Factors and Models for the Bending Properties of Sawn Timber from Finland and North-Western Russia. Part II: Scots Pine

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Abstract

The aim of the study was to increase knowledge on differences in mechanical properties of Scots pine sawn timber from selected log procurement areas in Finland and north-western Russia and to study the prediction of bending strength and modulus of elasticity, which are important properties in the construction uses of sawn timber. Support to the optimal sourcing of roundwood for structural products of sawmills as well as for the development of manufacturing value added products by improving sorting and grading of logs and sawn timber was targeted for, the sorting being based either on log measurements or log and sawn timber measurements together. The study was a continuation to the corresponding study of Norway spruce.

Pine logs and centre yield sawn pieces (N = 934) were collected from five geographic growing regions, three from Finland and two from Russia. The levels and statistically significant differences in local longitudinal modulus of elasticity (E_{12}) and bending strength ($f_{m,12}$) of sawn timber were determined, along with several physical characteristics of sawn timber and logs. Multiple linear regression models were calculated to predict E_{12} and $f_{m,12}$ using sawn timber and log properties as predictors, and it was analysed if any regional differences remained thereafter.

Generally, the levels of $f_{m,12}$ were much higher in Finland than in Russia, being highest in northern Finland and lowest in Novgorod region, albeit the large within-region variations. For E_{12}, the variations between the regions were somewhat smaller, but more fertile growing conditions seemed to provide sawn timber with lower E_{12}. Air-dry density, knot area ratio (KAR) and annual ring width (RW) were the best predictors for E_{12}, and E_{12}, KAR and RW for $f_{m,12}$. If only log properties, only sawn timber properties or log and sawn timber properties together were considered, 60%, 76% or 77% of the variation in $f_{m,12}$ could be accounted. Generally, higher coefficients of determination were reached for pine in this study than for spruce in the previous study. Compared with the earlier studies on Scots pine, the bending properties were somewhat lower, and the geographic variation was more obvious, more systematic and larger.

Key words: Bending strength, model, modulus of elasticity, multiple linear regression, *Pinus sylvestris*, sawn timber

Introduction

Bending strength and longitudinal modulus of elasticity, later referred as MOE, are the two main raw material factors affecting the use of timber in construction, because they affect strongly the static, long term strain properties in wooden structures (Bodig and Jayne 1982, Winandy and Rowell 1984, Glos 1995). Strength of wood describes the load bearing capacity of a structure without breaking, while modulus of elasticity is the ability of a structure to maintain its form under stress. There is a strong positive correlation between strength and MOE, so it is worthwhile to use MOE to estimate strength, because the ultimate strength is hard to determine without breaking the test piece (Kollman and Coté 1968, Zobel and van Buijtenen 1989, Bodig and Jayne 1992).

For softwood species, bending strength and MOE correlate with the basic wood properties that are more easily measured, such as density, annual ring width and proportion of latewood. Increase in the proportion of latewood correlates positively with density for softwoods, whereas an increase in ring width correlates negatively with density, and therefore affects negatively the level of strength and MOE (Zobel and van Buijtenen 1989, Kärkkäinen 2007). These correlations are found to be somewhat weaker for MOE than for strength (e.g. Bodig and Jayne 1982). Before-mentioned basic wood properties are fairly easily measurable or readily available, but as with all indirect methods for predicting strength, uncertainty always remains (Glos 1995, Ranta-Maunus et al 2001).

The levels of strength and MOE are widely studied for different tree species, but there is a large variation in the properties according to different studies (e.g. Wood Handbook 1999, Diebold et al. 2000, Ranta-Maunus 2009, Nocetti et al. 2010, Ranta-Maunus et al. 2011). The differences of clear wood specimens in strength and stiffness are caused mainly by variation in density, which is affected, for example, by growth rate and irregularities of wood, as well as by the characteristics of the testing methods (e.g. Isaksson 1999, Bowyer et al. 2007). Most studies have concentrated on testing of and modelling for small clear test specimens. This approach does not take knots, slope of grain or mechanical defects of wood into consideration, hence, the strength of sawn timber in construction use can be substantially lower (e.g. Doyle and Markwardt 1966, Zhou and Smith 1991, Flæte et al. 2001, Saranpää and Repola 2001). Strength decreasing defects of sawn timber as well as the size effects (e.g. Bohannan 1966, Barrett et al. 1992, Isaksson 1999) are accounted for in structural design and in visual strength grading by large safety margins, which can result in inefficient utilization of strength properties (Bodig and Jayne 1982, Johansson et al. 1992, Boström 1994, 1999, Ranta-Maunus et al. 2001). Finally, morphological, physical and mechanical properties of the material combined with the environmental conditions like moisture content and temperature, chemical treatment and time dependent effects ultimately form the actual performance of the wooden structure over time (e.g. Bodig and Jayne 1982, Meyer and Kellogg 1984, Hoffmeyer 1990, Blass et al. 1995).

The levels of different strength properties, MOE and density as affecting factors have been studied early for the clear wood of Finnish softwoods by Jalava (1945) and Siimes and Liiri (1952). More widely speaking, Hudson (1967) studied the density, MOE and strength properties of clear wood specimens from pine and spruce sawn timber imported to UK from European boreal and temperate countries, including Finland and northern parts of the Soviet Union. Verkasalo (1992) studied the effects of selected anatomical and physical characteristics of wood on the MOE of southern Finnish pine in bending. Verkasalo and Leban (2002) studied and modelled bending strength and MOE of Finnish pine and spruce and French pine, spruce and fir based on simple physical characteristics of wood related to site, geographic origin and tree dimensions. Regarding tree species composition in a stand, Saranpää and Repola (2001) studied the bending strength of spruce from monocultures and mixed stands of spruce and birch in Finland and Sweden. Regarding thinning wood, Stöd and Verkasalo (2008) studied and modelled modulus of elasticity and strength in bending and compression of Scots pine in southern Finland, and Kask and Pikk (2009) in Estonia, considering also the effects of site type and tree age. Aleinikovas and Grigaliunas (2006) and Aleinikovas (2007) studied the pine wood mechanical properties in relation to forest site type and diameter growth in Lithuania. Chuchala et al. (2013) studied the importance of density and the related mechanical behaviour of pine wood for cutting forces in four regions in Poland.

Fewer studies are available on the strength or MOE of full size sawn timber than clear wood. Less results are available on Scots pine than Norway spruce, as well, because pine is not so well known and commonly used as a construction material as spruce (e.g. Virtanen 2005). In Finland, Lindgren (1997) made the first study on the bending properties of sawn timber, for pine in one geographic region and spruce in three geographic regions, the pieces being machine-graded for strength, measured for morphological and physical properties and tested for ultimate strength and MOE destructively. The strength was predicted using single and multiple linear regression models.

Boren studied (2001) the bending and compression strength and stiffness of pith enclosed round and sawn timber of pine and spruce from thinning stands in southern Finland, and Stöd and Verkasalo (2008) studied and modelled the bending strength and MOE and strength grade distributions of pine sawn timber from thinning stands with final cutting stands as the reference. In these studies, accurate measurements of trees, logs, and wood were combined with destructive results of the mechanical properties.

Ranta-Maunus et al. (2001) presented results on the levels of strength and MOE for pine and spruce sawn timber in Finland and Sweden. Ranta-Maunus (2009) and Ranta-Maunus et al. (2011) presented wide ranges of results on strength and MOE, compiled from the datasets of Pan-European research projects on strength grading during 2000's. Lindström et al. (2009) studied the MOE of approximately 60 to 65 cm specimens of Scots pine from mature stands in Finland and Sweden both with the natural defects and after cutting them off, and the potential of acoustic measurements and dynamic MOE of trees or logs for the estimation of actual MOE of sawn timber billets.

Hanhijärvi et al. (2005) studied the potential of different non-destructive measurements in predicting bending strength and MOE for sawn pieces from sawmills in south-eastern Finland using single and multiple linear regression analysis. As it could be expected, MOE was the best single predictor for strength in the different methods providing R^2 values of 0.7–0.8 for pine and 0.5–0.6 for spruce. The best results were achieved by combining stiffness parameters with knot or density measurements. Good results were also obtained from log measurements using X-ray and acoustic frequency methods. Hanhijärvi and Ranta-Maunus (2008) reached parallel results in their further study on a larger sample with wide geographic represent ability in Europe (see before). Baltrusaitis and Aleinikovas (2012) studied recently the potential of predicting and modelling strength properties of Scots in Lithuania using two commercially available non-destructive methods, as well.

The strength and stiffness properties of Russian timber have been studied little, and published rarely in English, albeit the extensive use of Russian logs in Finland and Baltic countries since the early 2000's (e.g. Viitanen and Karvinen 2010, Hautamäki et al. 2012). Some results on East-European pine and spruce sawn timber were presented in the before-mentioned Pan-European projects by Ranta-Maunus (2009), Stapel and Denzler (2010) and Ranta-Maunus et al. (2011).

Despite the recent development work, there is a further need for cost-efficient, end-user oriented grading of sawn timber for strength, where, on one hand, the best grades meeting the highest construction requirements can be detected with high yield, and, on the other hand, the reject grades can be eliminated efficiently for high homogeneity of deliveries. All the possibilities of using log and sawn timber measurements and models based on appropriate variables should be considered. Early control of natural strength variation in wood, proper sourcing of logs based on the strength and optimization of the entire production chain of sawn timber would also increase the competitive ability of wood against other materials.

The objective of this study was to examine the variation in and predictability of bending strength and modulus of elasticity of Scots pine centre yield sawn pieces from selected log procurement regions in Finland and north-western Russia. The aim was to find out how accurately ultimate bending strength and local modulus of elasticity could be predicted from measurable external characteristics of logs and/or properties of sawn pieces using linear regression modelling procedure. Simultaneously, it was analysed whether any regional differences remained thereafter. This paper is a continuation to the corresponding study on Norway spruce, which was published before by Hautamäki et al. (2013). Therefore, the results on Scots pine are discussed here in relation to Norway spruce, as well.

Materials and Methods

Data and measurements

The data consisted of Scots pine logs and sawn timber from the operations of three sawmills and their respective wood procurement regions in Finland, Lappeenranta for south-eastern Finland, Merikarvia for western Finland and Iisalmi for northern Finland, and two regions in north-western Russia, The Republic of Karelia representing southern and fertile growing conditions and Vologda area representing more continental and colder growing conditions. The geographic origin of the pine material was similar to that of spruce material in the previous study, except for the Novgorod region replacing Republic of Karelia in north-western Russia (Hautamäki et al. 2013, Figure 1).

The logs were sampled at the mills in connection of unloading the timber trucks or railway wagons among the log receipt and measurement operations. Five log diameter classes were defined as the basis for sampling (see Table 1) and the minimum log length of 5.2 meters was applied for practical reasons of sawing the test materials. The principle of random sampling was followed by sampling five logs at the maximum from each load and without any quality assessment.

Before sawing the logs, they were cut into 4.5 m length and several features were measured physically or evaluated visually from them. Disc specimens were cut from both ends for the measurement of ring width, proportion of latewood and proportion of heartwood. Measurements were made in laboratory using binocular microscope equipped with video camera and a sliding table to which the disc was attached. Diameter of the largest knot, the largest dry knot, and the largest sound knot were also measured from each log. Descriptive data on the features of logs and wood are shown in detail in Hautamäki et al. (2010).

After the logs were measured and sawn, one centre-yield piece was chosen per log for the studies, the pieces being cut opposite to those for assessing visual strength and appearance grade by Hautamäki et al. (2010). The number of logs and the number of sawn pieces in the respective dimension class that underwent all phases of measurements in this study, after omitting the mechanically damaged pieces from the strength tests (see Hanhijärvi and Ranta-Maunus 2008) and picking some pieces to parallel tension, shear and compression strength tests (Poussa et al. 2007), are shown by species and region in Table 1. In total, 934 sawn pieces from the 1069 pieces in the original material could be used in this study.

The destructive measurements of ultimate bending strength ($f_{m,12}$) and modulus of elasticity (E_{12}) were performed on the sawn pieces at the Technical Research Centre of Finland (VTT) according to EN 408 standard (CEN 2003). Modulus of elasticity was determined by two ways: "locally" based on the deflection of the constant moment region between the presses, and "globally" based on the deflection of the whole span; the variable used in this study was local MOE. The density of each piece was measured on small slices

Table 1. Number of logs by diameter class and number of sawn pieces by respective dimension class, by region

Region	Diameter class of the log with bark, min top diameter, mm					
	160	175	210	280	310	
	Dimension of the sawn piece, mm					
	38*100	50*100	50*150	63*200	44*200	Total
South-eastern Finland	41	43	39	31	26	180
Western Finland	44	41	41	32	24	182
Northern Finland	41	42	40	38	32	193
Novgorod, Russia	38	43	39	40	27	187
Vologda, Russia	41	42	35	42	32	192
	205	211	194	183	141	**934**

cut from the neighbourhood of the failure location, at approximately 12% moisture content.

All natural and technical wood defects were measured of each piece before testing, knot area ratio, later referred to as KAR, being calculated based on the knot measurements (see Hanhijärvi and Ranta-Maunus 2008). After the failure, knot pattern of the broken cross-section was recorded by drawing on mm-paper. KAR was chosen to represent the knot variables because it combines the effect of individual knots and because the quality of the knots does not have a strong influence on either strength or modulus of elasticity.

Statistical Methods

Multiple linear regression and general linear model procedures of PASW Statistics program version 17.0 were used for modelling ultimate bending strength and local MOE because of their generally good fit in describing the relationships between mechanical properties of wood and timber. All the categorical factors were assumed fixed.

The levels of strength, local MOE, KAR and density were examined by region, and one-way ANOVA procedure was used to detect the possible differences between geographic regions in these properties. If variances between groups were unequal, Welch and Brown-Forsythe tests for the equality of means were used. Post-hoc-tests were used to find out where the differences between regions appeared.

Tables of correlation were generated between the studied variables to get an overall picture of the interrelations between them and to choose the explanatory variables for the models. The explanatory variables were hand-picked and the combinations with the highest coefficient of determination (R^2) and statistical significance (p-value $d \leq 0.05$) were chosen to the final models.

The presumptions of linear regression were checked through graphical examination (scatter plots), and the residuals were examined for normality and homoscedasticity. For simple linear regression models, logarithmic transformations were made to some variables to improve the linearity of the dependence between independent and dependent variables. For multiple regressions, multicollinearity of the potential explanatory variables was examined through variance inflation factor, tolerance and collinearity diagnostics of PASW Statistics program.

First, simple linear regression models were calculated for the single explanatory variables, then combinations of MOE, KAR, ring width and density were used to explain strength, and KAR, ring width and density to explain MOE. Then models using only visible log variables were used to generate multiple regression models. In addition, models using sawn timber properties and all possible explanatory variables were calculated to find the best possible combination of predictors. The performance of the models was evaluated based on their coefficients of determination (R^2) and root mean square errors ($RMSE$).

Results

Mechanical and physical properties by region

Both for the strength ($f_{m,12}$), local MOE (E_{12}) and density (ρ_{12}), sawn pieces from northern Finland had the highest values followed by western and south-eastern Finland, albeit none of the within-country differences were significant. Sawn timber from Novgorod had the lowest average values along with Vologda, and the differences between Russia and Finland were significant (Table 2).

The amount and size of knots were highly variable of the strength determining factors. When geographic areas were compared for the KAR, sawn timber from northern Finland had significantly smaller knottiness than that from Novgorod, where the KAR value was largest. South-eastern and western Finland had almost equal values and they differed significantly from Russian areas and also at the 5% level of confidence from northern Finland (Table 2).

Models for sawn timber

Strength

For the strength, the explanatory power of each independent variable is presented in Table 3.

Table 2. Means and standard deviations of variables measured from logs and sawn pieces by region

Property		South-eastern Finland		Western Finland		Northern Finland		Novgorod		Vologda	
	N	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
$f_{m,12}$ (MPa)	933	42.8	12.1	43.8	12.1	46.6	13.9	31.8	11.2	34.0	11.2
E_{12} (GPa)	933	11.8	2.5	11.8	2.3	12.1	2.3	10.0	2.2	10.0	2.1
ρ_{12} (kg/m^3)	933	481.6	52.9	491.6	56.7	495.4	55.1	439.7	44.0	435.5	46.1
KAR	909	0.21	0.12	0.21	0.14	0.17	0.10	0.29	0.12	0.24	0.12
Ring width (sawn piece, mm)	890	2.0	0.7	1.9	0.7	1.6	0.5	2.6	0.7	2.6	0.8
Latewood % (sawn piece)	890	28.5	3.9	23.6	3.9	36.1	4.5	21.8	3.6	24.6	6.5
Ring width (log, mm)	1050	1.7	0.5	1.6	0.4	1.3	0.3	1.8	0.4	1.9	0.5
Latewood % (log)	1050	29.3	3.7	25.4	3.5	36.5	4.6	24.2	3.3	28.4	6.2
Heartwood %	1090	57.1	9.9	59.0	9.0	62.3	10.7	68.9	7.8	65.3	8.2
Largest dry knot (mm)	1107	20.1	13.8	21.6	13.6	18.6	12.2	31.1	14.7	24.8	13.4
Largest knot (mm)	1107	24.1	16.5	25.2	17.0	22.2	16.2	33.5	16.5	26.0	14.2
Taper (cm/m)	1107	1.3	0.8	1.6	1.2	1.6	0.7	1.1	0.5	1.1	0.5
Number of year rings	1050	74.6	25.2	85.1	27.3	101.1	22.2	69.8	16.4	80.4	27.1

Local MOE had the best explanatory power with 63% of the variation in strength explained, while density, KAR and ring width of the sawn piece each explained 41–47%. Ring width of the log explained 30% of the variation and the proportion of latewood 22%. The explanatory power of knots was rather high, since 40–44% of the variation in strength was explained using diameter of the largest knot or the largest dry knot as explanatory variables. Number of year rings explained 18% of the variation, while taper and proportion of heartwood explained both less than 10%.

When modelling strength using categorical explanatory variables, geographic area explained approximately 19% of the variation. Quality of the log and the log type explained 15–18% of the variation and showed the significant difference between butt logs and upper logs in strength. The dimension of the sawn piece explained only 1% of the variation (Table 4).

A combination of MOE and ring width explained 68% of the variation in strength, compared with 67% added still with KAR. Combinations of density, KAR and ring width explained 52–57% of the variation (Table 5).

Table 3. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where continuous explanatory variables are used to predict bending strength

	Estimate (S.E)	Estimate (S.E)	R^2	*RMSE*
	Intercept	B		
Strength, MPa (Sawn piece properties)				
E_{12} (GPa)	-8.91 (1.24)	0.004 (0.00)	0.63	8.20
$\log_{10}$ ring width (mm)	57.43 (0.71)	-58.67 (2.1)	0.47	9.80
$\log_{10}\rho_{12}$ (kg/m^3)	-416.52 (17.38)	171.04 (6.52)	0.43	10.20
KAR	55.57 (0.72)	-70.36 (2.79)	0.41	10.40
Latewood %	15.04 (1.59)	0.91 (0.06)	0.22	11.90
Strength, MPa (Log properties)				
Largest dry knot (mm)	55.27 (0.66)	-0.64 (0.02)	0.44	10.10
Largest knot (mm)	53.97 (0.67)	-0.52 (0.02)	0.40	10.40
$\log_{10}$ ring width (mm)	51.03 (0.7)	-57.92 (3.0)	0.30	11.30
Latewood %	11.29 (1.84)	1.00 (0.06)	0.22	12.00
Number of year rings	22.9 (1.27)	0.212 (0.02)	0.18	12.30
Heartwood %	62.90 (2.64)	-0.37 (0.04)	0.08	12.90
Taper (cm/m)	33.61 (0.87)	4.95 (0.61)	0.07	13.00

All parameters were significant at 1% confidence level

Table 4. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where single categorical explanatory variables are used to predict bending strength

Strength, MPa	Estimate (S.E)	R^2	*RMSE*
Region			
Intercept	33.94 (0.88)	0.19	12.10
South-eastern Finland	8.86 (1.26)		
Western Finland	9.82 (1.26)		
Northern Finland	12.64 (1.25)		
Novgorod (* *p*-value 0.083)	-2.17 (1.25)		
Vologda	Reference group		
Butt log vs. upper log			
Intercept	46.04 (0.63)	0.15	12.90
Upper log	-10.69 (0.86)		
Butt log	Reference group		
Quality of log			
Intercept	35.36 (0.52)	0.18	12.20
High quality butt log	16.85 (1.31)		
Lower quality butt log	8.42 (0.89)		
Lower quality upper log	Reference group		
Dimension of sawn piece			
Intercept	36.76 (1.13)	0.01	13.40
38*100 mm	4.25 (1.46)		
50*100 mm	3.85 (1.47)		
50*150 mm (* *p*-value 0.067)	2.72 (1.49)		
63*200 mm (* *p*-value 0.038)	3.13 (1.51)		
44*200 mm	Reference group		

All parameters were significant at 1% confidence level, except for those marked with *

Table 5. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where MOE, density, KAR and ring width of the sawn piece are used to predict bending strength

Strength, MPa	**ρ_{12}+KAR**	**KAR+ring width**	**E_{12} +KAR**
R^2	0.52	0.57	0.68
RMSE	9.33	8.95	7.92
Intercept	4.46 (3.56)*	66.98 (0.91)	3.876 (2.1)**
E_{12} (GPa)			0.004 (0.00)
ρ_{12} (kg/m³)	0.1 (0.01)		
KAR	-44.54 (3.07)	-44.92 (2.85)	-21.57 (2.87)
Ring width (sawn piece, mm)		-8.03 (0.46)	

Strength, MPa	**ρ_{12}+ring width**	**E_{12}+ring width**
R^2	0.55	0.68
RMSE	9.12	7.70
Intercept	12.59 (3.69)	11.72 (2.20)
E_{12} (N/mm²)		0.003 (0.00)
ρ_{12} (kg/m³)	0.09 (0.01)	
KAR		
Ring width (sawn piece, mm)	-7.69 (0.48)	-4.74 (0.43)

All parameters were significant at 1% confidence level, except for those marked with * (*p*-value 0.210) and with ** (*p*-value 0.66)

If only log properties were used as explanatory variables, 60% of the variation in strength was explained with ring width of the log, proportion of latewood, proportion of heartwood, diameter of the largest dry knot and geographic region. When MOE, KAR, ring width of sawn piece and the dimension of the sawn piece were used as predictors, 76% of the variation was explained. The best model was reached when MOE, KAR, ring width of the log, proportion of heartwood, diameter of the largest dry knot and diameter of the sawn piece were used as explanatory variables, resulting in the explanatory power of 77% (Table 6).

MOE

For the local MOE, the explanatory power of each independent variable is presented in Table 16. Density was the best single predictor explaining 58% of the variation in MOE. KAR and diameter of the largest knot or largest dry knot were also good predictors explaining 45% and 38–40% of the variation, respectively. Ring width of the sawn piece had a better explanatory power than ring width of the log (39% and 23%). Proportion of latewood explained 25–26% of the variation, while number of year rings explained 26%. Log taper explained 10% of the variation, but proportion of heartwood only 1% (Table 7).

Geographic region explained 14% of the variation in MOE, while quality of the log explained approximately 24%. Log type (butt logs versus upper logs) explained 18% of the variation, while dimension of the sawn piece explained only 4% (Table 8).

Table 6. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where log properties, sawn timber properties and all explanatory variables are used to predict bending strength

Strength, MPa	**Log properties**	**Sawn timber properties**	**Log and sawn timber properties**
	Estimate (S.E.)	**Estimate (S.E.)**	**Estimate (S.E.)**
R^2	0.60	0.76	0.77
RMSE	8.62	6.71	6.57
Intercept	65.14 (3.79)	12,184	28.68 (3.58)
E_{12} (GPa)		0.003 (0.00)	2.84 (0.14)
KAR		-35.08 (2.83)	-28.88 (3.00)
Ring width (sawn piece, mm)		-2.25 (0.41)	
Ring width (log, mm)	-8.74 (0.76)		-3.88 (0.64)
Latewood % (log)	0.38 (0.08)		
Heartwood %	-0.23 (0.04)		-0.16 (0.03)
Largest dry knot (mm)	-0.33 (0.03)		-0.09 (0.02)
South-eastern Finland	3.70 (1.06)		
Western Finland	5.62 (0.98)		
Novgorod (**p*-value 0.108)	1.50 (0.93)		
Northern Finland (* *p*-value 0.931)	-0.10 (1.16)		
Vologda	Reference group		
Upper log	-3.41 (0.75)		
Butt log	Reference group		
Dimension of sawn piece			
38*100 mm		10.42 (0.86)	6.92 (1.01)
50*100 mm		10.47 (0.81)	7.47 (0.91)
50*150 mm		6.02 (0.81)	4.56 (0.83)
63*200 mm		2.69 (0.78)	2.28 (0.77)
44*200 mm	Reference group		

All parameters were significant at 1% confidence level except for those marked with *

When KAR, density and ring width of the sawn piece were used as explanatory variables, 57–65% of the variation in MOE was explained. Density combined with KAR or ring width resulted in explaining 65% and 62% of the variation, respectively, but KAR and ring width alone resulted in nearly as high an explanatory power, 57% (Table 9).

If only log properties were used as predictors, 58% of the variation in MOE was explained using ring width of the log, proportion of latewood, proportion of heartwood and diameter of the largest dry knot as continuous variables, and geographic region and diameter class of the log as categorical variables. Sawn timber properties, such as density, KAR, ring width of the sawn piece and diameter of the sawn piece, explained 68 % of the variation. The model with the highest explanatory power (69%) was reached when density, KAR, ring width of the log and diameter of the largest dry knot were used as explanatory variables (Table 10).

Table 7. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where continuous explanatory variables are used to predict local MOE

	Estimate (S.E)	Estimate (S.E)	R^2	*RMSE*
	Intercept	β		
Local MOE, GPa (Sawn piece properties)				
$\log_{10} \rho_{12}$ (kg/m³)	-85.48 (2.72)	36.21 (1.02)	0.58	1.60
KAR	14.12 (0.13)	-13.32 (0.49)	0.45	1.83
$\log_{10}$ ring width (mm)	14.04 (0.14)	-9.71 (0.41)	0.39	1.92
Latewood %	6.27 (0.28)	0.18 (0.01)	0.26	2.11
Local MOE, GPa (Log properties)				
Largest knot (mm)	13.71 (0.12)	-0.10 (0.004)	0.40	1.90
Largest dry knot (mm)	13.74 (0.13)	-0.11 (0.005)	0.38	1.90
Number of year rings	7.46 (0.22)	0.05 (0.003)	0.26	2.10
Latewood %	5.62 (0.33)	0.19 (0.01)	0.25	2.10
Ring width (mm)	15.05 (0.26)	-2.41 (0.15)	0.23	2.16
Taper (cm/m)	9.80 (0.15)	1.06 (0.10)	0.10	2.30
Heartwood %	12.91 (0.50)	-0.03 (0.01)	0.01	2.40

All parameters were significant at 1% confidence level

Table 8. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where single categorical explanatory variables are used to predict local MOE

Local MOE, GPa	Estimate (S.E)	R^2	*RMSE*
Region			
Intercept	10.05 (0.16)	0.14	2.28
South-eastern Finland	1.71 (0.24)		
Western Finland	1.71 (0.24)		
Northern Finland	2.05 (0.23)		
Novgorod (**p*-value 0.792)	-0.06 (0.23)		
Vologda	Reference group		
Butt log vs. upper log			
Intercept	12.36 (0.11)	0.18	2.20
Upper log	-2.11 (0.15)		
Butt log	Reference group		
Quality of log			
Intercept	10.26 (0.09)	0.24	2.10
High quality butt log	3.64 (0.23)		
Lower quality butt log	1.54 (0.16)		
Lower quality upper log	Reference group		
Dimension of sawn piece			
Intercept	11.58 (0.20)	0.04	2.90
38*100	-0.71 (0.26)		
50*100	-1.09 (0.26)		
50*150 (**p*-value 0.097)	-0.44 (0.27)		
63*200 (**p*-value 0.516)	0.18 (0.27)		
44*200	Reference group		

All parameteres were significant at 1% confidence level, except for those marked with *

Table 9. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where density, KAR and ring width of the sawn piece are used to predict local MOE

Local MOE, GPa	ρ_{12} +KAR	KAR+ring width	ρ_{12} +ring width
R^2	0.65	0.57	0.62
RMSE	1.46	1.64	1.51
Intercept	1.74 (0.56)	15.85 (0.17)	1.56 (0.61)*
ρ_{12} (kg/m³)	0.02 (0.001)		0.03 (0.001)
KAR	-7.07 (0.48)	-1.23 (0.08)	
Ring width (sawn piece, mm)		-9.39 (0.52)	-0.95 (0.08)

All parameters were significant at 1% confidence level, except those marked with * (*p*-value 0.011)

Table 10. Parameter estimates, coefficients of determination (R^2) and *RMSE* values of the models where log properties, sawn timber properties and all explanatory variables are used to predict local MOE

Local MOE, GPa	Log properties	Sawn timber properties	Log and sawn timber properties
R^2	0.58	0.68	0.69
RMSE	1.59	1.38	1.38
Intercept	13.65 (0.89)	3.70 (0.69)	5.08 (0.63)
ρ_{12} (kg/m³)		0.02 (0.001)	0.02 (0.001)
KAR		-6.42 (0.54)	-5.38 (0.51)
Ring width (sawn piece, mm)		-0.59 (0.09)	
Ring width (log, mm)	-1.62 (0.16)		-0.68 (0.11)
Latewood % (log)	0.13 (0.01)		
Heartwood %	-0.03 (0.01)		
Largest dry knot (mm)	-0.06 (0.01)		-0.03 (0.004)
South-eastern Finland	0.70 (0.20)		
Western Finland	1.12 (0.19)		
Northern Finland	0.70 (0.17)		
Novgorod	-0.74 (0.2)		
Vologda	Reference group		
Diam. class min 160 mm	-1.53 (0.21)		
Diam. class min 175 mm	-1.43 (0.20)		
Diam. class min 210 mm	-0.52 (0.19)		
Diam. class min 280 mm (**p*-value 0.321)	0.19 (0.19)		
Diam. class min 310 mm	Reference group		
Dimension of sawn piece			
38*100 mm		0.75 (0.18)	
50*100 mm (**p*-value 0.039)		0.35 (0.17)	
50*150 mm		0.68 (0.17)	
63*200 mm		0.55 (0.16)	
44*200 mm		Reference group	

All parameters were significant at 1% confidence level, except for those marked with *

Discussion

Data considerations

The study focused on modelling strength and MOE of sawn timber from the readily measurable properties of logs, sawn timber or both together, which could eventually be utilized in practical sawmill environment in sorting and grading of logs and sawn timber, and adding information on how well different properties and their combinations perform in predicting the respective mechanical properties. Moreover, the aim was to add information on the mechanical properties of Nordic and Russian pine to support optimal sourcing of logs for structural products of sawmills, in general. The aims were taken into account in the sampling of the log and sawn timber materials and in the consistent execution of their physical measurements, mechanical tests and visual evaluations. All works to collect and process the data was done by experienced research staff of the Finnish Forest Research Institute.

The aim to determine the overall levels of and variations in bending strength and MOE appeared in an attempt to even sampling of top diameter classes of logs and the corresponding sawn timber dimensions. This could be realized as it was planned in the three smallest diameter classes of logs, but the number of observations remained somewhat lower in the two largest diameter classes. The even sampling of the logs in the selected log diameter classes does not fully correspond with the actual diameter distributions at sawmills, where logs of smaller diameter are typically more frequent than logs of large diameter. In practice, the proportion of the largest log classes is rather small in saw milling in Finland (e.g. Virtanen 2005), but essentially larger in Russia (Viitanen and Karvinen 2010, Hautamäki et al. 2012).

The data used in this study was sufficiently large to represent the differences between growing conditions in Finland and north-western Russia and the results of different silvicultural practices in each country to the timber from mature final-felling stands. The sampling of the empirical materials was performed in connection of commercial log procurement operations, which limited the possibility for objective sampling and regional represent ability for the characteristics of the timber stands. However, the principle of random sampling was followed by limiting the number of logs from one load to maximize the spread of log sourcing and by paying no other attention to log properties except for the desired log diameters and minimum lengths.

Bending properties and geographic differences

Statistically significant differences in the mechanical properties were confirmed between geographic areas in this study on Scots pine, similarly to Norway spruce but with larger differences (Hautamäki et al. 2013). The levels of strength and MOE were clearly higher in the Finnish regions than in the Russian regions, and the between-region differences within the regions were less pronounced in each country.

In Finland, both strength and MOE were apparently higher in northern Finland compared to the regions of more fertile growing conditions, the differences being in line with the little higher density and clearly smaller knottiness; however, the differences were insignificant owing to the larger within-region variations. The high density and especially the high latewood percentage in northern Finland were rather unexpected results (comp. with Hudson 1967, Hakkila 1968, Björklund and Walfridsson 1993, Grekin and Verkasalo 2010); respectively, the small knottiness was well in line with the prevailing perceptions (Björklund and Moberg 1999, Verkasalo et al. 2007).

In Russia, the strength was apparently higher but MOE was the same in Vologda region compared with Novgorod region. In Vologda, despite the higher latewood percentage the density seemed little lower than in Novgorod, but the knottiness was clearly smaller. Knots appeared to affect strength more for pine than for spruce, compared to the effects of density and ring width (see Hautamäki et al. 2013). This can be attributed to the facts that the strength is affected more by local weak spots (e.g. knots) than MOE, and that the variation in the clear wood properties is larger for pine. KAR values appeared parallel with the assumed differences in growing conditions both in Finland and Russia (see Hautamäki et al. 2013). It should be noted that the growth of conifers in the boreal zone typically correlates with air temperatures of the growing season (Drobushev 2004, Lopatin et al. 2007).

The lower levels of mechanical properties in Russia and their generally large variations were most obviously due to the different growing conditions, silvicultural practices and uncontrolled composition of the logging stands in the data, regarding such factors as fertility and tree spacing. In the Russian data, thinnings did not obviously belong to the forest management practices. This could lead in the Russian logs to more frequent internal knots in comparable climatic and soil conditions than in the Finnish logs, the dry knots in particular. In addition, there is evidence for Nordic Scots pine that forest management aiming at tall, slender trees with high set crowns provides timber with higher MOE (Lindström et al. (2009)). The generally long rotation ages in Russia (Karvinen et al. 2006, Lopatin et al. 2007, Hautamäki et al. 2010) obviously lead to more frequent internal defects, such as heart checks and wetwood, compared to Finland where final felling is typically done at a lower age. Log bucking was not probably optimized for length or quality in Russia, which might lead to more inefficient utilization of tree quality than in Finland with highly developed bucking control in mechanized cutting (Karvinen et al. 2006). In Finland, the logs could be traced back to individual stands, while in Russia the procurement regions were larger, with the start point of railway transportation being the only information available on the source of logs.

The levels of bending strength and MOE were somewhat lower than in some previous studies for Scots pine (e.g. Lindgren 1997, Hanhijärvi et al. 2005, Ranta-Maunus 2009). This might be partly explained by the data from Finland eventually comprising more sawn timber from upper logs and younger thinning stands than in the reference studies (see also Stöd and Verkasalo 2008). However, comparative studies made according to the same measuring standards are scarcer for pine than for spruce.

Lindgren (1997) found for Scots pine sawn timber from south-western Finland the average bending strength and MOE of 51.4 MPa and 12.7 GPa, respectively, the variations in the properties being larger for pine than for spruce. Stöd and Verkasalo (2008) found a high bending strength and MOE for pine sawn timber from second thinnings in eastern Finland, 52.6 MPa and 12.8 GPa, the values being higher than for the timber from final cuttings, 46.3 MPa and 11.7 GPa, and also higher than in this study in south-eastern Finland. Instead, sawn timber from first thinnings showed a lower strength of 42.0 MPa, reaching however the level of south-eastern Finland, and an especially low MOE of 10.2 GPa, remaining at the level of Russian regions. Vertical location of log in a tree affected vitally the results, and the values of the timber from butt logs, omitting the logs from first thinnings, clearly exceeded those observed in this study. Also the timber from middle logs of second thinnings showed higher values than what we observed in any region of this study.

Ranta-Maunus (2009) studied the levels of and differences in bending properties of pine, among other softwood species, from several European countries based on existed results to define the borders of growth areas to be applied in machine strength grading. Consistent with this study, Russian timber provided weaker strength (33.5 MPa) than the other regions, of which Finland showed the highest values (almost 45 MPa) being slightly above France (44.4 MPa) and more clearly above Latvia (41.8 MPa) and Germany (37.6 MPa). For MOE, Russian timber showed again the lowest level (9.2 GPa) and France the highest level (12.5 GPa), followed closely by Latvia, Finland and Germany (1.18–12.2 GPa). Of the affecting factors, density varied largely between the regions from 438 kg/m^3 in Russia to 557 kg/m^3 in France, being as high as 510 kg/m^3 in Germany, 493 kg/m^3 in Finland but only 486 kg/m^3 in Latvia. KAR was as low as 0.19 in Finland and 0.25 in Russia and France. The European wide results were, again, more variable and more growth region dependent for pine than for spruce. – For ungraded populations, the coefficient of variance was larger in Nordic countries for pine (32%) than spruce (27%), whereas in Central Europe the between-species difference was slightly smaller. The results suggested that Nordic countries, Central Europe and Russia belong to different groups according to bending strength, concerning both pine and spruce. Moreover, the criterion of having 90% of observations within the confidence limits in a country cannot be met if the country has different growth conditions of timber. However, the criterion is easier to fulfil when representative samples of countries are combined than when sub-samples of different growth regions of the same countries are jointly analysed.

The results of Stapel and Denzler (2010) on Scots pine timber were very much parallel to those of Ranta-Maunus (2009) timber, showing a considerably lower bending strength in Poland than in Sweden with the difference of over 5 MPa, but an opposite difference of 1 GPa in MOE. The density was 521 kg/m^3 in Poland and 480 kg/m^3 in Sweden, whereas KAR was as low as 0.21 in Sweden and 0.26 in Poland.

Models of strength and MOE

Individual predictors

In this study, MOE provided the highest R^2 in predicting strength for pine, similarly to spruce (Hautamäki et al. 2013). Density was a better predictor for pine than for spruce, and knot parameters, such as KAR and diameters of the largest knots of the logs performed better, as well. Strikingly for the strength (but not for MOE), KAR, ring width of sawn piece and log and diameter of the largest dry knot of the log provided R^2 just as high as density. Similarly to spruce, approximately 10% more of the variation in the strength could be explained in the studies of Lindgren (1997) and Hanhijärvi et al. (2005), excluding the models where ring width was used as the predictor. Compared to the results of Ranta-Maunus (2009), the values of R^2 were approximately at the same or higher level.

Density was the best predictor of MOE for pine, similarly to spruce, but, again, knot parameters overcame ring width in the predictive ability. As in Hanhijärvi et al. (2005), density was a better predictor for MOE than for strength, since stiffness is generally more related to overall properties of wood, such as density. Comparative results of Hanhijärvi et al. (2005) and Hanhijärvi and Ranta-Maunus (2008) showed higher

R^2 when using density and ring width as predictors. However, in this study, KAR turned out to be a better predictor for MOE.

Geographic region alone was a significant but only a moderate predictor for strength and MOE, and its explanatory power was much larger for pine than for spruce (R^2 of 0.19 vs. 0.03). The between-species difference was obviously due to the larger between-region variation both in density and knot properties. In the prediction of MOE for pine, geographic region was a weaker predictor than log quality.

The stronger effects of knots on the bending properties of pine than of spruce appeared also in the predictions based on log type or log quality. Log diameter class or sawn timber dimension were generally poor predictors the standard errors of the coefficients being large. The smaller dimensions provided higher strength (but not MOE) than the reference dimension of 44 × 200 mm, with two of the smallest dimensions providing a higher level than the reference group.

The differences between pine and spruce in the critical properties and their predictive ability appeared rather clearly on the basis of this study. Generally, the variation in both log, wood and timber properties of pine was larger and their predictive ability was stronger. This was especially obvious for knot parameters, with larger R^2 for pine than for spruce when predicting strength or MOE. Knot parameters are usually affected by forestry practices, showing up especially in the quality of pine. In both Russian regions, KAR of pine was higher than in Finland. Generally, the geographic region turned out more important for pine than for spruce, because of the relative homogeneity of the properties of spruce timber.

Multiple regression models

Strength and MOE were predicted with multiple variables to reach the highest R^2 and the lowest *RMSE,* and to take all significant variables into the use. When externally detectable properties of the log and separation of butt logs and other logs were used as predictors for strength and MOE, R^2 of 0.60 and 0.58 was reached, the values being approximately 0.20 higher than for spruce (Hautamäki et al. 2013). Considering geographic region along with the log properties improved the predictions significantly, the improvement being small however. Strength could perhaps be explained at a comparable accuracy by measuring the log dimensions combined with the information of the ring width and latewood proportion, and possibly by measuring knot properties and heartwood proportion.

Similarly to spruce, the sawn timber properties appeared better predictors for strength and MOE of pine sawn timber than the log properties (R^2 = 0.76 and 0.69). For strength, MOE, KAR, ring width of the sawn piece and dimension of the sawn piece were then used as predictors. For both variables, an increase of only one unit of percentage was reached by adding log variables, the largest knot of the log and proportion of heartwood to the model (strength only). Lastly, KAR affected clearly more on strength than MOE, and MOE clearly outweighed density as a predictor for strength, although density correlated strongly with MOE.

The root mean square error (*RMSE*) is used to describe the difference between the values predicted by the model and the actually observed values. Generally, the higher R^2 the lower the *RMSE* is. In this study, *RMSE* ranged from 6.57 to 13.4 MPa in the strength models, and from 1.38 to 2.9 GPa in the MOE models. *RMSE* was regularly slightly higher in the models of pine than in the models of spruce (Hautamäki et al. 2013).

Comparison with earlier studies

The results of this study mainly followed the guidelines of some earlier results concerning the predictive ability of single parameters, such as MOE, KAR, ring width and density and some combinations of these parameters (e.g. Lindgren 1997, Hanhijärvi et al. 2005, Hanhijärvi and Ranta-Maunus 2008, Ranta-Maunus 2009). However, the values of R^2 were often lower than in the before mentioned studies. This could be due to the several sawn timber dimensions used in this study in parallel simple and multiple regression models, while only one dimension was used at one time in earlier studies. However, according to Ranta-Maunus (2009), adding cross-sectional dimensions in the models of bending strength increased the R^2 only marginally for pine sawn timber. Again, in this study, dimension of the sawn piece was included in models where all sawn timber properties were available.

In Table 11, the values of R^2 in the strength and MOE models are compared between this study and some earlier studies.

When different parameters are combined in the prediction models, the R^2 rises, as it was shown by Lindgren (1997), Hanhijärvi et al. (2005), Hanhijärvi and Ranta-Maunus (2008) and Ranta-Maunus (2009). It is difficult to substantially increase already high R^2 with auxiliary measurements, but MOE or density combined with knot parameters and ring width lead to this result. Adding significant predictors, such as diameter class of the log or proportion of latewood can increase the R^2 little, but may not be necessary in practical working environment. The reliable measurement of MOE combined with ring width measurements and/or knot parameters seems to be the best combination for predicting

Table 11. Coefficient of determination (R^2) in the models for bending strength and MOE of Scots pine sawn timber in this study and some earlier studies

Variables	Strength				MOE	
	1	2	3	4	1	3
KAR	41	54	54	41	45	35
Ring width	29	25	34		23	33
Density	41	53	58	29	56	65
KAR+Ring width	57	58	60		56	
KAR+density	52	70		55	65	
MOE	63	68	68	53		
MOE+ring width	66					
MOE+KAR	66	76		69		

1 – This study, 2 – Lindgren (1997), 3 – Hanhijärvi et al. (2005), 4 – Ranta-Maunus (2009)

strength, although using density and some auxiliary measurements gives almost as good a prediction.

Lindgren (1997) calculated linear regression models for the strength of pine and spruce sawn timber from Finland. In her study, pine models performed better than spruce models, the values of R^2 were generally higher than in this study, except for the models using ring width as a predictor. Only one sawn timber dimension of 45 × 150 mm was used as the basis of models, while in this study, though, the five dimensions were mixed in global models. For pine, MOE explained 68% of the variation in strength, and combined with KAR or density, 76% and 71%, respectively. KAR alone explained 54%, and combined with density 70%, while density alone explained 53%. Ring width explained approximately 25% of the variation, and combined with KAR 58%.

Hanhijärvi et al. (2005) and Hanhijärvi and Ranta-Maunus (2008) studied the possibilities of different non-destructive measurements in predicting bending strength of spruce and pine sawn timber. In Hanhijärvi et al. (2005), the models explaining strength with MOE, KAR, density and ring width provided R^2 values higher with 0.10 units than in this study, excluding the models using ring width in the models of pine which showed rather similar results to this study. The same results were apparent with the models for MOE. R^2 of 0.69 was reached for pine when strength was predicted using X-ray measurements and combined measurements of density, knot and ring width parameters (comp. with 0.45 for spruce). The results for MOE were similar to this study, while 55–60% of the variation in MOE was explained. The authors concluded that adding other variables could further improve the sorting of logs.

Hanhijärvi and Ranta-Maunus (2008) evaluated several methods for their ability to predict strength and MOE including X-ray scanning, frequency measurements, ultrasonic transit time methods, visual and manual characteristic determining methods and machine timber grading. High R^2, approximately 0.60 for pine, was reached when knot properties of logs were measured with X-ray methods. R^2 was also here generally higher for pine than for spruce. The strength was predicted weaker than the global MOE. Different dynamic MOE measurements on sawn pieces combined with density explained the strength and global MOE the best with the highest values of R^2 up to 0.60–0.90. Knots were a better predictor for the strength of pine (0.57–0.69) than for spruce (0.18–0.36). Generally, 40–60% of the variation in strength could be explained with different methods.

Ranta-Maunus (2009) presented models for the bending strength of pine and spruce using a large European sample including MOE, dynamic MOE, dimensions of the sawn piece, density, KAR and the ratio of MOE to density as explanatory variables. Compared to this study, density and MOE performed there strikingly worse as single predictors of strength, which was probably due to the larger geographic cover of the material. Instead, KAR performed as well in both studies. Hence, combining KAR with density or MOE resulted in even slightly better prediction of strength than in this study.

Stöd and Verkasalo (2008) presented linear mixed models for bending strength of Scots pine from first and second thinnings and final cuttings with R^2 of 0.80 or 0.72, with MOE included among or excluded from the predictors. In the first model, increase in MOE and density increased and increase in knot sum (corresponds to KAR) and growth ring width decreased significantly the strength. In the second model, density, knot sum and growth ring width affected similarly and increase in vertical log position in a tree decreased the strength. MOE could be explained by 65 % using density, knot sum, ring width as well as stand type and board dimension as predictors. Sawn timber from second thinnings represented the highest MOE and timber from first thinnings the lowest MOE, and an increase in the board dimensions increased MOE.

Baltrusaitis and Aleinikovas (2012) studied the relationships of modulus of elasticity and bending strength of Lithuanian Scots pine sawn timber with log characteristics and dynamic modulus of elasticity (based on log natural frequency, density and moisture content). Density of fresh cut logs was not a significant predictor and log diameter or cambial age could not be related with structural strength, thus providing worse prediction potential than what we observed in this study. However, dynamic MOE of wet and dried boards correlated significantly, below physically feasible limit of 20 GPa.

Conclusions

Scots pine is much less studied on the mechanical properties of sawn timber in structural uses than many other softwood species, such as Norway spruce. This study brought up new information on the level of, variation in and prediction of bending strength and stiffness for pine timber. These results can be applied in the planning of log procurement and sawn timber purchase from the regions concerned in this study when knowledge on the bending properties is of interest. Moreover, the results provide basic information on the prediction of bending properties and their geographic differences, based on log properties, sawn timber properties, or both. Studies concerning the prediction of strength and MOE of sawn pieces and using there a multivariable principle are more scarcely available than the studies on clear wood specimens; hence, the study provides a notable methodological contribution in this respect.

There is a need to diversify the value-added end-uses of Scots pine from the traditional carpenter, joinery and furniture product markets where visual appearance and functionalities of wood are appreciated to the growing building product markets where high-level mechanical properties, stability and moisture, mould etc. resistance are required. The trend that the pine log sources will be more and more in planted or directly sown forests and thinning forests and the rotation periods are coming shorter in forest management further calls for the development. In the future, when more cultivated grown timber reaches saw log size, the quality of available timber may change, even considerably from the current level in the naturally regenerated forests. Planted trees grow faster due to the less competition in the juvenile stage and the genetically improved tree material, which definitely have effects on wood density, knottiness, juvenile wood characteristics etc. In thinning operations the trees in the logging recovery are generally younger with their specific wood properties and should represent the smaller and lower quality trees in a stand if thinning regimes toward higher growth and better quality in the remaining stock are followed.

The results revealed larger regional differences in the timber properties between the sub-regions in Finland and north-western Russia, between the countries, and between Scots pine and Norway spruce as well, compared with the earlier research results and the perceptions from the practical industrial operations in the respective countries. Generally, the variation in strength and MOE is clearly larger for pine than for spruce, and the variation in MOE is smaller than in strength.

Boreal grown Scots pine timber, especially its northern origins, seem to have a good potential for structural uses regarding the strength, especially the potential yields of high strength grades. Due to the larger variation in the mechanical properties, and the rather good predictability of strength, the upper end of the strength distribution could be used to answer to the need of high strength sawn timber products. Different glue-laminated products (beams and columns) and jointed timber products (trusses, joists etc.) could utilize the mid-strength and low-strength pine timber to provide products with adequately high and homogenous strength properties, lower anisotropy and even controllable appearance for different purposes in construction and interior carpentry.

Better utilization of regional differences in timber quality of Scots pine could make it possible to use its different origins together with selected Norway spruce grades, for example, depending on the end-product. Density and proportion of sapwood of pine generally decrease from the south to the north and from uplands to lowlands, but wood characteristics such as proportion of heartwood, ring width and its homogeneity, knottiness in different forms and proportion of compression wood and juvenile wood rather add to the potential of northerly grown pine versus southerly grown pine.

The results clearly indicated that there is development potential in using log properties to predict strength (or MOE) for Scots pine timber, and the geographic region should then be taken into account in log sourcing. The approach is applicable for grading and/or pre-sorting of logs in connection of the cutting operations in the forest or in the roundwood terminals or log yards. In addition, saw mills which do not want to invest much to the automation of log grading or allocation of logs to structural or other uses may apply the principle. Early allocation of different log types and qualities, including the identification of knots and ring width and maybe density obviously lead to more efficient utilization of the raw material.

The results confirmed that efficient combinations of few key variables of sawn timber properties lead to the best estimate for strength and MOE of pine timber. It is commonly known that accurate measurement or prediction of MOE is the key solution. According to this study, measuring KAR and ring width and identifying the dimensions of sawn piece together add to the predictive power. If these sawn timber properties can be measured in the saw mill, the log properties add only marginally the efficiency of final sorting and grading of structural timber. The need to consider geographic origin of logs seems then questionable, however, the result being valid only for Finland and north-western Russia. Pan-European studies with a large geographic cover instead indicated that sources of logs should be considered in the set-up of machine strength grading methods.

Potentially cost effective measuring techniques that provide reliable prediction of the strength properties need to be further developed. Since wood is a natural material, it exhibits certain variations in the properties affecting mechanical properties and visual quality compared to substituting materials. There is a further need for precise information and more accurate standardization of wood materials when competing with for example concrete, steel, plastics and polymeric composites, in construction and joinery industries.

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ФАКТОРЫ И МОДЕЛИ СВОЙСТВ ПРИ ИСКРИВЛЕНИИ ПИЛОМАТЕРИАЛОВ ЕЛИ ИЗ ФИНЛЯНДИИ И СЕВЕРО-ЗАПАДА РОССИИ. ЧАСТЬ II: СОСНА ОБЫКНОВЕННАЯ

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Резюме

Цель исследования – улучшение знаний о различиях в механических свойствах пиломатериалов из сосны в выборочных регионах Финляндии и Северо-Запада России, а также - изучение прогнозирования таких важных характеристик, при использовании пиломатериалов в строительстве, как прочность при искривлении и модуль упругости. Задача состояла в поддержке развития производства продукции с добавленной стоимостью на лесопильных заводах путем улучшения сортировки и оценки бревен и пиломатериалов. Сортировка основывалась на производимых замерах бревен или пиломатериалов, или во внимание принимались оба показателя. Данный анализ является продолжением аналогичного исследования, проведенного на основе материалов из ели.

Бревна сосны и образцы средней части древесины (N=934) были собраны в пяти лесозаготовительных регионах: три в Финляндии и два в России. Были определены уровни и статистически значимые различия в модулях продольной упругости (E_{12}) и прочности искривления ($f_{m,12}$) пиломатериалов, а также ряд физических характеристик пиломатериалов и бревен. Для прогнозирования E_{12} и $f_{m,12}$ были рассчитаны модели множественной линейной регрессии с использованием свойств пиломатериалов и бревен в качестве предикторов и проведен анализ возможного сохранения региональных различий.

Как правило, уровни $f_{m,12}$ в Финляндии были намного выше, чем в России, являясь самыми высокими в Северной Финляндии и самыми низкими в Новгородском регионе, хотя и при значительном варьировании в этом регионе. Варьирование показателя E_{12} между регионами не было таким очевидным, однако более плодородные условия - при более низком показателе E_{12} . Плотность высушенной на открытом воздухе древесины, доля площади поперечного сечения, занятую сучком или сучками (KAR) и ширина годичных колец (RW) были лучшими предикторами E_{12}, а E_{12} и, KAR и RW для $f_{m,12}$. Если рассматривать свойства только древесины, свойства только пиломатериалов или свойства древесины и пиломатериалов вместе, то 60%, 76% или 77% от изменений показателя $f_{m,12}$ может быть объяснено. На общем уровне по сравнению с аналогичным исследованием на основе ели, более высокие коэффициенты были достигнуты. При сравнении показателей, полученных в результате предыдущих исследований сосны, касающихся уровня способности искривления, показатели - более низкие, а значение переменной географического варьирования является более очевидным, систематическим и значительным.

Ключевые слова: сила искривления, модель, модуль упругости, множественная линейная регрессия, сосна обыкновенная, пиломатериалы