the case of timber from each C class (except for C18), the highest MOR value was observed for timber from butt logs.

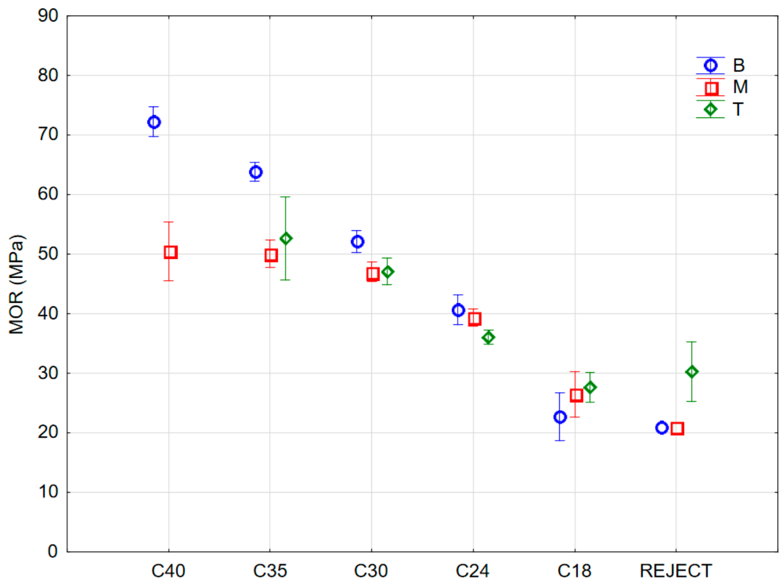

Figure 5. MOR distribution within timber strength classes.

In higher strength classes, the difference between the average MOR values of butt logs, as compared to middle and top logs, grows gradually bigger. The ANOVA (Table 2) confirmed the impact of strength class and type of log on the MOR values. MOR is a basic mechanical parameter that determines wood quality [16,34]. The process of machine strength grading takes into account individual physical and mechanical characteristics of wood, whose correlation with wood resistance is the highest.

Table 3 presents the values of determination coefficients between the given physical and mechanical properties of timber, determined on the basis of non-destructive and destructive tests.

Table 3. Determination coefficients between the individual physical and mechanical parameters.

Log Type	DEN/MOE	DEN/MOR	MOE/MOR	MOE/MOE_dyn	MOE_dyn/MOR
Butt	0.64	0.51	0.66	0.90	0.52
Middle	0.60	0.24	0.59	0.88	0.29
Top	0.47	0.17	0.65	0.84	0.32
All	0.71	0.51	0.71	0.91	0.50

The tested batch of timber had a coefficient of determination between density and MOE of 0.71, while the coefficient of determination between density and MOR amounted to 0.51. Another study of a different batch of pine timber [42] produced the values of coefficient of determination between density/MOE of 0.65, and between density/MOR of 0.52. The coefficient of determination of MOE/MOR for the tested batch of 510 timber pieces amounted to 0.71. In previous studies [42], the analogous coefficient of determination amounted to 0.69. Tests of German pine timber [21] resulted in a coefficient of determination between MOE and MOR of 0.50. A similar relation between MOE and MOR was observed by Steiger and Arnold [56]. Coefficients of determination R^2 between MOE and MOR up to 0.49–0.64 are reported in the literature [43,57].

Findings of Halabe et al. [58] were confirmed, who also noticed that the MOR values correlate better with the statically determined modulus than with the dynamic one. A similar conclusion was drawn by Krzosek [42] on the basis of his studies of pine wood. They stated that the main reason for this was that static bending was a direct measurement technique, whereas non-destructive testing (NDT) measurements were indirect. The correlation between MOE and MOE_dyn is very good, and the lowest obtained coefficient of determination is 0.84 (in case of all tested samples determination coefficient is 0.91). Similar results were obtained by Steiger and Arnold [56], where the R^2 between MOE and MOE_dyn amounted to 0.80 for spruce timber. These coefficients of determination are within the range reported by other researchers [14,59].

4. Conclusions

1. Actual values of density and MOE for the tested timber from butt and middle logs were higher than the minimum limit values resulting from the C strength classes into which the timber pieces were sorted during machine strength grading.
2. The higher the C class of the sawn timber from the bottom and middle logs, the higher the percentage of fulfillment of required values according to EN 338.
3. The highest values of the coefficient of determination were obtained from timber from butt logs.
4. The lowest mechanical properties were obtained from sawn timber made of top logs.
5. The greater efficiency of higher strength classes C was obtained for sawn timber originating from butt logs compared to middle logs. The share of sawn timber of higher strength classes was the lowest for sawn timber made of top logs.

Author Contributions: Conceptualization, I.B.-K. and S.K.; methodology, I.B.-K., P.M. and S.K.; software, I.B.-K. and P.M.; validation, I.B.-K. and S.K.; formal analysis, I.B.-K., P.M. and S.K.; investigation, I.B.-K., P.M. and S.K.; resources, I.B.-K., P.M. and S.K.; data curation, I.B.-K., P.M. and S.K.; writing—original draft preparation, I.B.-K., P.M. and S.K.; writing—review and editing, I.B.-K.; visualization, I.B.-K.; supervision, S.K.; project administration, I.B.-K. and S.K.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the support of the National Centre for Research and Development, Poland, under "Environment, agriculture and forestry"–BIOSTRATEG strategic R&D program, Agreement No. BIOSTRATEG3/344303/14/NCBR/2018.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Marek Grześkiewicz (Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences, SGGW) for his help with the calculations of the dynamic modulus of elasticity for the timber.

Conflicts of Interest: The authors declare no conflict of interest.

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