Factors and Models for the Bending Properties of Sawn Timber from Finland and North-Western Russia. Part I: Norway Spruce

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Abstract

The aim of the study was to increase knowledge on differences in mechanical properties of Norway spruce sawn timber from selected log procurement regions 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 logs 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 on log measurements, sawn timber measurements or both together.

Spruce logs and centre yield sawn pieces (N=1,162) 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 higher in Finland than in Russia, being highest in northern Finland, albeit the large variation in that region. For E_{12}, the variation between countries was not so clear, but more fertile growing conditions seemed to provide sawn timber with lower E_{12}. Air-dry density (12% MC), 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, 40%, 70% or 57% of the variation in $f_{m,12}$ could be accounted. The results of this study were mainly in line with the previous studies concerning the levels of bending properties for spruce sawn timber, but the geographic variation was more obvious, systematic and larger.

Key words: Bending strength, model, modulus of elasticity, multiple linear regression, *Picea abies*, 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 wood 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 to the level of strength and MOE (e.g. 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). Beforementioned basic wood properties are fairly easily measurable or readily available, but as with all indirect methods for predicting strength, uncertainty always remains (e.g. 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 concentrate 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, Nokelainen et al. 1989, Zhou and Smith 1991, Johansson and Kliger 2000, Saranpää and Repola 2001, Flæte et al. 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, Lukkarinen et.al 2005). 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. 2005).

The levels of different strength properties, MOE and density as affecting factors have been studied for the clear wood of Finnish softwoods, for example, by Jalava (1945) and Siimes and Liiri (1952). Hudson (1967) studied the density, MOE and strength properties of clear wood specimens from spruce and pine sawn timber imported to UK from European boreal and temperate countries, including Finland and northern parts of the Soviet Union. Saranpää and Repola (2001) studied the bending strength of spruce in Finland and Sweden from monocultures and mixed stands of spruce and birch. Verkasalo and Leban (2002) studied and modelled bending strength and MOE of Finnish spruce and pine and French spruce, fir and pine. In addition to determine the levels of strength or MOE, models to predict strength properties of Finnish spruce and pine from clear specimens have been presented, for example by Kärkkäinen and Hakala (1983) and Kärkkäinen and Dumell (1983), who studied the effects of density, ring width and size of the log on bending strength.

Fewer studies are available on the variation in or prediction of strength or MOE of full size sawn timber of Finnish softwoods. Lindgren (1997) studied the bending properties of sawn timber, spruce from three geographic regions and pine from one geographic region, 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. Hanhijärvi et al. (2005) studied the potential of different non-destructive measurements in predicting bending strength and MOE for spruce and pine sawn pieces from sawmills of south-eastern Finland using 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 0.5 – 0.6 for spruce and 0.7 – 0.8 for pine. 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. Density seemed to explain MOE better than strength, because stiffness is a more global parameter and therefore more related to density. Hanhijärvi and Ranta-Maunus (2008) reached parallel results in their further study on a larger sample with a wider geographic representability.

Flæte et al. (2001) explored the bending strength and MOE of spruce sawn timber from Finland and Sweden from monocultures and mixed stands of spruce and birch. Ranta-Maunus et al. (2001) presented results for the levels of strength and MOE of both spruce and pine sawn timber from Finland and Sweden. Ranta-Maunus (2009) and Ranta-Maunus et al. (2011) presented wide ranges of results on strength and MOE from different European countries using linear regression models to predict strength.

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 during the last 10 years (e.g. Viitanen and Karvinen 2010, Hautamäki et al. 2012). A limited study considered the bending properties of spruce sawn timber from Finland and northern Russia (Lukkarinen et al. 2005). Some results on East-European spruce and pine sawn timber were recently presented by Ranta-Maunus (2009), Stapel and Denzler (2010) and Ranta-Maunus et al. (2011).

There is a further need for cost-efficient, end-user oriented grading of sawn timber for strength, where all the possibilities of using log and sawn timber measurements and models based on appropriate variables are utilized and the high-strength pieces can be detected more efficiently. 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 actual strength and modulus of elasticity of Norway spruce 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.

Materials and methods

Empirical materials and measurements

The data consisted of 1,162 logs from three sawmills and their respective domestic wood procurement regions, Kitee for south-eastern Finland, Kyröskoski for western Finland, Kajaani for northern Finland, and two regions in north-western Russia, The Republic of Karelia (with additional logs from Novgorod region) representing southern and fertile growing conditions and Vologda region representing more continental and colder growing conditions (Figure 1).

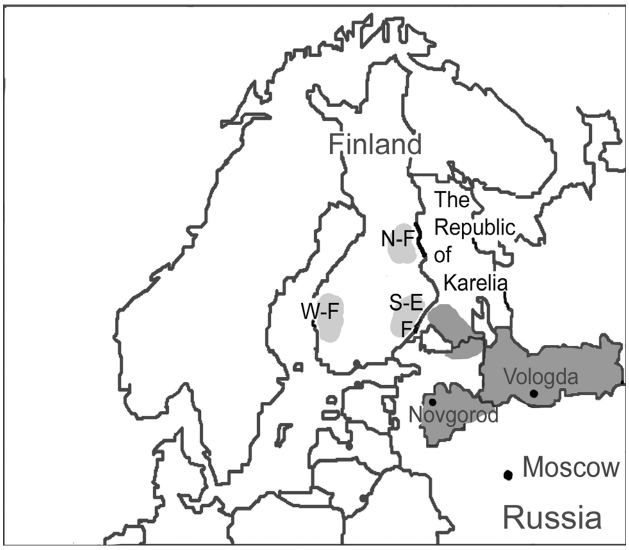

Figure 1. Approximate sampling regions in Finland and in Russia. W-F representing western Finland, N-F northern Finland and S-E F south-eastern Finland

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 are shown by species and region in Table 1.

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					
	155	170	205	275	305	
	Dimension of the sawn piece, mm					
	38*100	50*100	50*150	63*200	44*200	
South-eastern Finland	45	44	44	44	44	221
Western Finland	44	44	44	44	44	220
Northern Finland	44	44	44	44	44	220
Vologda, Russia	44	44	44	44	44	220
Republic of Karelia,Russia	44	57	60	60	60	281
	221	223	236	236	236	**1,162**

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 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 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 homoskedasticity. 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

For the strength ($f_{m,12}$), sawn pieces from northern Finland had the highest values followed by Vologda, then by western Finland, south-eastern Finland and the Republic of Karelia. Timber from northern Finland had a higher strength than that from south-eastern Finland or the Republic of Karelia, while timber from Vologda had higher values than timber from the Republic of Karelia. Differences between other regions were insignificant (Table 2).

For the local MOE (E_{12}), the level of MOE was significantly lower in the Republic of Karelia than in other regions excluding south-eastern Finland. Sawn pieces from Vologda had higher MOE than those from south-eastern Finland, but the difference was barely significant (Table 2).

Sawn pieces from northern Finland had significantly higher density (ρ_{12}) compared with any other geographic region. On the other hand, pieces from the Republic of Karelia had significantly lower density than pieces from any other region. Other differences were insignificant (Table 2).

KAR was the highest in south-eastern Finland, which significantly differed from northern Finland and Vologda. Western Finland also differed from northern Finland and Vologda. Other differences were insignificant. Although KAR was almost the same in western Finland and in the Republic of Karelia, larger variation in Russia caused the differences to be insignificant (Table 2).

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

Property		South-eastern Finland		Western Finland		Northern Finland		Republic of Karelia		Vologda	
	N	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
$f_{m,12}$ (MPa)	920	42.4	11.1	44.3	11.0	47.0	12.0	42.0	11.5	45.3	10.6
E_{12} (GPa)	920	11.8	2.2	12.3	2.0	12.2	2.2	11.4	2.0	12.4	2.0
ρ_{12} (kg/m³)	920	437.1	40.0	440.7	38.8	456.7	42.2	420.2	42.8	436.2	40.9
KAR	909	0.21	0.08	0.19	0.08	0.17	0.08	0.19	0.10	0.17	0.08
Ring width (sawn piece, mm)	908	2.5	0.8	2.2	0.7	1.4	0.7	2.3	0.9	1.7	0.7
Latewood % (sawn piece)	908	30.0	5.3	26.3	5.6	24.6	5.5	23.7	5.6	21.6	2.7
Ring width (log, mm)	1154	2.2	0.7	1.9	0.6	1.3	0.6	1.8	0.6	1.4	0.5
Latewood % (log)	1154	30.0	5.0	26.5	5.6	24.5	5.2	24.4	4.9	22.5	2.7
Heartwood %	1156	65.3	7.6	68.0	7.7	70.0	7.5	71.2	8.0	75.3	11.3
Largest dry knot (mm)	1169	15.2	7.3	16.1	5.8	13.2	4.1	17.6	6.5	17.7	7.3
Largest knot (mm)	1166	23.8	7.9	25.9	8.5	24.2	8.3	22.9	8.9	20.7	7.9
Taper (cm/m)	1166	2.8	1.3	2.8	1.2	3.2	1.4	2.7	1.2	2.2	1.1
Number of year rings	1154	61.8	21.0	70.2	24.1	107.7	37.4	90.8	34.7	100.3	39.4

Models for sawn timber

Strength

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

Local MOE had the best explanatory power with 57% of the variation in strength explained. Density and ring width (measured from the sawn piece or log) each explained 27 – 30% of the variation, while proportion of latewood explained only 3 – 5%, and KAR 20%. Number of year rings explained 10% of the variation, while other log variables, such as proportion of heartwood, diameter of the largest dry knot or taper explained less than 10%.

Categorical explanatory variables, such as geographic region, quality of the log and log type (butt logs versus other logs) each explained only 3 – 5% of the variation in strength, while dimension of the sawn piece was a better explanatory variable explaining 13%. Generally, sawn pieces from butt logs were stronger than those from other logs, and sawn pieces of smaller dimensions were stronger than those of larger dimensions. This was most probably due to the “weakest link” effect” of large pieces and to the fact that smaller pieces were sawn from smaller logs, which appeared to have smaller knots (Table 4).

When KAR, MOE, density and ring width of the sawn piece were used to predict strength in different combinations, they explained 36 – 59% of the variation in the strength. MOE was the best single explanatory variable, and combined with KAR or ring width it ex-

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

Strength, MPa (Sawn piece properties)	Estimate (S.E)	Estimate (S.E)		
Variable	**Intercept**	**β**	**R^2**	**RMSE**
E_{12} (GPa)	-4.51 (1.43)	0.004 (0.00)	0.57	7.51
Ring width (mm)	59.11 (0.83)	-7.40 (0.38)	0.30	9.52
ρ_{12} (kg/m³)	-16.36 (3.33)	0.14 (0.01)	0.27	9.75
KAR	54.71 (0.79)	-56.48 (3.79)	0.20	10.23
$\log_{10}$ latewood %	7.54 (5.43)	26.27 (3.90)	0.05	11.10
Strength MPa (Log properties)				
$\log_{10}$ ring width (mm)	50.88 (0.49)	-33.61 (1.85)	0.28	9.73
Number of year rings	35.59 (0.93)	0.10 (0.01)	0.10	10.80
Largest knot (mm)	53.57 (1.08)	-0.41 (0.04)	0.09	11.06
Largest dry knot (mm)	50.53 (0.95)	-0.41 (0.06)	0.06	11.00
Latewood %	34.24 (1.79)	0.38 (0.07)	0.03	11.18
Taper (cm/m)	47.71 (0.88)	-0.03 (0.07)	0.02	11.27
Heartwood %	39.39 (3.00)	0.07 (0.04)	0.003	11.38

All parameters were significant at 1% confidence level.

Table 4. Parameter estimates, coefficients of determination 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	41.89 (0.82)	0.03	11.25
South-eastern Finland (*p-value 0.66)	0.50 (1.14)		
Western Finland (*p-value 0.038)	2.44 (1.17)		
Northern Finland	5.07 (1.19)		
Vologda	3.44 (1.16)		
Republic of Karelia	Reference group		
Butt log vs. upper log			
Intercept	46.15 (0.52)	0.03	11.2
Upper log	-4.1 (0.74)		
Butt log	Reference group		
Quality of log			
Intercept	39.24 (1.30)	0.05	11.12
High quality butt log	7.72 (1.43)		
Normal quality upper log (*p-value 0.018)	3.36 (1.42)		
Lower quality butt log (*p-value 0.031)	3.75 (1.74)		
Lower quality upper log	Reference group		
Dimension of sawn piece			
Intercept	35.57 (0.9)	0.13	10.58
38*100 mm	10.01 (1.17)		
50*100 mm	12.66 (1.16)		
50*150 mm	10.69 (1.15)		
63*200 mm	5.70 (1.23)		
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 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	KAR+ E_{12}
R^2	0.38	0.36	0.58
RMSE	8.96	9.11	7.44
Intercept	0.21 (3.35)**	62.66 (0.88)	2.01 (1.94)***
E_{12} (GPa)			0.004 (0.00)
ρ_{12} (kg/m³)	0.12 (0.01)		
KAR	-45.05 (3.39)	-34.46 (3.72)	-15.63 (3.11)
Ring width (sawn piece, mm)		-5.96 (0.40)	
	Ring width+ρ_{12}	**Ring width+ E_{12}**	
R^2	0.36	0.59	
RMSE	9.10	7.28	
Intercept	19.10 (4.35)	7.69 (2.12)	
E_{12} (GPa)		0.003 (0.00)	
ρ_{12} (kg/m³)	0.08 (0.01)		
KAR			
Ring width (sawn piece, mm)	-5.11 (0.43)	-2.62 (0.34)	

All parameters were significant at 1% confidence level, except for those marked with ** (p-value 0.949) and *** (p-value 0.302).

plained nearly 60%. Density combined with KAR or ring width explained less than 40% of the variation (Table 5).

If only log properties were used as explanatory variables, the model including ring width of the log, latewood proportion, heartwood proportion, diameter of the largest dry knot, log type and diameter class of the log as explanatory variables explained 40% of the variation in strength. Geographic region did not appear significant in the model. If sawn timber properties were used, 70% of the variation was explained when MOE, KAR, ring width and dimension of the sawn piece were used as explanatory variables. This combination turned out to be the best, and adding other variables did not increase the explanatory pow-

Table 6. Parameter estimates, coefficients of determination 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	0.40	0.70	0.57
RMSE	8.84	6.23	7.48
Variable			
Intercept		10.25 (2.03)	12.71 (3.54)
E_{12} (N/mm²)		0.003 (0.00)	
ρ_{12} (kg/m³)			0.09 (0.01)
KAR		-30.63 (2.94)	-56.57 (3.24)
Ring width (sawn piece, mm)		-1.51 (0.31)	
Ring width (log, mm)	-7.79 (0.49)		-2.22 (0.46)
Latewood % (log)	0.29 (0.06)		
Heartwood %	-0.11 (0.04)		
Largest dry knot (mm)	-0.25 (0.05)		
Upper log	-2.48 (0.62)		
Butt log	Reference group		
Diam. class min 155 mm	5.57 (1.06)		12.78 (0.30)
Diam. class min 170 mm	8.66 (1.02)		12.45 (0.85)
Diam. class min 205 mm	6.88 (1.01)		9.74 (0.84)
Diam. class min 275 mm	4.48 (1.05)		4.37 (0.88)
Diam. class min 305 mm	Reference group		
Dimension of sawn piece			
38*100 mm		10.88 (0.74)	
50*100 mm		10.12 (0.71)	
50*150 mm		7.21 (0.71)	
63*200 mm		2.51 (0.74)	
44*200 mm		Reference group	

All parameters were significant at 1 % confidence level.

er. When MOE was replaced with density and all predictors were available, 57% of the variation was explained using KAR, ring width of the log, diameter of the log and density as explanatory variables (Table 6).

MOE

For the local MOE, the explanatory power of each independent variable is presented in Table 7.

Density was the best single predictor explaining 46% of the variation. Ring width of sawn piece or log and KAR were also good predictors explaining 21 – 30%. Number of year rings explained 16% of the variation, while all other explanatory variables including latewood proportion, diameter of knots, heartwood and taper explained less than 6%.

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

Local MOE. GPa (Sawn piece properties)	Estimate (S.E)	Estimate (S.E)		
Variable	**Intercept**	**β**	**R^2**	**RMSE**
ρ_{12} (kg/m³)	-2.74 (0.53)	0.03 (0.001)	0.46	1.55
Ring width (mm)	14.78 (0.15)	-1.37 (0.07)	0.30	1.77
KAR	14.1 (0.14)	-10.90 (0.69)	0.21	1.87
Latewood %	9.87 (0.30)	0.08 (0.01)	0.05	2.05
Local MOE GPa (Log properties)				
Ring width (mm)	14.67 (0.17)	-1.55 (0.09)	0.25	1.82
Number of year rings	10.00 (0.17)	0.02 (0.002)	0.16	1.94
Latewood %	9.85 (0.33)	0.08 (0.01)	0.05	2.06
Largest knot (mm)	13.12 (0.21)	-0.05 (0.01)	0.04	2.08
Largest dry knot (mm)	12.80 (0.18)	-0.05 (0.01)	0.02	2.09
Heartwood %	10.32 (0.56)	0.02 (0.01)	0.01	2.10
Taper (cm/m)	12.54 (0.16)	-0.04 (0.01)	0.01	2.10

All parameters were significant at 1% confidence level

Explanatory power of categorical variables was modest (3 – 6%), but as for strength, significant differences between categories were found. Butt logs provided generally sawn timber with higher MOE than other logs, and better quality logs provided higher MOE than lower quality upper logs. Smaller sawn pieces seemed to have modestly higher MOE than larger sawn pieces (Table 8).

When KAR, ring width of sawn piece and density were used as explanatory variables, 37 – 57% of the variation in MOE was explained. Density combined with KAR and ring width explained the variation best (Table 9).

If only log properties were used as explanatory variables, 37% of the variation in MOE was explained using ring width, latewood proportion and the 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 KAR, density and ring width of the sawn piece explained 59% of the variation. Both log and sawn timber properties explained 61%, the model including density, KAR, ring width of the log, diameter of the largest dry knot, geographic region and diameter of the sawn piece as predictors (Table 10).

Table 8. Parameter estimates, coefficients of determination 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	11.37 (0.15)	0.03	2.08
South-eastern Finland (*p-value 0.046)	0.42 (0.21)		
Western Finland	0.93 (0.22)		
Northern Finland	0.85 (0.22)		
Vologda	1.02 (0.21)		
Republic of Karelia	Reference group		
Butt log vs. upper log			
Intercept	12.37 (0.10)	0.03	2.08
Upper log	-0.72 (0.14)		
Butt log	Reference group		
Quality of log			
Intercept	11.04 (0.24)	0.06	2.05
High quality butt log	1.54 (0.26)		
Normal quality upper log	0.72 (0.26)		
Lower quality butt log (*p-value 0.125)	0.49 (0.32)		
Lower quality upper log	Reference group		
Dimension of sawn piece			
Intercept	11.26 (0.18)	0.04	2.07
38*100 mm (*p-value 0.091)	0.39 (0.23)		
50*100 mm	1.02 (0.23)		
50*150 mm	1.19 (0.23)		
63*200 mm	0.92 (0.24)		
44*200 mm	Reference group		

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

Table 9. Parameter estimates, coefficients of determination 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	KAR+ρ_{12}	KAR+ring width	ρ_{12}+ring width
R^2	0.57	0.37	0.50
RMSE	1.40	1.67	1.50
Intercept	0.24 (0.52)**	15.48 (0.16)***	1.59 (0.72)
ρ_{12} (kg/m³)	0.03 (0.001)		0.03 (0.001)
KAR	-8.00 (0.53)	-7.06 (0.68)	
Ring width (sawn piece, mm)		-1.06 (0.07)	-0.62 (0.07)

All parameters were significant at 1% confidence level, except for those marked with ** (p-value 0.662) and *** (p-value 0.027)

Discussion

Data considerations

The aim of this study was to determine the overall levels of and variations in bending strength and

Table 10. Parameter estimates, coefficients of determination 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
	Estimate (S.E)	Estimate (S.E)	Estimate (S.E)
R^2	0.37	0.59	0.61
RMSE	1.67	1.36	1.31
Variable			
Intercept	13.50 (0.47)	1.58 (0.66)	2.78 (0.68)
ρ_{12} (kg/m³)		0.03 (0.001)	0.03 (0.001)
KAR		-7.94 (0.60)	-7.50 (0.58)
Ring width (sawn piece, mm)		-0.23 (0.07)	
Ring width (log, mm)	-1.72 (0.1)		-0.53 (0.09)
Latewood % (log)	0.07 (0.01)		
Largest dry knot (mm)	-0.05 (0.01)		-0.03 (0.01)
South-eastern Finland	0.45 (0.19)		0.22 (0.15)
Western Finland	0.89 (0.18)		0.41 (0.14)
Northern Finland (* p-value 0.307)	-0.19 (0.19)*		-0.66 (0.15)
Novgorod (* p-value 0.230)	0.44 (0.18)		0.17 (0.14)*
Republic of Karelia	Reference group		
Diam. class min 155 mm	-0.71 (0.20)		
Diam. class min 170 mm (* p-value 0.900)	0.02 (0.19)		
Diam. class min 205 mm	0.27 (0.19)		
Diam. class min 275 mm	0.53 (0.20)		
Diam. class min 305 mm	Reference group		
Dimension of sawn piece			
38*100 mm		0.70 (0.16)	0.33 (0.17)
50*100 mm		0.81 (0.15)	0.53 (0.16)
50*150 mm		0.83 (0.15)	0.61 (0.15)
63*200 mm		0.61 (0.16)	0.46 (0.16)
44*200 mm	Reference group		

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

MOE of Norway spruce sawn timber, which appeared in the even sampling of top diameter classes of logs and the corresponding sawn timber dimensions. 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 spruce to support optimal sourcing of logs for structural products of sawmills, in general.

The data used in this study were 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 procurement of the empirical materials was commercial, which limited the possibility for objective sampling and regional representability for the characteristics of the timber stands. The even sampling of the logs in the selected log diameter classes did not fully correspond with the actual diameter distributions at sawmills, where logs of smaller diameter are typically more frequent than logs of large diameter.

Bending properties and geographic differences

Statistically significant differences in the mechanical properties emerged between geographic regions in this study. The levels of strength and MOE were generally higher in Finland than in the Russian regions, but the differences between the Finnish regions were less pronounced. The levels of MOE were apparently a little higher in northern Finland compared to other regions in Finland, but the variation was also large in northern Finland. As it could be expected, the levels of density followed the levels of strength in the geographic regions, and the variation in MOE was smaller than in strength.

The differences in the mechanical properties between Finland and Russia were smaller, but Vologda and the Republic of Karelia differed significantly from each other. For the strength, northern Finland differed from the regions of more fertile growing conditions (the

Republic of Karelia, south-eastern Finland), but for MOE this difference did not appear. This could be due to the smaller effect of knots for spruce; strength is affected more by local weak spots (knots) than MOE, which is a more general parameter, and for spruce, the variation of clear wood is smaller. The variation in density was consistent with the variation in strength between the geographic regions, but the KAR was generally more parallel with the fertility of the assumed growing conditions.

The lower levels of mechanical properties in Russia and overall variations were obviously due to the different growing conditions, silvicultural practices and uncontrolled composition of the logging stands in the data, regarding fertility and tree spacing. In Russia, thinnings did not obviously belong to the forest management practices, which could lead in the Russian logs to more frequent internal knots than in the Finnish logs, the dry knots in particular. It is notable that dry knots generally reduce strength more than MOE (Bodig and Jayne 1982, see also Lukkarinen et al. 2005). Also, the generally long rotation ages in Russia 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 of stand (Kärkkäinen 2007, Hautamäki et al. 2010). 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. 2005). 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 bending strength and MOE were approximately at the same level than in some previous studies of spruce, except for the high levels of northern Finland (e.g. Lindgren 1997, Hanhijärvi et al. 2005, Lukkarinen et al. 2005, Ranta-Maunus 2009). Lindgren (1997) found that spruce timber from northern Finland provided higher bending strength and MOE values than more southern origins (approximately 54 MPa vs. 47.1 – 47.4 MPa for strength and 13.1 GPa vs. 12.6 – 12.7 GPa for MOE). For MOE the differences were less pronounced, and opposite to this study, the variation in mechanical properties was smaller in northern compared to southern origins. In the study of Lukkarinen et al. (2005), spruce timber from northern Finland provided higher strength in lower altitudes than higher altitudes (45.6 MPa vs. 43.5 MPa) but much lower strength in north-western Russia at the same latitude (40.0 MPa). MOE was 11.8 GPa in northern Finland, being lower than in southern Finland, 12.6 GPa, but, again, higher than in north-western Russia, 10.9 GPa. Sawn timber from southern Finland provided strength and MOE of similar levels to this study.

Ranta-Maunus (2009) studied the levels of and differences in bending properties of, for example, spruce from several European countries based on the existed results to define the borders of growth regions to be applied in machine strength grading. The study included results from Finland, Sweden, Baltic countries, Russia, UK and Central Europe. Northern regions provided spruce timber with generally higher strength compared to Central Europe, different settings being recommended for machine strength grading. The Baltic countries provided timber with a similar strength level to Finland. In Sweden, the effect of climate on the strength of spruce was obvious in the north-south direction, northern origins providing sawn timber with better strength.

In the data of Stapel and Denzler (2010), spruce timber from eastern Europe had somewhat lower bending strength than the timber from Sweden, the difference being 5 MPa, but the timber from Slovenia slightly outweighed the timber from Sweden, the difference being less than 1 MPa. For MOE, any differences between eastern European countries and Sweden did not appear in the variation of individual strata, ranging from 9.6 MPa to 11.5 MPa. Larger knottiness through higher KAR in eastern European countries was probably the main reason for the differences; while KAR was 0.21 – 0.22 in Sweden, it was 0.24 – 0.31 in eastern European countries.

Models of strength and MOE

Individual predictors

In this study, MOE provided the highest coefficients of determination in predicting strength for spruce, as it could be expected. Density was not particularly good a predictor, and knot parameters, such as KAR and diameters of the largest knots of the logs performed worse. Ring width of sawn piece or log was as good or even a better predictor than density. In general, approximately 10% more of the variation in the simple linear regression models for the strength could be explained in the studies of Lindgren (1997) and in Hanhijärvi et al. (2005), excluding ring width as a predictor. In comparison to the results of Ranta-Maunus (2009), the coefficients of determination were approximately same, or better.

Density was the best predictor of MOE. 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. Ring width of sawn piece or log overcame knot parameters clearly. Comparative results of Hanhijärvi et al. (2005) and Hanhijärvi and Ranta-Maunus (2008) showed higher coefficients of determination when using density and ring width as predictors, but in this study, KAR turned out to be a better predictor for MOE.

The significance of geographic region alone was very small for strength or MOE, when better predictors were available (R^2 =0.03), and adding log quality to the model did not lead to R^2 of more than 0.05. Significant effects appeared more through such properties as knottiness, density, ring width, proportion of latewood or quality of the log, which seemed to have larger variations within regions than between them. Log diameter class or sawn timber dimension were rather good predictors for the strength, but not for MOE. Generally, the smaller dimensions provided higher strength and MOE than the reference dimension of 44*200 mm. The colder growing conditions in northern Finland and in Vologda seemed to provide smaller KAR.

Multiple regression models

Strength and MOE were predicted with multiple predictive variables to reach the highest coefficient of determination and the lowest residual error, and to take all significant variables in the use. When externally detectable properties of the log were used as predictors for strength or MOE, coefficients of determination of 0.40 and 0.37 were reached. Adding geographic region to log properties did not improve the prediction significantly. Strength could perhaps be explained at this accuracy by measuring the log dimensions combined with the information of the ring width and latewood proportion, and possibly by measuring of knots.

The sawn timber properties were better predictors for strength and MOE than the log properties (R^2 = 0.70 and 0.59). The best model was reached for strength when only sawn timber properties were used as predictors, whereas adding log variables did not improve the result. 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 the coefficient of determination, the lower the root mean square error. In this study, RMSE ranged from 6.23 to 11.39 MPa in the strength models and from 1.31 and 2.1 GPa in the MOE models.

It can be concluded that accurate and efficient measurement of sawn timber properties can result in a similar predictive power than adding log variables to the equation. This does not exclude the usefulness of sorting logs before sawing process, which further adds to the potential of timber with good strength properties when valuable information especially on the knottiness of the log is used.

Comparison with earlier studies

The results of this study were rather parallel with 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, Ranta-Maunus et al. 2011). However, the coefficients of determination in this study were somewhat lower, in general. 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, in this study, dimension of the sawn piece was included in models where all sawn timber properties were available. Comparison of coefficients of determination in the strength and MOE models generated in this study and some earlier studies is presented in Table 11.

Table 11. Coefficient of determination in the models for bending strength and MOE of Norway spruce sawn timber in this study and some earlier studies

Variables	Strength				MOE	
	1	2	3	4	1	3
KAR	20	26	21	34	21	16
Ring width	26	29	38		25	48
Density	27	34	37	20	46	50
KAR+Ring width	37	43	52		37	
KAR+density	39	49		48	57	
MOE	57	64	65	61		
MOE+ring width	59	64				
MOE+KAR	58	68		67		

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

When different parameters are combined in the prediction models, the coefficient of determination rises, as it was shown by Lindgren (1997), Hanhijärvi et al. (2005), Hanhijärvi and Ranta-Maunus (2008), Ranta-Maunus (2009) and Ranta-Maunus et al. (2011). It is difficult to substantially increase already high R^2 with auxiliary measurements, but MOE or density combined with knot parameters and ring width still increase R^2. Adding significant predictors, such as diameter class of the log or proportion of latewood can increase R^2 by a few present, 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 strength for both tree species, although using density and some auxiliary measurements gives almost as good a coefficient of determination.

Lindgren (1997) calculated linear regression models for the strength of pine and spruce sawn timber from Finland. In her study, spruce models performed worse than pine models, and coefficients of determination were generally higher than in this study, except for these models using ring width as a predictor. She used only one sawn timber dimension of 45*150 mm as the basis of models, while in this study we had five dimensions mixed in global models. MOE combined with ring width or KAR explained 66 – 68 % of the variation in strength, while KAR or ring width alone explained 26 – 29 %. Density combined with KAR resulted in explaining 43 –49%, and density alone 34%. Adding density in the models with MOE did not improve the result (64% for both).

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 of spruce with MOE, KAR , density and ring width provided R^2 higher with 0.10 units than in this study, excluding the models for strength using KAR as an explanatory variable. The same results were apparent with models for MOE. R^2 of 0.47 was reached for spruce when strength was predicted by using X-ray measurements and combined measurements of density, knot and ring width parameters. The results for MOE were basically similar to this study, though only 35 – 37% of the variation in MOE could be explained. They 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, for example, X-ray scanning, frequency measurements, ultrasonic transit time methods, visual and manual characteristic determining methods and machine timber grading. High coefficient of determination, approximately 0.45 for spruce, was reached when knot properties of logs were measured with the X-ray methods. 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 with the highest coefficients of determination up to 70%. Knots could predict 18 – 36% of the variation in the strength of spruce. Generally, 40 – 50% of the variation in strength could be explained with different methods.

Ranta-Maunus (2009) and Ranta-Maunus et al. (2011) presented models for the bending strength of spruce and pine 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. The results on the models parallel to this study were somewhat poorer for spruce. Density was an exception performing better as an explanatory variable than in this study. The large geographic cover of the material probably resulted in larger variation in his study in, for example, knot size, which improved the predictive power of knottiness. Density and MOE were approximately as good predictors in both studies.

Conclusions

This study brought up some new information on the prediction of mechanical properties for Norway spruce sawn timber from Finland and Russia. It mostly confirmed earlier results and practical perceptions concerning differences in timber properties between the sub-regions in Finland, but new information was created between Finland and north-western Russia. The results of the study can be applied in the planning of log procurement and sawn timber purchase from the regions concerned when knowledge on the strength properties is of interest, considering the before mentioned uncertainty in the representative ability of the Russian data. Moreover, the results provide basic information on the prediction of strength properties and their geographic background, based on log properties, sawn timber properties, or both. Studies concerning the prediction of strength and MOE of sawn pieces and using multiple variables are more scarce compared to those predictions for clear specimens, hence, the study provides a notable contribution to this knowledge.

It was sufficiently confirmed that there is development potential in using log properties to predict the strength of sawn timber. Early allocation of different log qualities, and measuring knots, ring width and possibly density can lead to a fairly good result to efficient utilization of timber raw material. For sawn timber properties, it was confirmed that efficient combination of the few key variables leads to the best estimate for strength and MOE. 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 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.

Due to the larger variation in the mechanical properties, the upper end of the strength distribution could be used to answer 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 class timber to provide products with adequately high and homogenous strength properties, lower anisotropy and even controllable appearance for different purposes in building with wood. In addition, the better utilization of regional differences in timber quality could make it possible to use, for example, northern spruce. In the future, when more cultivated grown softwood timber reaches saw log size in Finland, the quality of available timber may change from the current source from naturally regenerated forests. In particular, planted spruce grows faster because of less competition at the juvenile stage of growth and genetically improved tree material. Consequently, in the first plantations basic density of 20 kg/m^3 lower than in the naturally regenerated forests has been observed for spruce timber (e.g. Kärkkäinen and Dumell 1983, Ropponen 2010).

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ФАКТОРЫ И МОДЕЛИ СВОЙСТВ ПРИ ИСКРИВЛЕНИИ ПИЛОМАТЕРИАЛОВ ЕЛИ ИЗ ФИНЛЯНДИИ И СЕВЕРО-ЗАПАДА РОССИИ. ЧАСТЬ 1: ЕЛЬ ОБЫКНОВЕННАЯ

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Резюме

Цель исследования – улучшение знаний о различиях в механических свойствах пиломатериалов из отобранных регионов Финляндии и Северо-Запада России, а также - изучение прогнозирования таких важных характеристик, при использовании пиломатериалов в строительстве, как прочность при изгибе 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.

Бревна ели и образцы средней части древесины (N=1,162) 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 при изгибе ($f_{m,12}$) 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 выше, чем в России, являясь самыми высокими в Северной Финляндии, хотя и при значительном варьировании в этом регионе. Варьирование показателя E_{12} между странами не было таким очевидным, однако более плодородные условия - при более низком показателе E_{12}. Плотность высушенной на открытом воздухе древесины (12% MC), 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 40%, 70% или 57% от изменений показателя $f_{m,12}$ может быть объяснено. Полученные результаты подтверждают данные предыдущих исследований, что касается уровня способности изгиба ели, но значение переменной географическюго варьирования было более очевидным, систематическим и значительным.

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