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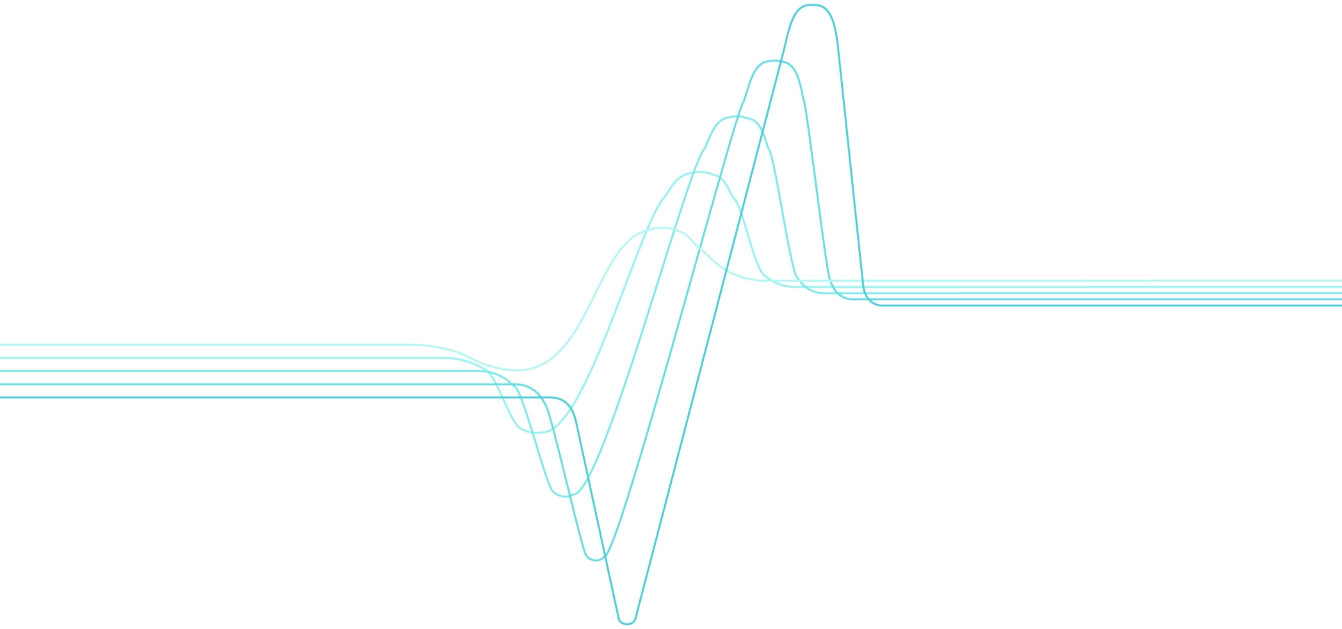

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Keywords sawn timber, strength grading, combined measurement, measuring methods, non-destructive testing, x-ray scanning, acoustic measurement, density measurement, stiffness, gamma rays

Abstract

About 100 pieces of both spruce (*Picea abies*) logs and pine (*Pinus sylvestris*) logs were sampled and sawn timber produced. Non-destructive measurements of logs and sawn timber were made by 15 organisations producing 40 different measured quantities for each test piece. Finally, test material was loaded to failure in bending, and grade determining properties (modulus of elasticity, bending strength and density) were measured.

Degrees of determination were calculated between non-destructively measured indicators and grade determining properties. Also strength grading procedure determined by prEN 14081 was simulated numerically, and effectiveness of some potential grading methods was analysed.

It was concluded that the coefficient of determination between strength and most non-destructive indicators was remarkably higher with pine than spruce. Especially knot size and density are potential grading parameters for pine but not for spruce. This does not, however, indicate that yield to high grades would be in general better with pine than spruce, but it indicates that pine has larger variability of knot sizes and density, and consequently higher variability of strength. Log scanning can also produce strength indicators which are on the level of some existing grading methods.

Simulation of European machine grading procedure indicated that there is a random factor which affects the yield to different grades. It can be counteracted by increasing the sample size when determining the settings for grading.

Preface

This research has been made as the first part of "Combigrade" project. The objective of the work has been to experimentally compare existing and potential strength grading methods of sawn timber. The experimental work has been done during 2004.

The project is financed by TEKES National Technology Agency of Finland and Wood Focus Finland. In addition, collaborating organisations have made important parts of the work on their own expense, which is briefly summarized as follows:

1. Bintec Oy made X-ray scanning of the logs.
2. SLU (Swedish University of Agricultural Sciences) made natural frequency and acoustic measurements of the logs.
3. FinScan Oy made optical scanning of sawn boards at a Stora Enso sawmill.
4. CBS-CBT/Sylvamatic made ultrasonic measurements of boards in a glulam factory.
5. Microtec made X-ray and natural frequency measurements of boards in their laboratory.
6. Raute Timgrader Users' Group made Raute Timgrader measurements at Sepa Oy in Keitele.
7. Brookhuis Micro Electronics / TNO Building and Construction Research made natural frequency measurements in laboratory.
8. TU-Graz and VTT made grain angle measurements with Metriguard equipment in laboratory.
9. Tampere University of Technology / Institute of Measurement and Information Technology made the annual ring width measurements based on digital photography in laboratory. Work was done in conjunction of the Metsäteho Oy coordinated project Timber Quality Assessment and Scaling.
10. VTT made compression stiffness measurements in laboratory.

Pine logs were sampled and planning was made with the help of Stora Enso Timber. Spruce logs were sampled by UPM Kymmene.

Contribution of these organisations is gratefully acknowledged.

Project has been lead by a management team under the chairmanship of Vesa Pölhö (Stora Enso Timber). Other members of management team have been Jouko Silen (Stora Enso Timber), Ismo Heinonen (Vapo Timber), Risto Laaksonen and Jaakko Lehto (UPM-Kymmene), Aarni Metsä and Markku Lehtonen (Wood Focus), Timo Pöljö (Finnforest), Jaakko Riihinen (Fin Scan), Juha Vaajoensuu (Tekes), Laura Apilo, Alpo Ranta-Maunus and Antti Hanhijärvi as secretary (VTT).

Contents

List of symbols

C.o.V.	Coefficient of variation
E_{dyn}	Dynamic modulus of elasticity = dynamic MOE
E_{dyn} (Freq.)	Dynamic modulus of elasticity calculated based on natural frequency measurement and default density
E_{dyn} (Freq. & Dens.)	Dynamic modulus of elasticity calculated based on natural frequency measurement and density measurement
E_{stat}	Static modulus of elasticity in NDT-measurement
INSTA rules	Nordic visual strength grading rules for timber
I.P., Ind.Prop.	Indicating property
KAR	Knot Area Ratio (Figure 3)
KCL	Knot Cluster (Figure 3)
MC	Moisture Content (dry basis)
MOE	Modulus of elasticity
MOR	Modulus of rupture = Longitudinal bending strength
NDT	Non-destructive testing
R_{u}	Density at test moisture content
R_0	Density at 0% MC
r	Correlation coefficient in linear regression analysis

r^2	Coefficient of determination in linear regression analysis
R.W.	Ring Width
T-class	Strength classes according to the INSTA rules
U.S.	Ultrasonic
V	Coefficient of variation of measurement error

1. Introduction

1.1 Strength grading of timber and the European system of strength classes

The objective of strength grading of timber is to ensure that a particular piece of timber to be placed as a particular structural member will have the capacity to carry the design load. To achieve the objective, a system of strength classes has been adopted. The European system defines twelve strength classes of sawn softwood timber: C14, C16, C18, C20, C22, C24, C27, C30, C35, C40, C45 and C50, where the number after "C" refers to the characteristic value of bending strength (in MPa) of timber pieces graded to that particular class (Table 1, see also ref. Glos 1995). The characteristic value (denoted with subscript *k*) is defined as the fifth percentile value, which means that 5% of the pieces graded in the class may have a lower strength value than indicated by the strength class characteristic value and at least 95% exceed it. To ensure that even the few pieces with strength below the characteristic value will not fail during service, an additional material safety factor is used, which is 1.3 for structural timber. Another safety factor is used to account for the uncertainty of loads. In addition to the requirement for the (1) bending strength, the European system of strength classes (EN 338, CEN 2003a) sets requirements for two other properties: (2) density (characteristic value) and (3) bending stiffness (mean value of modulus of elasticity [MOE]). These three properties of timber can be named as the *grade determining properties*. All other properties given in Table 1 are assumed to follow, if the three grade determining properties are shown to be satisfied by the graded timber.

Table 1. Strength classes and characteristic values according to EN338, coniferous species.

		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
in MPa													
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30
Tension perp.	$f_{t,90,k}$	0,4	0,5	0,5	0,5	0,5	0,5	0,6	0,6	0,6	0,6	0,6	0,6
Compression	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29
Compr. perp.	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2
Shear	$f_{v,k}$	1,7	1,8	2,0	2,2	2,4	2,5	2,8	3,0	3,4	3,8	3,8	3,8
in GPa													
Mean MOE	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16
5% MOE	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7
Mean MOE perp.	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53
Mean shear mod.	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00
in kg/m^3													
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460
Mean density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550

NOTE: The tabulated properties are compatible with timber at a moisture content consistent with the temperature of 20^{0}C and relative humidity of 65%. Bending and tension parallel to grain strengths are given for timber width 150 mm, tension strength perpendicular to grain for reference volume 0,01 m^3.

The system of strength classes based on bending strength and bending stiffness properties supplemented by density has been adopted, because bending is the most important loading mode in the structural use of sawn timber and consequently bending strength usually is the critical strength property. On the other hand, bending properties are straightforward to measure. However, an important application, where not the bending strength but the tension strength of sawn timber is of most importance, is the grading of gluelam lamellas. Even if the glulam itself is usually under bending load, the most highly loaded lamellas experience either tension or compression, and out of these, tension is the more critical for timber material due to the brittleness of tension failure. The European system defined in EN 1194 (CEN 1999) allows strength grading of gluelam lamellas based directly on measured tension strength or based on the calculational tension properties of the C-classes as defined above. Out of the two methods the one based on direct prediction of tension strength is more advantageous, because the calculational tension strength values are conservative and underestimate the real value. The strength classes of glulam as defined in the European standard EN 1194 are shown in Table 2 and Table 3.

Table 2. Strength classes and characteristic values of "homogeneous gluelam" according to EN1194.

Strength class		GL24h	GL28h	GL32h	GL36h
in MPa					
Bending	$f_{m,g,k}$	24	28	32	36
Tension parallel	$f_{t,0,g,k}$	16,5	19,5	22,5	26
Tension perp.	$f_{t,90,g.k}$	0,4	0,45	0,5	0,6
Compression	$f_{c,0,g,k}$	24	26,5	29	31
Comp. perp.	$f_{c,90,g,k}$	2,7	3,0	3,3	3,6
Shear	$f_{v,g,k}$	2,7	3,2	3,8	4,3
in GPa					
Mean MOE	$E_{0,mean,g}$	11,6	12,6	13,7	14,7
5% MOE	$E_{0,05,g}$	9,4	10,2	11,1	11,9
Mean MOE perp.	$E_{90,mean}$	0,39	0,42	0,46	0,49
Mean shear mod.	G_{mean}	0,72	0,78	0,85	0,91
in kg/m^3					
Density	$\rho_{k,g}$	380	410	430	450

Table 3. Strength classes and characteristic values of "combined gluelam" according to EN1194.

Strength class		GL24c	GL28c	GL32c	GL36c
in MPa					
Bending	$f_{m,g,k}$	24	28	32	36
Tension parallel	$f_{t,0,g,k}$	14	16,5	19,5	22,5
Tension perp.	$f_{t,90,g.k}$	0,35	0,4	0,45	0,5
Compression	$f_{c,0,g,k}$	21	24	26,5	29
Comp. perp.	$f_{c,90,g,k}$	2,4	2,7	3,0	3,3
Shear	$f_{v,g,k}$	2,2	2,7	3,2	3,8
in GPa					
Mean MOE	$E_{0,mean,g}$	11,6	12,6	13,7	14,7
5% MOE	$E_{0,05,g}$	9,4	10,2	11,1	11,9
Mean MOE perp.	$E_{90,mean}$	0,32	0,39	0,42	0,46
Mean shear mod.	G_{mean}	0,59	0,72	0,78	0,85
in kg/m^3					
Density	$\rho_{k,g}$	350	380	410	430

1.2 The problem of predicting strength of individual pieces of timber

To measure the strength of a particular piece of timber, one has to break the piece, but afterwards it is no more useable for its intended purpose as a load carrying component. True strength can only be determined in a destructive test. Actually, for strength grading purposes, it would not be necessary to test load the pieces to failure but only to the required value. Such a loading would knock off too weak pieces with 100% certainty, and such a method has been used in special cases. However, such a test loading could damage those pieces, whose strength is only slightly above the test load value and their residual load could be below the required value. Also, heavy test loading is not suitable for a fast manufacturing process.

Therefore, practically all strength grading is based on indirect methods, where measurements or observations of other properties of timber pieces are used to predict the strength. The measurements are made by some suitable *non-destructive testing* (*NDT*) methods. Obviously, predicting strength of individual pieces with indirect methods always includes some uncertainty, because the capability of an indirect measurement to predict strength can never be perfect and always includes measurement errors. The uncertainty of predictions of strength (and other grade determining properties) has been dealt with in the strength grading system by setting *requirements to the statistical distribution of the grade determining properties* of timber pieces that fall into a certain strength class (EN 14081). The requirements for the statistical distribution of properties include minimum values for the characteristic value (bending strength, density) and mean value (bending MOE). Simply speaking, the whole development of strength grading system by the European system requires the demonstration that the required statistical properties can be met with sufficient confidence level by the NDT-measurements to be adopted.

The properties that are obtained by NDT-methods and used as predictors of grade determining properties are called *grade indicating properties*. The effectiveness of a system depends on the prediction capability of the grade indicating properties and the accuracy by which they can be measured. Thus, the problem with stress grading focuses on these two key questions: (1) how to predict the strength of timber pieces by measuring other properties with the best possible reliability and (2) how to measure the predictor parameters with the best possible accuracy. The ability to give a good answer to only one of the above questions is not enough for a good strength grading method, and both questions must get a satisfactory answer.

1.3 Timber material

1.3.1 Defects and other sources of variability

Structural timber can be characterised as a highly *inhomogeneous* and highly *anisotropic* material. Inhomogeneity means that wood material is not of uniform structure but has a variety of defects. The most numerous defects are knots. Although knots are not defects for the living tree, they certainly are defects from the point of view of structural strength, since failure usually originates at or near a knot. Other defects include resin-pockets, dull-edges and sometimes decay and cracks. Not even the seemingly homogeneous part of timber is truly homogeneous. The growth conditions in particular parts of the tree stem affect the wood material and anomalies known as juvenile and reaction wood are results of irregular growth situations. Juvenile and reaction wood are defects, as well, but are not so easily recognised.

The defectless parts of timber are often referred to as "defect-free" or "clear wood". Even clear wood is not homogeneous, since the growth process of trees during growth seasons, produces annual rings, each containing one early- and one latewood layer, whose density is different. Different conditions during successive years lead to varying amount of thickness growth of the stem and varying annual ring width. How much the properties of clear wood actually affect the strength of sawn timber pieces, depends on the existence of defects in the vicinity. If there are only few and small defects in the neighbourhood of the stressed location, the properties of clear wood have a great effect on the strength. In any case, clear wood has a stronger effect on the stiffness, because stiffness is to a greater degree determined by average properties than by local weak spots.

The other above mentioned characteristic, the anisotropy, implies that wood is a very oriented material. The strength and stiffness in the growth direction of the tree stem are much higher than in the transverse plane (cross-section plane of the stem); see Table 1. For a living tree and also for structural use of timber, the anisotropy of wood is a highly positive property: it provides for a much higher load carrying capacity as a thin structural element (the stem in case of living tree; beam or post in case of structural timber). However, for strength grading, high anisotropy raises the problem that the grain direction (the growth direction in the stem) is not always parallel to the sawing direction of boards or planks. This causes that the grain angle is inclined (often called 'inclined grain' or 'slope of grain'). High slope of grain can seriously decrease the bending strength.

All of the above factors – defects, anomalous wood and slope of grain – are sources of variation to the strength of timber. Besides these, natural variability between tree species, between individual tree stems, between different growth locations in the stem increase the variation of strength of timber. The number of factors that determine the strength of a particular piece of timber can be truly high. The development of an all-inclusive strength prediction system seems unattainable at this point.

1.4 Strength of timber

1.4.1 Different modes of loading and strength

In the sawmilling process, logs are sawn into boards and planks, which can be described as long and narrow structural components with rectangular cross-sections, very suitable for construction as load bearing elements. As a load bearing component, timber may be subject to different *modes of loading*. Most commonly timber pieces act as beams, in which case the applied load imposes both *bending* and *shear* action on the piece. If the function of the piece is to act as a post, the main load action on it is *compression*. In addition, the timber may act as a tension bar and then the main action is *tension*. In the case of bending, two different loading situations can be distinguished, edgewise bending and flatwise bending depending, whether the load is exerted on the flat side or on the edge of the plank (Figure 1). In all of these loading situation timber possesses a different strength value, so that we can define the following strengths: edgewise bending strength, flatwise bending strength, tension strength, compression strength and shear strength. As described above, these are defined for the longitudinal direction of the timber pieces (= the grain direction). Similar strengths can also be defined for other material directions (transverse directions = perpendicular to grain directions), but they are not described here.

In practice, edgewise bending is the most important of all the loading modes and consequently the edgewise bending strength is the most important strength characteristic of timber. Furthermore, all the other strength values are correlated either to the edgewise bending strength and to density, and in the strength class system characteristic values for all other strengths are defined, even if no measurement or prediction of them is required.

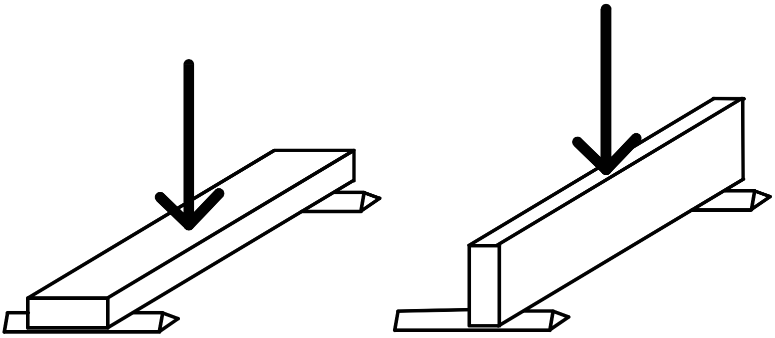


Figure 1. Illustration of flatwise (left) and edgewise (right) bending of sawn timber.

In the strength class system, edgewise and flatwise bending are considered equal, even if for individual pieces these may differ from each other. For simplicity, they are referred to as 'bending strength' and a distinction is made only when it is necessary. The same is adopted in this publication.

1.4.2 Effect of ambient conditions on strength

In addition to the structural characteristics of wood mentioned already (knots, density, inclined grain etc.), the strength of timber is a function of environmental conditions, in particular the moisture content of it. Wood absorbs moisture from humid air and desorbs it to dry air, or precisely speaking, it tends to equilibrium moisture content with the surrounding air. Strength is a function of the moisture content of timber in such a way that moist wood has a lower strength than dry wood. When arranging strength tests according to the standardised methods (EN 384, CEN 1995; EN408, CEN 2003b), test pieces are first allowed to attain the equilibrium moisture content in the standard conditions: temperature T = 20°C and relative humidity RH = 65%, and then tested. Unless tests are made after controlled climatic conditions, the results may be ambiguous and it is difficult to compare results with other tests.

1.5 Regression analysis as a source of prediction model

The strength of timber can be predicted by the measurement or quantification of properties that have a clear effect on strength, or, on those measurable properties that do not directly affect strength but are good indicators of it. For example, knots are known to be one of the key factors that define strength. Stiffness (modulus of elasticity, MOE), on the other hand, is not a direct factor to define strength, but because it is dependent on the same factors that define strength, is a good indicator of strength. Both types of properties can be considered as predictors of strength. In strength grading of structural timber the greatest emphasis should naturally be put on those non-destructively measurable parameters (predictors) that have the greatest ability to predict strength.

The basis of strength grading with non-destructive measurements is the existence of a relation between the strength and one or more predictor parameters. The relation must be described mathematically. The exact (deterministic) relation cannot be formulated due to its complexity, but it can be established from empirical observations (results of experiments) using mathematical statistical methods, usually regression analysis. It should be noted that statistical methods are not the only possible way to develop a strength grading system: basically any method that can be shown to produce a sample whose characteristic value is above the required value is sufficient.

In the analyses of this work, different NDT-methods are evaluated by regression, and, in all cases only simple linear regression analysis is adopted. The regression analysis yields among other results the so called '*coefficient of correlation*', r. Its square is called '*coefficient of determination*', r^2. The value of r^2 indicates the portion of the total variation of the predicted variable which is explained by the predictor. E.g., if $r^2 = 1$, the predictor can explain the variation perfectly, if $r^2 = 0.5$ it can explain half of it, if $r^2 = 0$, it cannot explain anything about the variation. In this work, the coefficient of determination is used solely as a measure of the ability of a method to predict the grade determining properties.

It is not possible to go into details about the regression analysis procedure itself, but it should be noted that there are two important things that should be taken into account when using it:

- If the variation of the predictor properties (indicating parameters) in the experimental data is small, it is meaningless to carry out a regression analysis.

- The result of a regression analysis should not be used for prediction with values of the indicating parameter that are outside the variation range of it in the experimental data set, on which the regression analysis was based. One has to be very careful with extrapolation.

1.5.1 Coefficient of variation of measurement error

The quality of a strength grading system is not only a function of the ability of the selected predictor (or predictors) to predict strength, but depends also on the accuracy and reliability by which the value of the predictor(s) can be measured. This is because we have to take into account also the uncertainty in the value of the indicating parameter due to measurement error. The inaccuracy of the measurement can be quantified by the standard deviation of the measurement error or, equivalently, by the coefficient of variation, denoted by V. We will not go into details of how to calculate V, but just recognise that it is a quantitative measure of measurement error level, i.e. a small value of V indicates high accuracy and large value indicates poor accuracy of the measurement device.

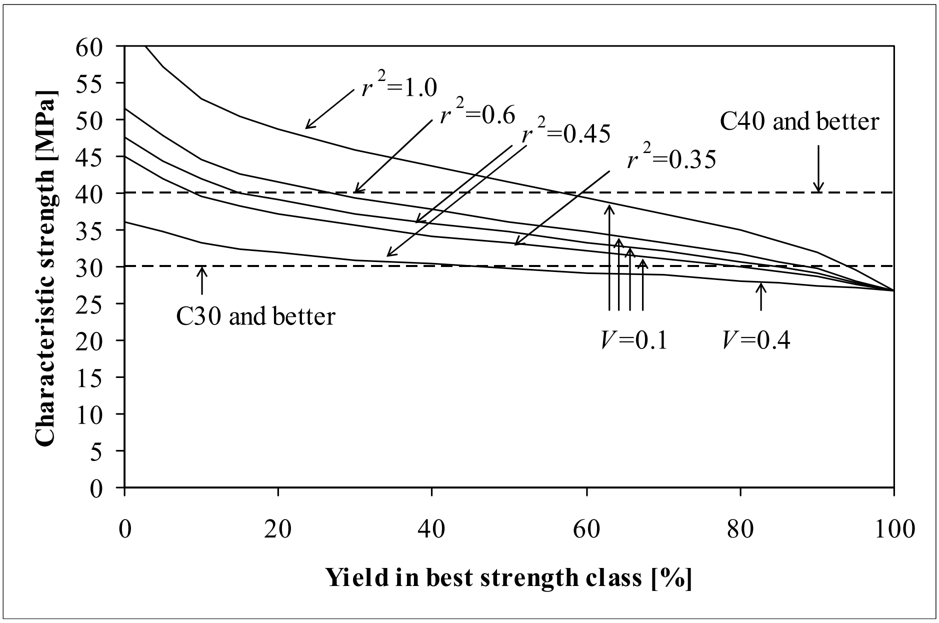
In the case when the regression analysis is made based on NDT-parameters that have been measured in the same conditions and same apparatus that will be used in the actual strength grading machine, the measurement error is already included in the NDT-data set. Then the regression analysis and r^2 already contain the effect of measurement error and V. However, if measurements are made in laboratory conditions, the measurement error may be smaller than in actual industrial conditions. Then an extra effect of V, which decreases the effectiveness of strength grading system, should be taken into account.

1.6 Effect of the quality of measurements and prediction model on efficiency of grading system

In the following, an example adopted from Hoffmeyer (1995) will be used as an example to show how the two factors (quality of prediction model and quality of measurement represented by r^2 and V, respectively) that define the quality of a strength grading system affect the yield in different strength classes. The example is directly taken from the statistical analyses made by Hoffmeyer (1995), who used the analysis method introduced by Glos and Michel (1982) and Pöhlmann and Rackwitz (1981). The analyses are based on using bending strength as the only grade determining parameter, even if the new European system uses three grade determining parameters as explained above. Although the other two properties may become significant in some cases, the bending strength is usually the most influential parameter and the examples do give a good picture of the effect of r^2 and V in different situations.

The example is illustrated with a fictional sample of structural timber that has a typical quality level for Nordic structural timber, which is not sorted by any means. The mean bending strength of the sample is 45 MPa and the 5th percentile value (of ungraded material) is 27 MPa.

Figure 2 illustrates the yield of the example sample in higher grades in terms of the quality of the grading system. For this timber quality (normal Nordic structural timber), it can be seen that strength class C27 is met wholly without grading (less than 5% of the sample has strength below 27 MPa). If $V = 0.1$, yield in C30+ (C30 or better) is 80–90%, if r^2 is between 35% and 60%. On the opposite, with poor measurement quality $V = 0.4$, yield in C30+ drops down to 45%. With $V = 0.4$ no grading to C40 can be made.



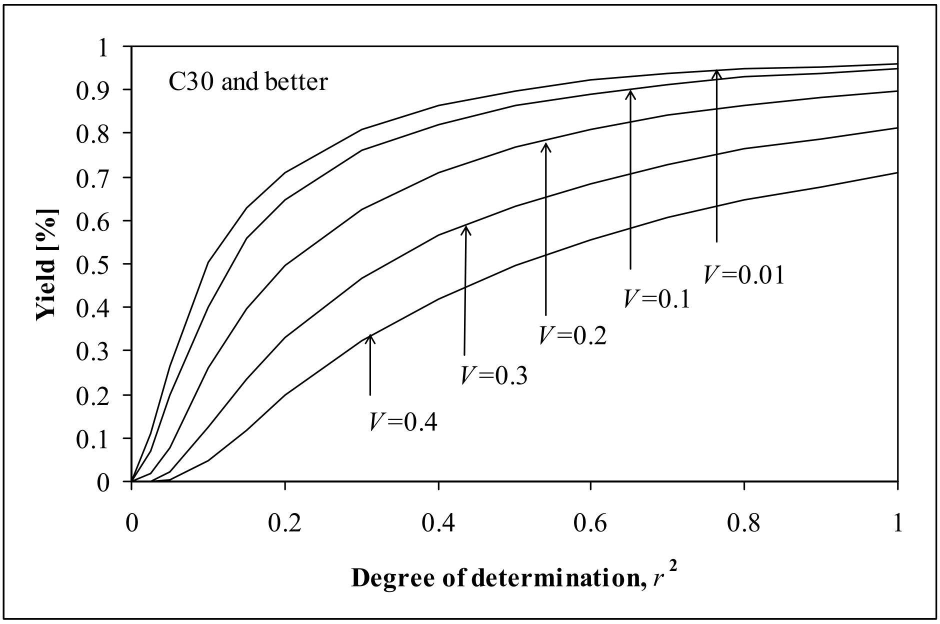


Figure 2. The effect of the quality of a strength grading system to the yield in higher strength classes – computational example, taken from Hoffmeyer (1995). Top – characteristic strength. Bottom – Yield to "C30 and better" as function of coefficient of determination r^2 and coefficient of variation of measurement error V.

1.7 Previous experimental results concerning non-destructive measurements as strength predictors

1.7.1 Ability of "exactly" measured parameters to predict strength

The following gives a review on some published results about the ability of different non-destructively measurable parameters to predict timber bending strength. The results are based on few wide investigations, even if the purpose of all these investigations has not necessarily been to find out information on the relation between non-destructive parameters and mechanical properties. Table 4 shows the observed coefficient of determination r^2 between diverse parameters as predictors of bending strength from several investigations (Hoffmeyer 1995, Fonselius et al. 1997). The non-destructive parameters presented in Table 4 have been measured as "exact". This means that the modulus of elasticity was determined in conjunction with destructive loading, when the strength was measured. Density was measured by weighing a piece cut by the side of the failure location after destructive testing. Knot variables have been determined with care in laboratory conditions, etc. In practical strength grading, the non-destructive parameters are not measured in this "exact" way but by some other practical method.

Table 4. Summary of previous experimentally obtained values for the coefficient of determination r^2, for "exactly" measured parameters for spruce timber (Hoffmeyer 1995, Fonselius et al. 1997).

Parameter	Coefficient of determination r^2				
Ref:	[1]	[2]	[3]	[4]	[5]
Knots	0.27	0.20	0.16	0.25	0.26
Annual ring width	0.21	0.27	0.20	0.44	0.29
Density	0.16	0.30	0.16	0.40	0.34
MOE, edgewise	0.72	0.53	0.55	0.56	0.64
Knots + annual ring width	0.37	0.42	0.39		0.42
Knots + density	0.38		0.38		0.48
MOE + knots	0.73	0.58	0.64		0.68

[1] – Johansson et al. (1992), [2] – Hoffmeyer (1984), [3] – Hoffmeyer (1990), [4] – Lackner et al. (1988), [5] – Fonselius et al. (1997).

From Table 4 the following conclusions can be made:

1. r^2 varies between the different investigations, which may be explained by differences in the material and methods of each investigation.

2. None of the parameters reaches higher r^2 value than approx. 0.7 = 70%.

3. Stiffness (modulus of elasticity [MOE]) is clearly the best single predictor of strength.

4. The second best predictors after MOE are knot size and density, but it is difficult to say which one of these is better.

5. The prediction capability (r^2 value) can be improved if two parameters are used together as predictors.

The visual strength grading systems (for example the INSTA grading rules in the Nordic countries, SFS 2000) are based mainly on the size of knots and their location. However, the correlation between knot size and strength is not very good, approx. 0.2. Therefore, the visual grading rules must be rather conservative. Nevertheless, this does **not** mean that knots would not be an important factor to determine strength. The result may indicate that the rather simple definitions of knot effect quantity in the visual grading rules are not good enough to describe properly the complex effect of knots on strength. Some quantities that have been used to describe knot effect are illustrated in Figure 3. A recent investigation by Foley (2003) suggests a more advanced knot quantity function, but her criterion has been tested only on a very small sample of timber.

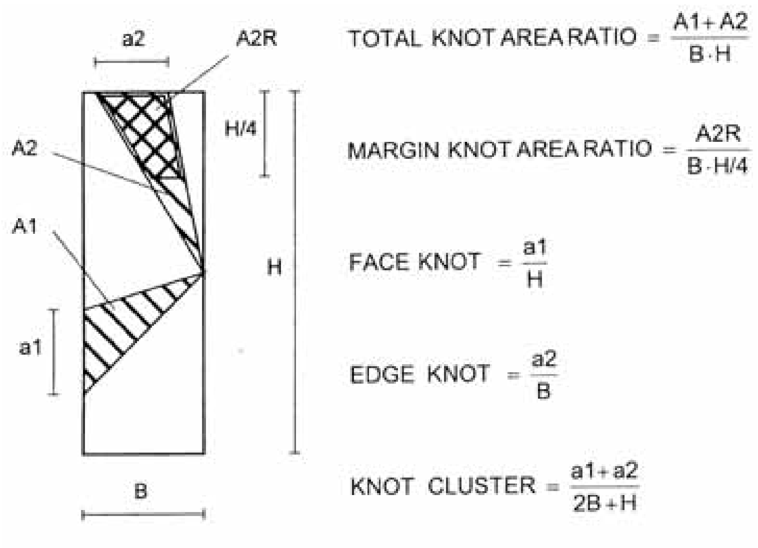


Figure 3. Some measures to quantify the effect of knots on weakening the cross-section (Fonselius et al. 1997).

Density of wood is a good predictor for the strength of clear, defect-free wood. However, for structural timber, density can account for approx. 16–40% of variation, as seen in Table 4. The lowest correlations are observed in those investigations where the variation of density in the tested sample is small. Annual ring width has a fair correlation to strength.

1.7.2 Ability of practical parameters to predict strength

There are many possibilities how the non-destructive parameters are measured. The non-destructive parameters presented in Table 4 were "exact". In practical strength grading, the non-destructive parameters can not be measured in the "exact" way in a laboratory but by some other practical method. Obviously, the way the measurements are made affects the measurement accuracy (a measure of this is *V* as described above). Table 5 contains results from some practical parameters to predict the strength of structural timber.

Table 5. Experimentally obtained values for the coefficient of determination r^2, for some practically measured parameters for spruce timber, result of MOE by "exact" measurement also included for comparison (Hoffmeyer 1995, Diebold et al. 2000).

Non-destructive parameter	Coefficient of determination r^2			
Ref:	[1]	[3]	[4]	[6]
Modulus of Elasticity, edgewise, "exact"	0.72	0.55	0.56	
Modulus of Elasticity, flatwise, Grading machine A	0.49		0.55	
Modulus of Elasticity, flatwise, Grading machine B	0.55	0.36		
Modulus of Elasticity, flatwise, Grading machine C				0.53
X-ray				0.42
Ultrasonic				0.53
Modulus of Elasticity, Grading machine A + knots	0.56		0.67	
Modulus of Elasticity, Grading machine C + X-ray				0.55
Ultrasonic + X-Ray				0.59
Dynamic-MOE (vibration) + X-Ray				0.66

[1] – Johansson et al. (1992), [3] – Hoffmeyer (1990),
[4] – Lackner et al. (1988), [6] – Diebold et al. (2000).

1.7.2.1 Measurement of stiffness (static modulus of elasticity)

Modulus of elasticity (MOE) can be measured in different loading modes – bending, tension and compression. Each one of these measurement types produces a different value for the MOE. Measurement of MOE can further be classified depending on whether it is based on static method or dynamic method. In a static method, a static load is applied and consequent deformation is measured, (or equivalently deformation is applied and the needed load is measured). In a dynamic method, vibrations are induced to the piece by an impact load and the natural vibration frequency is measured; a dynamic MOE can then be calculated.

Existing grading systems are based on measuring MOE in bending, either in static or dynamic loading. The static MOE is a better predictor of strength than the dynamic according to Table 5, but the dynamic method provides other advantages. In existing static machines flatwise bending is used, which requires smaller loads than edgewise bending. Use of flatwise bending reduces slightly the r^2 value compared to that of edgewise "exact" measurement as can be seen from Table 5.

1.7.2.2 Measurement of natural frequency (dynamic modulus of elasticity)

Dynamic measurement of the MOE is based on measurement of the natural frequency of a timber piece. The idea is to hit the board or plank with suitable impact load and measure the natural frequency of the board or plank. The method has the advantage that forces needed and deflections induced are fairly small. Dynamic measurement is also fast. Görlacher (1984) found that dynamic MOE correlates very well with the statically determined one. Blass and Gard (1994) obtained $r^2 = 0.45$ between dynamic MOE and strength of Douglas fir. In the same investigation the relation between "exact" static MOE and strength showed the r^2 value of 0.50.

1.7.2.3 Measurement of ultrasonic speed

The measurement of ultrasonic speed can also be categorised as a measure of the MOE, since speed of sound in wood material is proportional to its rigidity, in other words MOE. However, it should be noted that in principle ultrasonic speed is a separate property from MOE. Sandoz (1989) found r^2 values for a relation between strength and ultrasonic speed of approx. 0.45. Note also the result of Diebold et al. (2000) in Table 5.

1.7.2.4 Measurement of density

Density of wood can be measured in various ways: by direct weighing, by X-ray irradiation or gamma-ray irradiation. The underlying principle of the irradiation methods is that a decrease in intensity of radiation occurs because the rays become absorbed by wood. The absorption is dependent on moisture content and density and thickness of wood (e.g. Tiitta et al. 1993). If the moisture content of wood is known, the density can be determined. Because the density of knots is different than that of the stem itself, X-ray scanning allows also the measurement of knot volume (ratio), which can also be used for grading.

1.7.2.5 Measurement of the log properties

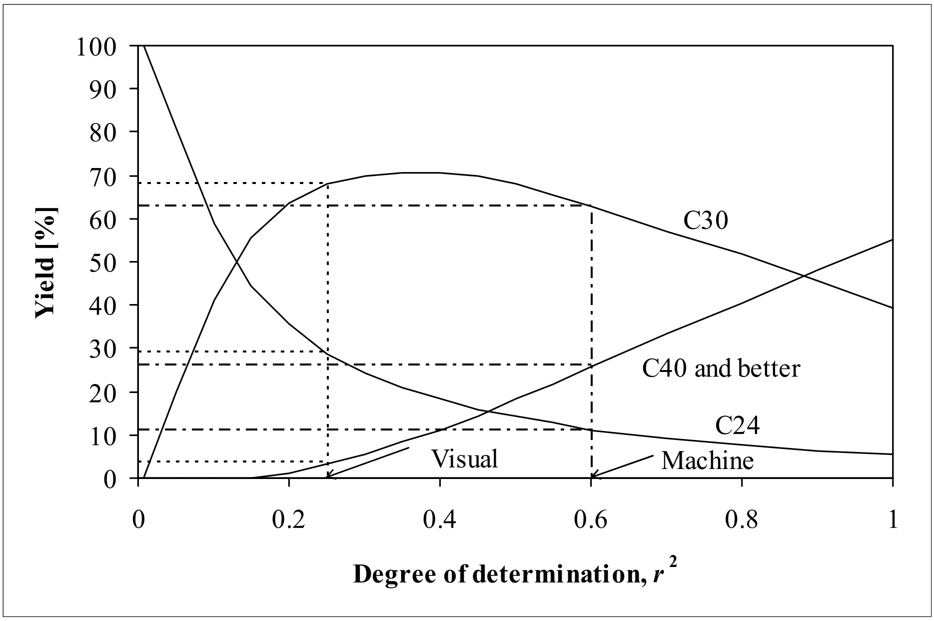
Some of the non-destructive measurements can be made also for logs. Naturally, a measurement made on logs has a different correlation and consequently r^2 value compared to properties measured on sawn timber pieces. Nevertheless, a measurement of log properties can be used as a grading parameter, if the correlation to the strength of sawn timber turns out to be sufficient.

At least the ultrasonic speed measurement and X-ray measurement have been used to assess quality of logs (Sandoz 1996, Oja et al. 2000). The X-ray measurement gives information on density and knot volume. With a prediction model based on X-ray scanning of logs, Oja et al. (2000) got an r^2 value of 0.41 for strength of boards sawn from the centre of the investigated logs. In this preliminary study, however, the number of tested specimens was low.

1.7.2.6 Potential of different strength grading systems in terms of yield

Based on results shown in Table 4 and Table 5 and the above introduced mathematical statistical methods, we can get a picture of the quality of various strength grading systems in terms of yield.

Figure 4 (taken from Hoffmeyer 1995) shows the yield of strength grading as function of r^2 for the fictitious timber sample that corresponds to typical Nordic timber without any sorting. Figure 4a shows, that a machine system based on measurement of stiffness or any other system which can reach r^2 value of 0.6, and targeting to three grades (C24, C30 and C40) gives a substantial yield for C40. On the contrary, in a similar situation, a visual grading system (based only on knots and assuming $r^2 = 0.25$) gives very small yield in C40. On the other hand, Figure 4b shows that if the targets are the two lower grades only, C24 and C30, then even the visual system can achieve 70% yield in "C30 and better" (yield of machine grading in this case is approx. 85% in "C30 and better"). This example shows that the choice of a grading system may depend on the target strength classes.



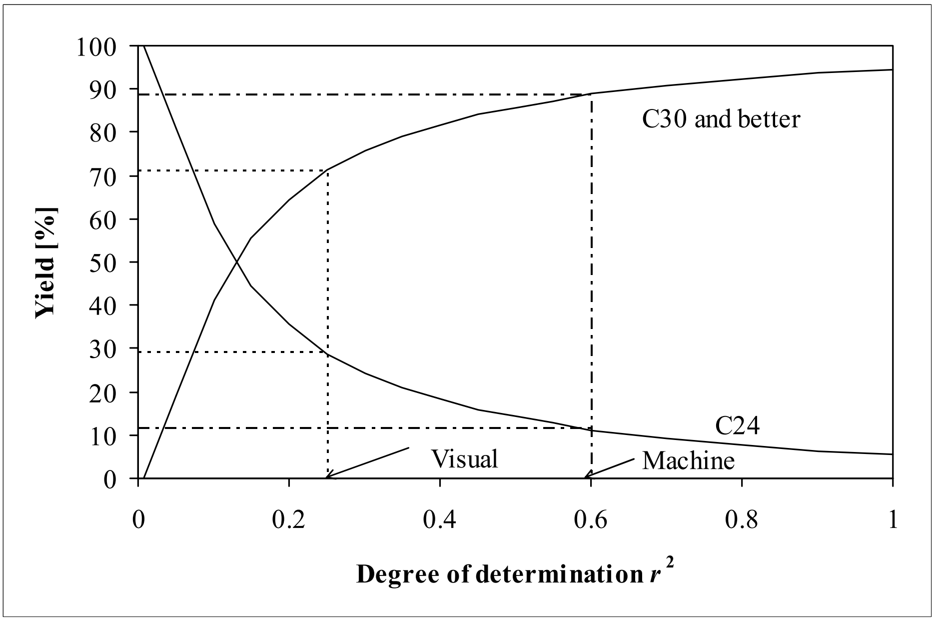


Figure 4. Computed yield of a typical sample of unsorted Nordic timber based on quality of strength grading system. a) Top – strength grading with target classes C24, C30 and C40. b) Bottom – target classes C24 and C30. (From Hoffmeyer 1995.)

1.7.2.7 Other factors affecting the strength of timber and its prediction

Many other factors have been observed to have an influence on timber strength. The correlation between these factors and strength may not be strong, but all these factors increase variation and decrease the correlation between the above mentioned parameters and sometimes explain why the correlations above are so low.

1.7.2.7.1 Tree species

Tree species affects the relation between different non-destructive parameters and strength and this effect can be very strong. For example, knots are a clearly better predictor of strength for pine than they are for spruce. In the investigation by Fonselius et al. (1997) knots could explain 57% of the strength of pine but only 26% of that of spruce. That correlation between different parameters and strength depends on tree species, which suggests that better grading rules can be achieved, if the rules are developed individually for each species.

1.7.2.7.2 Juvenile wood

The innermost annual rings in the tree stem have a different anatomical structure compared to the wood in the outer layers of the stem. The wood in the innermost rings is called 'juvenile wood' and it has different mechanical properties than the 'adult wood'. The stiffness and strength of juvenile wood are lower than that of adult wood, which can not be explained by density variation only (Brazier 1985). The amount of juvenile wood varies between stems.

1.7.2.7.3 Height in tree stem

Strength properties of timber vary along the height in the stem. Principally, most of the variation due to growth height can be explained by the greater amount and larger size of knots in the upper part of the stem than in the lower part. However, some investigations (Harvald 1988, Morsing 1990, referred to by Hoffmeyer 1995) show that the relation between stiffness and strength is different between pieces taken from the lower and upper part of stem.

1.7.2.7.4 Dimensions

Two different factors influence the effect of dimension on strength of timber. (1) It is well-known that the strength of timber decreases with size, because the larger the stressed volume, the higher is the probability that a weak link occurs in the volume. This effect is not very strong and has been taken into account in the building codes by a size dependent correction factor. Nevertheless, size-effect makes strength grading more complex. (2) Furthermore, it has been found that the influence of density and stiffness on determining strength decreases and effect of knots increases for small cross-section sizes (Adelhøj et al. 1984, Foslie & Moen 1972). This seems natural since in small cross-sections knots constitute a larger portion of the total cross-section. This complicates the development of grading rules, since the effect of different parameters depends on the cross-section size.

1.7.2.7.5 Stiffness in edgewise and flatwise bending

In the strength grading machines that use static stiffness, stiffness is usually measured in flatwise bending, since it requires lower forces and gives higher deflection. However, in practice the loading is usually edgewise bending. There is a significant difference between the stiffness measured flatwise and edgewise (Boström 1994). The difference can be explained by at least two factors: location of knots and variation of the modulus of elasticity within the cross-section.

1.7.2.7.6 Slope of grain

Grain angle (slope of grain) affects strength and severe slope of grain decreases strength strongly (Glos 2004). However, slope of grain shows only a weak correlation with strength, which is explained by the fact that severe slope occurs very seldom (Glos 2004). The effect of the slope of grain may depend greatly on species.

1.7.2.7.7 Growth location

The growth location of a stem has an influence on the correlations between different parameters and strength. Timber obtained from one growth location can show a high r^2 value for a given parameter but the r^2 value for the same parameter for a sample obtained from many growth locations can be low. This can be explained by different condition in soil, sun light, wind, etc. Therefore, for proper evaluation of a grading system, the sample to be tested should contain timber obtained from several and different growth locations.

1.8 Objective and motivation for the present study

The present study has originated from the anticipation that the importance of strength grading of sawn timber will increase in the future. In Europe, the gradual application of the CE-marking requires that an increasing amount of timber will go through strength grading. On the other hand, much of the potential of Nordic timber is nowadays unused in what comes to strength. A large portion of the timber reaches much higher strength level than its present design strength value. With reliable strength grading systems, this potential could be exploited.

The objective of this project was to study the potential of different NDT-methods and their combinations to predict the strength of Finnish softwood sawn timber material. Results of studies made with different samples of timber are difficult to interpret and compare, because the differences may be due to either the sample used or the measurement method. Although strength grading and the correlations between different NDT-parameters and strength have been studied in several research projects, there are only few reports in which several methods are applied to the *same sample* of sawn timber. In this study, the idea was to measure the same sample with different methods, giving a better starting point for evaluation. Even so, one must keep in mind the restriction of possible effect of chance, which is always possible when the sample is fairly small.

As a second and even more important objective, this project aimed to study the potential of increasing prediction accuracy with combined methods. This was pursued by testing systematically the combinations of different methods to find out economical strength grading systems for different needs.

2. Material

2.1 Selection of test material (logs)

The logs for the test material were obtained from two large sawmills in South-Eastern Finland, namely the Kaukas sawmill in Lappeenranta, where the spruce (*Picea abies*) logs were obtained, and the Honkalahti sawmill in Joutseno, where the pine (*Pinus sylvestris*) logs were obtained. At both sawmills, the logs were picked one at a time from the log supply during a long period of time and contained two different log sizes. E.g., every 10 000th log within the two size classes was picked. Both of these sawmills obtain their logs from a rather large area in South-Eastern Finland and North-Western Russia. Because logs were picked during a long period of time, it can be said with certainty that each log came from a different growth location.

Besides size classes, the pine logs were also subdivided according to quality class, so that for pine, there were altogether four log classes present, based on size and quality, whereas for spruce, two classes based only on size were used. The selection of logs is illustrated in Table 6. At the first pick, altogether 200 spruce logs and 200 pine logs were obtained. The logs were named as K1–K200 (spruce) and M1–M200 (pine). Logs K1–K120 and M1–M120 were the smaller diameter logs and K121–K200 and M121–M200 were the larger diameter ones.

Table 6. Selection of logs.

Species	Top diameter, mm	Log quality	Sawing pattern	Number after first pick	Number after selection
Spruce	195–204		2exlog	120	60
Spruce	285–299		4exlog	80	40
Pine	194–206	sound knots	2exlog	60	30
Pine	194–206	middle and butt logs	2exlog	60	30
Pine	284–310	middle and butt logs	4exlog	40	20
Pine	284–310	high quality butt logs	4exlog	40	20

A second selection reduced the number of logs to 100 spruce logs and 100 pine logs. This selection was based on non-destructive log measurements: log X-ray scanning of pine logs and natural frequency measurement (stress wave) of spruce logs. Based on the measurement result (density for pine and dynamic MOE for spruce) the logs within each class were ranked. Then within each class the best 1/8 and worst 1/8 was directly selected and from the rest every third log was picked. This way the number of logs was halved but the number of best and worst logs was assumed to be higher than in a random pick.

2.2 Sawing and drying of test material

The selected logs were sawn according to either the 2exlog pattern (smaller diameter logs) or the 4exlog pattern (larger diameter logs) into boards of nominal dimension 50 mm x 150 mm as illustraded in Figure 5. The sawing was made at a small sawmill, where the production speed was slow enough to allow the transfer of the log numbering onto the boards. Basically, only one board out of each log was picked to be used as a test specimen (either Y or A-board by random as illustrated in Figure 5). In addition, from a few logs more boards were taken in order to have some extra specimens to keep the number above 200 in case of loss during transportation, etc.

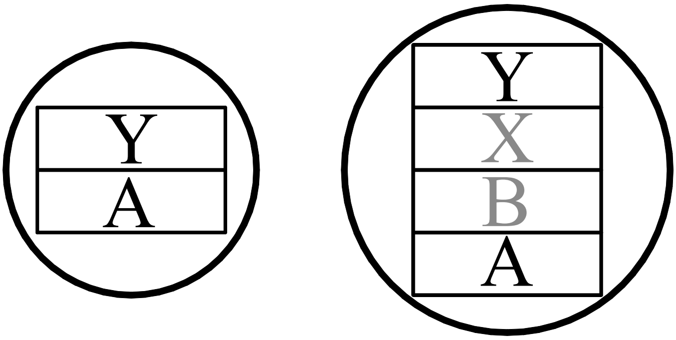


Figure 5. Sawing pattern of logs. Left – small diameter 2exlog. Right – large diameter 4exlog. Either one Y-specimen or A-specimen was picked from each log. (Only very few extras including X and B-specimens were picked.)

The boards were dried in a small kiln using a moderate drying schedule to avoid cracking. The target average final moisture content was 12%. The kiln control system had a slight malfunction, due to which the actually reached final average moisture content was lower, 9–10%, which is assumed to not affect the results by any means.

After drying, the boards were planed to dimensions 46 mm x 146 mm. The corners were rounded.

3. Methods

3.1 Basic method of study

As explained above in the introduction, the objective of the project was to study how well different NDT-methods and their combinations can predict the three grade determining properties, bending strength, stiffness and density. The idea of the study was to (1) make as many measurements as possible using various non-destructive test (NDT) methods to the test material, (2) make destructive tests to the test material to determine the grade determining parameters of each board and (3) finally analyse the NDT-data, compare it to the destructive data and evaluate the potential of the NDT-methods and their combinations to predict grade determining properties.

Strength grading equipment manufacturers were invited to participate as partners in the project and to perform measurements by their own equipment and provide the data to be used in the project. A list of participating companies or institutes along with the used techniques is given below in Table 7. The Combigrade project itself arranged the employment of few techniques which were assumed to be interesting but were not covered by any measurements by the participating partners. These measurements were carried out mainly by VTT.

Table 7. Partners and measurement methods.

Partner	**Method (auxiliary measurements in brackets)**	**Measured property**
Log measurements		
Bintec Oy	Log-Xray	Density, Knot parameters, Annual ring width
SLU, (Swedish University of Agricultural Sciences)	Log-Frequency Log-Acoustic tomography	Natural frequency (longitudinal), Transit time of sound
Board measurements		
FinScan Oy	Visual scanning of board sides	Knot parameters
CBS-CBT/ Sylvamatic	Ultrasound, (Electric resistance)	Transit time (Moisture content)
Metsäteho Oy/ Tampere Univ. of Technology	Visual scanning of board ends	Annual ring width
Microtec/ GoldenEye	Frequency X-ray	Natural frequency (longitudinal) Density, knot parameters
Raute Users' Group/ Raute Timgrader	Flatwise static bending	Flatwise bending modulus of elasticity
Brookhuis Micro Electronics/ TNO	Frequency	Natural frequency (longitudinal)
TU-Graz, VTT/ Metriguard	Dielectric constant	Slope of grain
VTT	Static compression	Compression modulus of elasticity (longitudinal)
Combigrade (VTT)	Weighing, (Electric resistance)	Density, (Moisture content)
Combigrade (VTT)/ Finnomoist	Gamma-ray	Density, (Moisture content)
Combigrade (Mikkeli Polytechnic)/, Finnograder	Gamma-ray Microwave IR	Density, Knot parameters, Slope of grain (Moisture content)
Combigrade (VTT)	Knot Area analysis	Knot parameters: TKAR and KNOT CLUSTER
Combigrade (VTT)	Visual scanning for documentation	–

3.2 NDT-measurement techniques

In the following, a brief description is given about how each non-destructive measurement was used in the project.

3.2.1 X-ray scanning of logs

The X-ray scanning of the logs was carried out with a machine by Bintec Oy. The equipment is running at a sawmill and can be used for quality grading of logs. The scan is performed by irradiating logs from several sides while they move past the machine. The intensity of the transmitted radiation is measured on the opposite side of the irradiators. By the method, a three dimensional picture of the log and its interior can be obtained and different parameters concerning the log calculated. These parameters include various density parameters, knot parameters and ring width parameters.

3.2.2 Frequency measurement of logs

The natural frequency of the logs was measured by Swedish University of Agricultural Sciences (SLU) using the Rion SA77 apparatus by Rion co. (Japan). The device is a general-purpose sound analyzer. This method measures the natural frequency of the log caused by the longitudinal vibration. The measurement itself is carried out by placing a vibration sensor on the log end and hitting the log with a hammer to excite the vibration. The measurement was made outside at a sawmill yard. Based on the measured natural frequency and an additional length measurement and assuming a default density value, the dynamic modulus of elasticity of the log can be calculated.

At the time of measurements, a sample disc was cut from each log, which was later used for density determination (green density). The green density can be used instead of a default value, when calculating the dynamic MOE value, which enhances the prediction capability.

3.2.3 Acoustic transit time of logs (acoustic tomography)

The sound transit time of the logs was measured by SLU using the FAKOPP 2D acoustic tomography apparatus by Fakopp Enterprice (Hungary). This method measures the time in which the sound (frequency 200–500 Hz) travels through the log longitudinally. The measurement itself is performed by attaching a starter and receiver transducer on the ends of the log. In this project, the measurements were performed at a sawmill yard and were repeated on two opposite sides of the logs. Based on the transit time measurement and length measurement a dynamic modulus of elasticity (assuming a default density value) can be calculated, but it should be noticed that this dynamic MOE is based on a different physical phenomenon than the one obtained by the natural frequency measurement. Unfortunately, the device failed after approx. 75% of the spruce logs had been measured, and the pine logs as well as the rest of the spruce could not be measured.

As with the natural frequency measurements of the logs, the green density value obtained from the sample discs cut from the logs can be used in calculation of the dynamic MOE based on transit time, which enhances its capability as strength predictor.

3.2.4 Visual scan of board sides

Visual scan of board sides was performed by FinScan Oy at a sawmill. The scan produces digital images of the board sides and edges, which can be analysed by image analysis techniques to obtain various parameters (e.g. knots). For this project an analysis that applied the Nordic INSTA 142 grading rules (SFS 2000) was performed.

3.2.5 Natural frequency measurement of boards (2)

The measurement of natural frequency of boards was made separately by two partners: Microtec S.r.l. and Brookhuis Microelectronics / TNO Building and Construction Research. Both measurements registered the natural frequency in longitudinal vibration and were carried out in laboratory. The measurement itself occurs by placing the board on two elastic supports and hitting one end of it by a hammer, or something similar, which excites the vibration. The frequency can be measured in several different ways (microphone, accelerometer, optically). Based on the natural frequency and length measurement and assuming a default value of density, a dynamic MOE can be calculated. If a measured density is used instead of a default density, a more accurate dynamic MOE value is obtained. Obviously the prediction capability of the one including information about density is higher than the one without it. Here the two are denoted as E_{dyn} (Freq.) and E_{dyn} (Freq. & Dens.).

3.2.6 X-ray scanning of boards

Microtec S.r.l. performed X-ray scanning of the boards using the Golden Eye strength grading machine. The board is fed through the machine and is irradiated from the other side. The transmitted intensity is recorded from the other side and a picture of the board and its interior is obtained. The measurement was made in laboratory. Various parameters concerning the board can be calculated including density and knot parameters.

3.2.7 Acoustic-ultrasonic measurement of boards

The acoustic-ultrasonic measurement was performed by CBS-CBT using the Sylvamatic strength grading machine. The measurement functions by attaching two probes on the ends of the board. An ultrasonic sound pulse is excited to the board at one end. At the other end the transit time and transmitted energy is measured. As an auxiliary measurement, the moisture content was measured by the electric resistance method. The measurements were made at a glulam factory. From the results the mechanical properties of the board can be predicted.

3.2.8 Slope of grain measurements

The slope of grain was measured by the Combigrade-project itself in co-operation with Technical University of Graz (TU-Graz) by using a Metriguard device owned by VTT. The device is an old one originating from the 1980's. The measurement functions by measurement of the dielectric constant shift by a rotating sensor (Mc Lauchlan et al. 1973). The boards were fed through the device, and the slope of grain value was registered every 1 cm distance at the middle line of the board on the bark side.

3.2.9 Density measurement by scale

The global density of the boards was measured by weighing and measuring the length of the specimens in laboratory. For determination of the volume the nominal board width and thickness were used.

3.2.10 Density measurement by gamma rays

The density was measured by the Finnomoist-machine owned by VTT in laboratory. The Finnomoist-device was developed in the 1980's by Innotec Oy and is no more available for purchase. It uses gamma rays, microwaves and IR-radiation to measure the density, moisture content and temperature. The values are output at 10 cm intervals. The measurement functions by irradiating the specimens from one side and measuring the transmitted intensity from the other side while the specimen is fed through the machine.

3.2.11 Measurements by gamma rays and microwaves (Finnograder)

The Combigrade project arranged measurements also by the Finnograder-machine. The Finnograder is a strength grading machine that was developed in the 1980's by Innotec Oy, but it is no more in production use. The machine, by which the measurements were done, is owned by Mikkeli Polytechnic, which also performed the measurements. The Finnograder machine uses gamma rays, microwaves and IR-radiation to determine various properties of the boards and uses them to predict strength. It was not possible to record the raw data, but data in a pretreated form. The data contained the following parameters at every 10 cm intervals: knottiness, knot eccentricity, slope of grain and slope of grain at knot, density, moisture content and predicted strength.

3.2.12 Flatwise bending stiffness (Raute Timgrader)

The Finnish Raute Timgrader Users' Group arranged the measurements with Raute Timgrader strength grading machine in industrial conditions. The machine functions by measuring the necessary force that is needed to effect a certain deflection in flatwise bending, i.e. stiffness. The boards are fed through the machine and the stiffness is output at approx. 10 cm intervals.

3.2.13 Compression stiffness measurements

VTT measured the compression stiffness of the boards in laboratory. During the measurement the boards were placed between a press and a fixed wall. The boards were laterally braced at approx. 1.5 m intervals. The boards were compressed to few MPa stress level and then the load was removed. The load-displacement curve was recorded and the compression-MOE determined.

3.2.14 Photographs of board ends for annual ring width measurements

Tampere University of Technology/Institute of Measurement and Information Technology (TUT/MIT) performed the measurement of annual ring width at the board ends. For this purpose, small slices (approx. 5 cm thick) were cut from the board ends. The slices were sandpapered and photographed with a digital camera in laboratory. The digital images were analysed with image analysis techniques developed by TUT/MIT and as a result average annual ring width was obtained.

3.2.15 Knot area measurements

The knot area measurement was made in conjunction with the destructive tests: after the failure the knot pattern of the broken cross-section was recorded by hand drawing on mm-paper. Based on the drawings, the total knot area ratio (TKAR) was determined for the boards. In addition, the so called knot cluster value (KCL), was determined. The KCL is calculated as the sum of the knot widths on the bark side and edges divided by the corresponding total width of edges and bark side (Figure 3).

3.3 Destructive tests

The bending strength, bending stiffness and density were determined by destructive tests according to EN 408 in four-point bending. The bending stiffness was measured 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 corresponding modulus of elasticity (MOE) values were denoted by "MOE-local" and "MOE-global". The density was measured on small slices cut from the neighbourhood of the failure location. The density was determined both at the testing condition at approx. 12% moisture content (R_u) and at absolute dry conditions (R_0). Simultaneously, the moisture content was determined from the slices. The testing details are shown in Table 8. All specimens were allowed to obtain equilibrium moisture content at 20°C and 65% RH before testing.

Table 8. Destructive test arrangement details.

Nominal board height, h	146 mm
Nominal board width, b	46 mm
Total span	2628 mm
Distance between presses	876 mm
Span of deflection measurement at constant moment region	730 mm

The positioning of each board to the test rig was determined so that the weakest point would be located between the presses (i.e. at constant moment region, the most highly loaded region). The presumed weakest point was determined based on those NDT-measurements which predict strength values as function of board axis, viz. Raute Timgrader, Microtec Goldeneye and Finnograder. If the three machines didn't agree on the weakest location, it was first seen whether two of them agreed and that position was selected. If all machines predicted different weakest points, one of them was selected at random. The choice of the edge to be under tension stress was made at random.

4. Results and analysis

4.1 Destructive test results and their correlations

The destructive test results are given in Appendix A. A statistical summary of them is shown in Table 9 below. It should be noted that the specimens in this work should NOT be considered as a typical sample of Finnish sawn timber, because in the log selection the "best" and "worst" logs were emphasized. Figure 6–Figure 9 show the frequency and cumulative distribution of the bending strength values for spruce and pine. It seems that the distribution is more even than normally: there appears to be more specimens with strengths either in the lower or higher range. This effect, however, seems to be more pronounced for pine than spruce.

Table 9. Statistical summary of the destructive test results. For comparison the results in ref. Ranta-Maunus et al. (2001) are also shown.

	MOR, N/mm^2	**MOE-Local**, N/mm^2	**MOE-Global**, N/mm^2	**Dens. R$_u$**, kg/m^3	**Dens. R$_0$**, kg/m^3	**MC**, %
SPRUCE						
Aver., this work, n=111	43.2	11465	11138	428	385	11.4
C.o.V.,	0.29	0.21	0.19	0.10	0.10	0.02
Aver., Ranta-Maunus et al., n=589	45.2	13000		448		
C.o.V.,	0.25	0.19		0.09		
PINE						
Aver. this work, n=108	45.0	12108	11777	486	437	11.0
C.o.V.,	0.37	0.25	0.22	0.12	0.12	0.04
Aver., Ranta-Maunus et al. n=286	45.1	11901		496		
C.o.V.,	0.34	0.26		0.11		

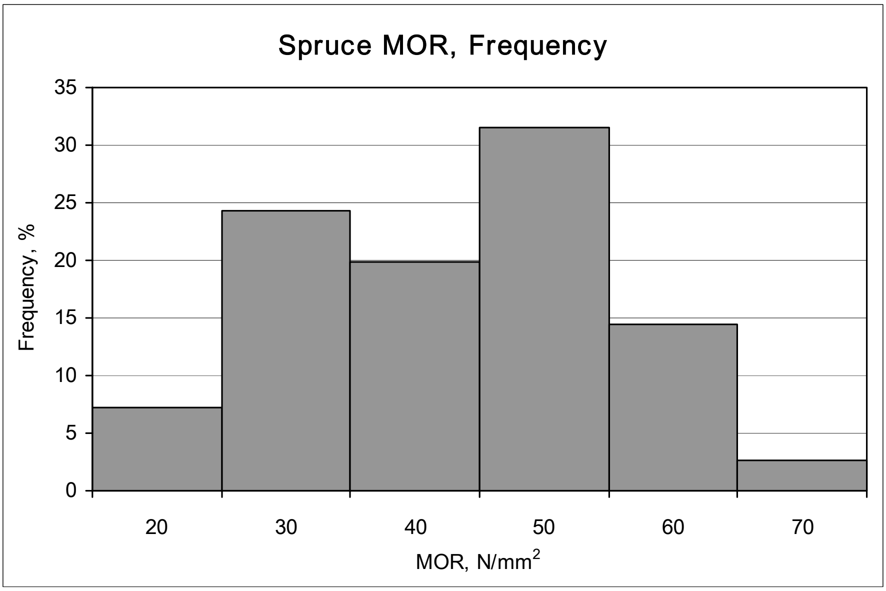


Figure 6. Frequency plot of the bending strength of spruce.

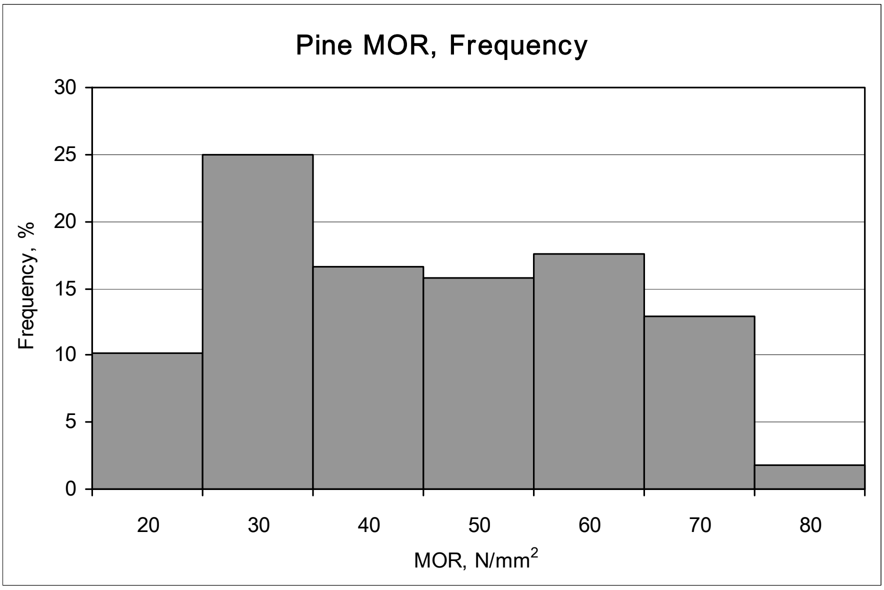


Figure 7. Frequency plot of the bending strength of pine.

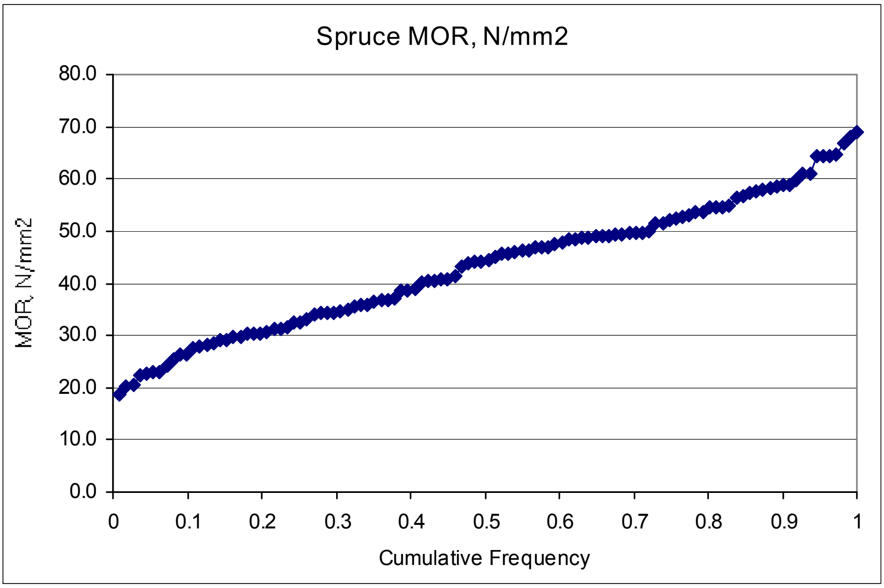


Figure 8. Cumulative frequency of the bending strength of spruce.

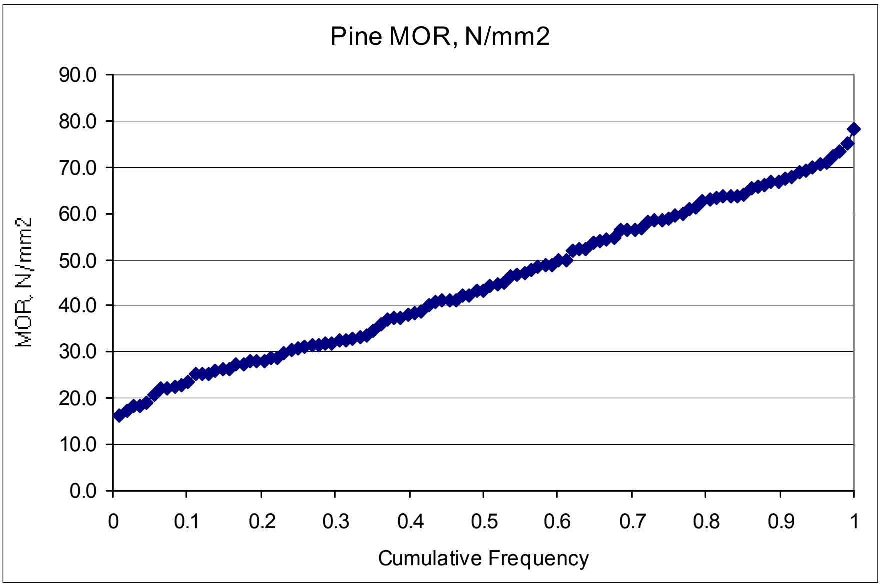


Figure 9. Cumulative frequency of the bending strength of pine.

As a first analysis, the correlations between the properties obtained in the destructive tests were calculated. The results are shown in Table 10 in terms of the coefficient of determination r^2. It can be noticed that the two densities, R_u and R_0, show perfect correlation and that the use of only one is sufficient.

Table 10. Correlations in terms of the coefficient of determination r^2 between the properties obtained from the destructive tests.

SPRUCE Source	to destruct. r^2 of	*MOR*	*MOE-Local*	*MOE-Global*	*Dens., R_u*	*Dens., R_0*
Destructive	MOR	1.00				
Destructive	MOE-Local	0.65	1.00			
Destructive	MOE-Global	0.67	0.92	1.00		
Destructive	Dens., R_u	0.37	0.50	0.58	1.00	
Destructive	Dens., R_0	0.36	0.50	0.58	1.00	1.00
PINE Source	to destruct. r^2 of	*MOR*	*MOE-Local*	*MOE-Global*	*Dens., R_u*	*Dens., R_0*
Destructive	MOR	1.00				
Destructive	MOE-Local	0.68	1.00			
Destructive	MOE-Global	0.69	0.95	1.00		
Destructive	Dens., R_u	0.58	0.65	0.72	1.00	
Destructive	Dens., R_0	0.57	0.65	0.72	1.00	1.00

4.2 Correlations between destructive results and individual NDT-results

As a basic treatment for the gathered NDT-data, correlation analyses between all individual NDT-parameters and the destructively measured properties were made. In this way, the coefficient of determination r^2 of each measured property in linear regression as a predictor for the destructively determined properties was obtained.

Table 11 contains specific information on the exact parameters used and how the analysis was made for the different measurements.

Table 12 and Table 13 list the r^2-values for each parameter for spruce and pine, respectively. Also, the indicating properties obtained from the strength grading machines used are included as single parameters, even if some of them require more than one measurement.

Table 11. Details about the parameters used in analysis of correlations.

Partner/ Method	**Analysis of raw measurement data**	**Parameters used in correlation analysis**	**Notes about correlation analysis**
Bintec Oy/Log-Xray	by partner	Density (heart and sap), Knot parameters Annual ring width	
SLU/ Log Frequency	by partner	Dynamic MOE (Freq.)	
SLU/ Log Acoustic	by partner	Dynamic MOE (Acoustic) on two sides of log	Average value of two opposite sides used
FinScan Oy/ Visual scan of sides	by partner	INSTA visual grading rules, T-Classes	
CBS-CBT/ Ultrasound	by partner	Indicating property for MOE Indicating property for MOR	
Microtec/ Natural Frequency	by partner	Dynamic MOE (Freq.) Dynamic MOE (Freq. + Dens.), I.P.	
Microtec/ X-ray	by partner	Density parameters (Aver., Clear, Min.) Knot parameters, I.P.	Destructive test loading position information used in analysis
Raute Users Group/ Flatwise static bending	by VTT	Flatwise bending MOE (I.P.)	Destructive test loading position information used in analysis
Brookhuis/TNO/ Natural Frequency,	by partner	I.P. for MOE based on Edyn (Freq. + Dens.) I.P. for MOR based on Edyn (Freq. + Dens.)	
TUT/MIT & Metsäteho Oy Photograph of board ends	by partner	Average annual ring width Aver. ring width at outer quarters Aver. ring width at inner half	
TU-Graz, VTT/ Dielectric const.	by VTT	Slope of grain angle	Destructive test loading position information used in analysis

Partner/ Method	**Analysis of raw measurement data**	**Parameters used in correlation analysis**	**Notes about correlation analysis**
VTT/ Static compression	by VTT	Compression MOE	
Weighing	by VTT	Global density	No moisture correction was applied
Finnomoist, Gamma ray, Microwave	by VTT	Density (Gamma ray)	
Finnograder Gammaray, Microwave	by Finnograder machine and VTT	Density (Gamma-ray) Knot parameter Knot eccentricity Slope of grain Slope of grain at knot Finnogr. strength I.P.	Destructive test loading position information used in analysis
Knot area analysis	by VTT	Total knot area ratio (KAR) Knot cluster (KCL)	Determined from the cross-section that was critical during testing

Table 12. Coefficient of determination r^2 of individual NDT-measurements or grading machines to destructively determined properties for spruce. NDT-measurement type codes: L = length, W = weighing (W_S = weighing of sampel discs), F = natural frequency, A = Acoustic tomography, P= digital image/photograph, X = X-ray (X_D = Xray with only density used), G = gamma-ray, I = IR, M = Microwave, U = Ultrasonic, R = Electric Resistance (for moisture content), B = Bending stiffness, C = compression stiffness, V = Visual inspection.

SPRUCE Source	Measurements included	to destruct. r^2 of	*MOR*	*MOE-Local*	*MOE-Glob.*	*Dens., R_u*
Destructive		MOR	1.00			
Destructive		MOE-Local	0.65	1.00		
Destructive		MOE-Global	0.67	0.92	1.00	
Destructive		Dens., R_u	0.37	0.50	0.58	1.00
SLU/Log-Freq.	F,L	Log-Edyn (Freq.)	0.23	0.32	0.37	0.13
SLU/Log-Freq. + Dens.	F,W_S,L	Log-Edyn (Freq. + Dens.)	0.27	0.38	0.42	0.24
SLU/Log-Acoust.	A,L	Log-Acoustic	0.36	0.45	0.53	0.25
SLU/Log-Acoust. + Dens.	A,W_S,L	Log-Acoustic + Dens.	0.52	0.68	0.73	0.49
Bintec/Log X-ray	X	Log-X knot A	0.23	0.14	0.13	0.04
Bintec/Log X-ray	X	Log-X knot B	0.15	0.09	0.11	0.02
Bintec/Log X-ray	X	Log-X knot C	0.20	0.14	0.14	0.01
Bintec/Log X-ray	X	Log-X density sapw.	0.02	0.01	0.01	0.04
Bintec/Log X-ray	X	Log-X density heartw.	0.03	0.03	0.03	0.25
Bintec/Log X-ray	X	Log-X annual ring width	0.19	0.23	0.23	0.09
FinScan/Visual	P	T Class (INSTA rules/machine)	0.22	0.14	0.12	0.02
MiCROTEC/Freq.	F,L	Edyn1 (Freq.) I.P.	0.46	0.64	0.67	0.19
MiCROTEC/Freq. + Dens.	F,X_D,L	Edyn1 (Freq. + Dens.)	0.60	0.82	0.89	0.62
MiCROTEC/Freq. + X-ray	F,X,L	Edyn1 + X-ray I.P.	0.67	0.84	0.91	0.94
MiCROTEC/X-ray	X	X-ray aver. density	0.37	0.51	0.59	0.94
MiCROTEC/X-ray	X	X-ray min density	0.43	0.57	0.66	0.90
MiCROTEC/X-ray	X	X-ray clear density	0.41	0.55	0.63	0.94

SPRUCE Source	Measurements included	to destruct. r^2 of	*MOR*	*MOE-Local*	*MOE-Glob.*	*Dens., R_u*
MiCROTEC/X-ray	X	X-ray Knot a	0.37	0.33	0.31	0.16
MiCROTEC/X-ray	X	X-ray Knot b	0.31	0.26	0.25	0.13
MiCROTEC/X-ray	X	X-ray Knot c	0.41	0.38	0.34	0.17
MiCROTEC/X-ray	X	X-ray Dens. + Knots I.P.	0.57	0.65	0.70	0.94
CBS-CBT/Ultrasonic	U,R,L	Ultrasonic I.P.-MOR	0.48	0.53	0.54	0.23
CBS-CBT/Ultrasonic	U,R,L	Ultrasonic I.P.-MOE	0.42	0.59	0.57	0.15
VTT/Metriguard	S	MG Slope of grain	0.02	0.01	0.03	0.01
VTT/Weighing by scale	W	Glob. density	0.37	0.51	0.59	0.94
VTT/Finnomoist	G,I,M	Gammaray density	0.33	0.45	0.55	0.88
Finnograder	G,I,M	FG Knot	0.31	0.27	0.20	0.05
Finnograder	G,I,M	FG Knot eccentricity	0.17	0.08	0.07	0.03
Finnograder	G,I,M	FG Slope of grain	0.07	0.03	0.02	0.01
Finnograder	G,I,M	FG Sl. of gr. at knot	0.11	0.07	0.07	0.00
Finnograder	G,I,M	FG Density	0.35	0.47	0.54	0.87
Finnograder	G,I,M	FG I.P.-MOR	0.38	0.35	0.35	0.22
RAUTE/flatwise stiffn.	B	Raute Estat (flatwise)	0.57	0.68	0.76	0.44
Brookhuis/TNO/Freq.	F,W,L	Edyn2 (Freq. + Dens.) I.P.-MOE	0.57	0.78	0.84	0.62
Brookhuis/TNO/Freq.	F,W,L	Edyn2 (Freq. + Dens.) I.P.-MOR	0.57	0.77	0.85	0.71
VTT/Compression	C,L	Ecompression	0.34	0.43	0.49	0.43
TUT/MIT & Metsäteho	P	Ring Width Aver.	0.38	0.48	0.53	0.35
TUT/MIT & Metsäteho	P	R.W. Aver., outer 1/4's	0.36	0.47	0.51	0.32
TUT/MIT & Metsäteho	P	R.W. Aver., inner 1/2	0.32	0.40	0.44	0.30
VTT/Visual/Manual	V	Total knot area ratio, KAR	0.21	0.16	0.11	0.03
VTT/Visual/Manual	V	Knot cluster, KCL	0.23	0.17	0.11	0.03

Table 13. Coefficient of determination r^2 of individual NDT-measurements or grading machines to destructively determined properties for pine. NDT-measurement type codes: L = length, W = weighing (W_S = weighing of sampel discs), F = natural frequency, A = Acoustic tomography, P= digital image/photograph, X = X-ray (X_D = Xray with only density used), G = gamma-ray, I = Infrared, M = Microwave, U = Ultrasonic, R = Electric Resistance (for moisture content), B = Bending stiffness, C = compression stiffness, V = Visual inspection.

PINE Source	Measurements included	to destruct. r^2 of	*MOR*	*MOE-Local*	*MOE-Glob.*	*Dens., R_u*
Destructive		MOR	1.00			
Destructive		MOE-Local	0.68	1.00		
Destructive		MOE-Global	0.69	0.95	1.00	
Destructive		Dens., R_u	0.58	0.65	0.72	1.00
SLU/Log-Freq.	F,L	Log-Edyn (Freq.)	0.35	0.55	0.60	0.40
SLU/Log-Freq. + Dens.	F,W_S,L	Log-Edyn (Freq. + Dens.)	0.36	0.66	0.69	0.48
Bintec/Log X-ray	X	Log-X knot A	0.63	0.48	0.45	0.39
Bintec/Log X-ray	X	Log-X knot C	0.30	0.19	0.19	0.13
Bintec/Log X-ray	X	Log-X Dens. sapw.	0.14	0.21	0.21	0.17
Bintec/Log X-ray	X	Log-X Dens. heartw.	0.39	0.42	0.44	0.51
FinScan/Visual	P	T Class (INSTA rules/machine)	0.55	0.43	0.43	0.32
MiCROTEC/Freq.	F,L	Edyn1 (Freq.), I.P.	0.62	0.77	0.79	0.50
MiCROTEC/Freq. + Dens.	F,X_D,L	Edyn1 (Freq. + Dens.)	0.69	0.87	0.92	0.81
MiCROTEC/Freq. + X-ray	F,X,L	Edyn1 + X-ray, I.P.	0.80	0.90	0.92	0.95
MiCROTEC/X-ray	X	X-ray aver. density	0.56	0.69	0.76	0.94
MiCROTEC/X-ray	X	X-ray min density	0.54	0.66	0.73	0.92
MiCROTEC/X-ray	X	X-ray clear density	0.60	0.70	0.77	0.95
MiCROTEC/X-ray	X	X-ray knot a	0.62	0.45	0.44	0.42
MiCROTEC/X-ray	X	X-ray knot b	0.68	0.48	0.46	0.43
MiCROTEC/X-ray	X	X-ray knot c	0.63	0.46	0.45	0.42
MiCROTEC/X-ray	X	X-ray Dens. + knots, I.P.	0.78	0.74	0.79	0.95

PINE Source	Measurements included	to destruct. r^2 of	*MOR*	*MOE-Local*	*MOE-Glob.*	*Dens., R_u*
CBS-CBT/Ultrasonic	U,R,L	Ultrasonic I.P. MOR	0.79	0.67	0.70	0.54
CBS-CBT/Ultrasonic	U,R,L	Ultrasonic I.P. MOE	0.66	0.74	0.75	0.48
VTT/Metriguard	S	MG Slope of grain	0.18	0.16	0.17	0.13
VTT/Weighing	W	Glob. density	0.55	0.67	0.75	0.93
VTT/Finnomoist	G,I,M	Gammaray density	0.54	0.61	0.67	0.87
Finnograder	G,I,M	FG Knot	0.61	0.34	0.34	0.39
Finnograder	G,I,M	FG Knot eccentricity	0.35	0.16	0.17	0.20
Finnograder	G,I,M	FG Slope of grain	0.02	0.03	0.04	0.01
Finnograder	G,I,M	FG Sl. of grain at knot	0.20	0.16	0.14	0.08
Finnograder	G,I,M	FG Density	0.54	0.59	0.65	0.90
Finnograder	G,I,M	FG I.P. -MOR	0.65	0.49	0.49	0.60
RAUTE/flatwise stiffn.	B	Raute Estat (flatwise)	0.72	0.82	0.87	0.78
Brookhuis/TNO/Freq.	F,W,L	Edyn2 (Freq. +.Dens.) I.P.-MOE	0.69	0.83	0.88	0.83
Brookhuis/TNO/Freq.	F,W,L	Edyn2 (Freq. + Dens.) I.P.-MOR	0.68	0.84	0.90	0.86
VTT	C,L	Ecompression	0.18	0.20	0.21	0.18
TUT/MIT & Metsäteho	P	Ring Width Aver.	0.34	0.33	0.40	0.38
TUT/MIT & Metsäteho	P	R.W. Aver., outer 1/4's	0.20	0.24	0.29	0.20
TUT/MIT & Metsäteho	P	R.W. Aver., inner 1/2	0.37	0.34	0.39	0.42
VTT/Visual/Manual	V	Total knot area ratio, KAR	0.54	0.35	0.34	0.35
VTT/Visual/Manual	V	Knot cluster, KCL	0.58	0.39	0.39	0.41

4.3 Correlations between destructive results and combinations of NDT-results

As a next step, multi-variable regression analyses with two or more NDT-parameters as simultaneous predictors of the destructively determined properties were carried out. Because not all parameters that were included in the single parameter analyses above are really relevant for the combination analyses, only selected ones were included. Parameters were excluded either because their potential to predict the grade determining parameters is low judged by the single parameter regression analysis (e.g. slope of grain, compression MOE) or because they are a duplicate to some other parameter (e.g. the two dynamic MOE values based on natural frequency and the density values determined by gamma-rays). Even for the selected parameters, not all possible combinations were analysed. The combinations were selected so that a certain measurement was first picked out and then judged, which could possibly bring new information to its prediction.

As a starting point, analyses with two parameters together were made. These combination analyses were made with exactly same parameter data as the single parameter regression analyses. Only a few analyses were made with three or more parameters. The results of the combination analyses are given in Table 14 in terms of r^2.

For both X-ray methods (log and board) a combination analysis of all parameters obtained from each one was made also, because the X-ray scannings provide several parameters, which are immediately available for strength prediction. A combination analysis was also made for the Finnograder parameters together. All of these are also reported in Table 14.

Table 14. Coefficient of determination r^2 of combined NDT-parameters as predictors of the destructively determined properties.

	Spruce			Pine		
	MOR	MOE global	Density	MOR	MOE global	Density
Log-Xray all parms.	0.47	0.46	0.51	0.69	0.58	0.58
Log-X knot A	0.23	0.13	0.04	0.63	0.45	0.39
+ Log-X heartw. dens.	0.24	0.15	0.28	0.67	0.57	0.58
+ Log-E_{dyn} (Freq.)	0.43	0.48	0.17	0.68	0.70	0.53
+ E_{dyn} (Freq. + Dens.)	0.65	0.90	0.63	0.78	0.92	0.81
+ Log Acoustic	0.50	0.57	0.25			
+ T class	0.32	0.18	0.04	0.71	0.53	0.44
Log E_{dyn} (Freq.)	0.23	0.37	0.13	0.35	0.60	0.40
+ Global density	0.44	0.71	0.94	0.57	0.82	0.93
+ Gammaray density	0.40	0.66	0.88	0.57	0.78	0.88
+ Ring width	0.42	0.60	0.35	0.43	0.64	0.48
+ Log X heartw. dens.	0.31	0.49	0.50	0.56	0.78	0.68
+ log-X knot A	0.43	0.48	0.17	0.68	0.70	0.53
Log Acoustic	0.36	0.53	0.25			
+ Global density	0.49	0.78	0.95			
+ Gammaray density	0.47	0.76	0.91			
+ Ring width aver.	0.42	0.61	0.37			
+ Log X heartw. dens.	0.52	0.74	0.72			
+ Log X knot A	0.50	0.57	0.25			
E_{dyn} (Freq.)	0.46	0.67	0.19	0.62	0.79	0.50
+ KAR	0.51	0.71	0.24	0.73	0.79	0.55
+ Ring width aver.	0.52	0.75	0.36	0.62	0.79	0.54
+ US I.P. MOR/MOE	0.52	0.68	0.23	0.80	0.83	0.58
E_{dyn} (Freq.+ Dens.)	0.60	0.89	0.62	0.69	0.92	0.81
+ Global density	0.60	0.90	0.94	0.70	0.92	0.94
+ X-ray clear dens.	0.60	0.90	0.92	0.69	0.92	0.95
+ X-ray knot a	0.63	0.89	0.62	0.75	0.92	0.82
+ KAR	0.65	0.90	0.65	0.77	0.92	0.81
+ Ring width aver.	0.60	0.90	0.62	0.69	0.92	0.81
+ US I.P. MOR/MOE	0.61	0.89	0.71	0.81	0.92	0.86
+ Log-X knot A	0.65	0.90	0.63	0.78	0.92	0.81
+ All X-ray params.	0.67	0.91	0.94	0.80	0.92	0.95
US. I.P.-MOR/MOE	0.48	0.57	0.23	0.79	0.75	0.54

	Spruce			Pine		
	MOR	MOE global	Density	MOR	MOE global	Density
+ Global density	0.59	0.85	0.94	0.81	0.89	0.93
+ Gammaray density	0.56	0.82	0.88	0.81	0.86	0.88
+ KAR	0.53	0.59	0.30	0.84	0.76	0.59
+ T class	0.51	0.57	0.25	0.80	0.77	0.54
+ Ring width aver.	0.56	0.70	0.37	0.79	0.76	0.59
+ E_{dyn} (Freq. + Dens.)	0.61	0.89	0.71	0.81	0.92	0.86
Flatw. bend. (Raute)	0.57	0.76	0.44	0.72	0.87	0.78
+ Global density	0.59	0.82	0.94	0.72	0.88	0.94
+ Gammaray density	0.58	0.81	0.88	0.72	0.87	0.90
+ X-ray clear density	0.60	0.83	0.94	0.72	0.88	0.95
+ KAR	0.63	0.81	0.56	0.76	0.88	0.78
+ Ultras. I.P.	0.63	0.82	0.50	0.82	0.89	0.80
+ Log-X knot A	0.62	0.77	0.44	0.79	0.87	0.78
X-ray All params.	0.57	0.70	0.94	0.78	0.79	0.95
+ E-dyn (Freq. + Dens.)	0.67	0.91	0.94	0.80	0.92	0.95
X-ray clear density	0.41	0.63	0.94	0.60	0.77	0.95
+ X-ray knot a	0.56	0.69	0.94	0.75	0.79	0.95
+ Ring Width	0.49	0.71	0.94	0.62	0.78	0.95
+ Knot a + R.W.	0.62	0.76	0.94	0.75	0.79	0.95
Ring width aver	0.38	0.53	0.35	0.34	0.40	0.38
+ Edyn (Freq.)	0.52	0.75	0.36	0.62	0.79	0.54
+ KAR	0.52	0.58	0.38	0.60	0.50	0.49
+ Global density	0.46	0.69	0.94	0.58	0.77	0.94
+ KAR + Global dens.	0.60	0.73	0.94	0.70	0.77	0.94
Global density	0.37	0.59	0.94	0.55	0.75	0.93
+ KAR	0.55	0.65	0.94	0.70	0.76	0.94
+ Ring width aver	0.46	0.69	0.94	0.58	0.77	0.94
+ KAR + Ring width	0.60	0.73	0.94	0.70	0.77	0.94
T Class (INSTA)	0.22	0.12	0.02	0.55	0.43	0.32
+ E_{dyn} (Freq. + Dens.)	0.64	0.89	0.65	0.77	0.92	0.81
+ Global density	0.54	0.66	0.94	0.71	0.80	0.94
+ Gammaray density	0.50	0.62	0.88	0.70	0.73	0.88
+ Ring width	0.51	0.57	0.35	0.62	0.56	0.48
+ Glob. dens. + Ring w.	0.59	0.74	0.94	0.72	0.81	0.94
+ Log E_{dyn} (Freq.)	0.37	0.42	0.14	0.63	0.72	0.51
+ Log Acoustic	0.45	0.55	0.25			
KAR	0.21	0.11	0.03	0.54	0.34	0.35

	Spruce			Pine		
	MOR	MOE global	Density	MOR	MOE global	Density
+ Edyn (Freq.)	0.51	0.71	0.24	0.73	0.79	0.55
+ Global density	0.55	0.65	0.94	0.70	0.76	0.94
+ Ring width aver	0.52	0.58	0.38	0.60	0.50	0.49
+ Global dens. + R.W.	0.60	0.73	0.94	0.70	0.77	0.94
FG density	0.35	0.54	0.87	0.54	0.65	0.90
+ FG knot	0.55	0.64	0.87	0.71	0.66	0.90
+ FG knot + knot ecc.	0.58	0.65	0.88	0.72	0.66	0.91
+ FG slope of grain	0.44	0.58	0.87	0.54	0.66	0.90
+ FG s.g + s.g. at knot	0.46	0.60	0.87	0.61	0.67	0.90
FG All parameters	0.63	0.67	0.88	0.77	0.69	0.91

5. Discussion and Conclusions

5.1 Sampling

The sample of sawn timber that was used in this work was a fairly small one – only approx. 100 pieces of both species. It is not large enough to retain statistical relationships of timber properties with sufficient reliability in order to make conclusions for settings of strength grading machines, which requires a minimum of 900 specimens (prEN 14081, CEN 2005). The small number of specimens was naturally dictated by the necessity to keep the cost of the work on an acceptable level.

Because the objective of the work was particularly to find out the capability of NDT-methods to differentiate between different timber material, the test material was selected in a special way in order to try to counterbalance the low number of specimens. The idea was to ensure that the sample would contain pieces from as many different origins as possible and pieces with extraordinary properties would be over-represented in the sample. These ideas led to the selection process described above. The success of the idea can be assessed by the obtained statistical distributions of the destructive properties. Table 9 shows the average values and coefficients of variation of the destructively obtained properties and compares them to a previous study with same cross-section size with a larger sample size (Ranta-Maunus et al. 2001). It can be seen that the averages of pine do not deviate much, whereas the averages of spruce of this work are lower. The CoV's in the present work are slightly higher than in the previous work. It appears that even if the special selection has not had a dramatic effect on these statistical parameters describing the properties, it has worked towards the anticipated direction to increase variability in the sample. Also, because the tested material per species was obtained from only one sawmill, there may have been the danger of obtaining a distribution of properties with smaller variation than normal, which indeed has been avoided. It may be said that on average the spruce used here has been lighter and weaker than in the previous study.

5.2 Correlations of single parameters

The correlations between destructively determined properties (Table 10) can be used as a baseline when assessing the correlations of the NDT-parameters. One of the facts that can be noticed directly from Table 10 is that spruce and pine do show different behaviour in regard to how the strength and stiffness can be predicted. This is further confirmed by the correlations of the NDT-methods shown in Table 12 and Table 13. Therefore the treatment of the two species separately is the only reasonable way to examine the results.

In the following outline, the NDT-parameters have been dealt with as categorised into five classes: stiffness, density parameters, knot parameters, X-ray parameters and other board measurement results. Parameters measured on logs are dealt with separately.

5.2.1 Stiffness parameters (boards)

The stiffness parameters (E_{stat}, E_{dyn}, US-ind.prop.) have the best single-variable correlations to bending strength (MOR r^2 values around 0.5–0.8). Naturally, their correlations to the stiffness measured in the destructive tests (especially MOE-global) are also the highest. They perform quite satisfactorily also in predicting the density of pine. The effectiveness of E_{dyn} is clearly better, when it is calculated based on a measured density value [E_{dyn} (Freq. & Dens.)] than on default density [E_{dyn} (Freq.)]. This holds especially for spruce, and it must be remembered that this in effect means the combination of two measurements.

The correlation between compression-MOE and strength was lower than expected. A reason to this may be that even if the boards were laterally braced at several locations during compression some lateral deflection occurred, which was enough to blur the relationship to strength.

5.2.2 Density parameters (boards)

The non-destructive density parameters, regardless of how the density was measured (weighing, X-ray, gamma-ray) have correlations to bending strength rather close to each other with r^2 around 0.3–0.4 for spruce and 0.5–0.6 for pine (the clear density measured with X-ray has the best value for both species, 0.41 and 0.60, respectively). These values are of the same magnitude or even higher than the destructively determined density itself has (0.37 spruce, 0.58 pine). It can be concluded that density as a physical variable determines the bending strength up to this amount. Notable is that for pine density is a much better predictor of strength than for spruce.

Density parameters typically give some 0.2 higher r^2 values for correlations to stiffness (MOE-global) than they give to strength. The well-known fact, that stiffness is a more global property than strength and thus more dependent on density, is revealed here. Again, pine gets higher correlations than spruce. Naturally, the correlation of the non-destructive density parameters to the destructively determined density is very strong, r^2 value approx. 0.9 or above.

5.2.3 Knot parameters (boards)

Knot parameters can be determined in several ways. In this study, the knot parameters which were determined by irradiation (X-rays, gamma-rays) performed slightly better than the parameters that were determined with only surface inspection (KAR, KCL) when predicting strength. Remarkable are the much higher r^2 values for pine than spruce: knots determine a greater percentage of the bending strength of pine than of spruce.

By knots, even the stiffness and density of pine can be rather well predicted (r^2 values approx. 0.35–0.5). For spruce, on the contrary, the correlation of KAR to the stiffness and density is poor (r^2 0.11 and 0.03) – but for the X-ray based knot parameters somewhat better (r^2 approx. 0.3 and 0.2). It was noticed that the low correlations of KAR and KCL was partly due to some boards, which had high value of KAR and KCL but still considerable strength. It might be possible to improve the correlations by somehow eliminating the effect of very high values for KAR and KCL.

5.2.4 X-ray parameters together (boards)

The combination of all X-ray parameters is considered here along with the single parameters, because all X-ray results are available immediately after the one measurement run. The X-ray measurement parameters together achieve the same level of correlation as the best single parameters (stiffness related); see Table 14. Moreover, the X-ray scan provides the information on the location of knots, which can help to cut out big knots or knot clusters out of the boards in order to upgrade the timber.

5.2.5 Other board parameters

The average ring width parameter shows a feature that is opposite to all other parameters: the correlations are at least as high as or even higher for spruce than pine. It shows correlations with r^2 value of 0.3–0.4 for all properties except the stiffness of spruce, for which the correlation has r^2 value of approx. 0.5. It may be speculated, if the annual ring width has a separate direct effect to the strength and stiffness of spruce, other than the effects of density.

All correlations of the slope of grain have such low r^2 values, that it can be concluded not to have relevant potential to predict the grade determining properties of either spruce or pine. However, severe slope of grain values cause a dramatic drop of strength, but their probability of occurrence is very low and thus not seen in correlations (Glos 2004).

The INSTA T-class cannot be classified with or compared to any of the above categories of parameters, because it only applies the visual INSTA rules to determine a strength class for the boards. Consequently, the only possible values it can get are the four classes T0, T1, T2 and T3. Nevertheless, a similar correlation analysis was done for it. The INSTA rules contain rules concerning various properties of the boards, although the main emphasis in practise is on knots. Probably consequently, the r^2 values obtained resemble closely those of KAR.

5.2.6 Log measurements

A surprising result is the high correlations that the log measurements have to the properties that were measured destructively from the sawn boards. No specific equipment is available for log-based strength grading and the methods used now were just adopted from other primary uses. The best knot parameter measured by log X-ray has as high r^2 value as 0.63 to the strength of pine. The dynamic MOE based on natural frequency measurement correlates to the stiffness of the pine boards with an r^2 value of 0.60.

For spruce, all correlations of the log measurements are lower than for pine. The best single parameter for spruce is the dynamic MOE based on acoustic transit time. Unfortunately, its value was not obtained for pine.

However, it is important to notice that all parameters obtained from the Log X-ray measurements are readily available at the same time, so their combined analysis (see Table 14) is without further measurement efforts available. Thus the Log X-ray measurement gives the highest correlations of log measurements for both spruce and pine.

5.3 Correlations of combined analyses

Based on the r^2-values of the combined analyses (Table 14), it can be said on a general level, that combining two sufficiently different measurements raises the r^2 value in many cases by about 0.1. But, it is more difficult to improve the best single measurements with already high r^2-values than the weaker ones by combination to other methods. The best correlations to bending strength obtained in the combined analyses are of the order of r^2 = 0.8–0.85 for pine and 0.6–0.65 for spruce.

It is difficult to improve greatly the high r^2-values of stiffness measurements with auxiliary measurements. However, combining knot or density measurements with them can improve the result. Especially, the combining of density measurement to E_{dyn} (freq.) or ultrasonic measurement improves the result for spruce, which shows relatively low correlation for natural frequency and ultrasonic measurement alone. Combining both knot and density measurement (by e.g. X-ray measurement) with them further improves the results.

Density and knot measurements together seem to be a rather effective combination. It increases the r^2 values to above 0.5 for spruce and to 0.7 for pine. If they are further supplemented by annual ring width measurement, even higher r^2-values result: approx. 0.6 for spruce and 0.7 for pine.

The combination analysis of the Finnograder parameters (resulting from gamma ray and microwave measurements) showed considerably better coefficient of determination than the Finnograder indicating property as a single parameter. The indicating property has been derived at a time when such number crunching possibilities were not available as are now. In any case, the result shows that the gamma ray and microwave measurement combination has good potential for strength grading.

5.4 Conclusion about correlations

It should be emphasized that the correlations and r^2 values given above for the different methods must be considered only as indicative, because uncertainty is linked with them due to the small sample size. Therefore small differences of r^2 values should not be used as indication of superiority of a certain method compared to another.

The results of the correlation analyses are compactly summarized in Table 15, where the middle column serves as a "vertical axis" containing r^2-ranges in order. Chosen single NDT-methods and their combinations are placed on both sides of the "vertical axes" beside the r^2 range that they could reach in the measurements of this project. The values for spruce are on the left side of the "axis" and pine on the right.

Table 15. A summary of the correlation analysis results. Raute = static stiffness by Raute Timgrader machine, E_{dyn} values represent values calculated with default density = E_{dyn} (Freq.). **Single measurements** *with boldface, logical operators AND/OR used for description of combinations.*

Spruce	r^2 range	**Pine**
	...0,9 0,8...	Ultras. AND (knot OR density OR Raute) E_{dyn} AND Board X-ray
	...0,8 0,7...	**Ultrasound**, E_{dyn} AND dens. AND knot, Raute AND knots, **Raute**, **Board X-ray**, E_{dyn} AND knot knot AND density
E_{dyn} AND (Board X-ray OR log X-ray) E_{dyn} AND (dens. AND (knot OR US)), Raute AND Knots	...0,7 0,6...	**Log X-ray**, E_{dyn} AND density knot AND (ring width OR log E_{dyn}) **E_{dyn}**
E_{dyn} AND Dens., Knot AND Density AND Ring w. **Raute**, **Board X-ray**, US AND density,	...0,6 0,5...	**knot**, log E_{dyn} AND density **density**
US, E_{dyn},(ring OR knot OR log knot) AND log Acoust **Log X-ray**, (dens OR ring OR log knot) AND log E_{dyn}	...0,5 0,4...	log E_{dyn} AND ring width
ring width, density, log Acoustic	...0,4 0,3...	**log E_{dyn}, ring width**
knot, log E_{dyn}	...0,3 0,2...	

5.5 Implications to strength grading yield

The effectiveness of various grading methods was analysed by the use of numerical simulation. The same method as described by Turk and Ranta-Maunus (2004) was used. The method included numerical generation of samples based on statistical parameters of experimental data, mean value vector and variance-covariance matrix. Firstly, determination of settings according to EN 14081 was made based on 100 samples with 250 generated values of strength, modulus of elasticity, density, and non-destructive grading parameters. prEN 14081 requires basically 4×250 test values. Settings were determined separately for each sample, and these settings were applied to another sample with generated 10000 specimens. Yield to different grades was calculated as well as strength parameters of graded timber were analysed. Finally, mean values and standard deviations of yields and strength parameters were calculated.

The analysis was limited to a few grading methods basically because the sampling of test material was obviously not adequate and representative to allow drawing firm conclusions. Anyway, it was considered useful to analyse, what would happen in grading, in case timber properties would follow the same distributions as in our sampling.

Following grading parameters were used in the analysis:

- dynamic modulus of elasticity calculated based on natural frequency and measured density (E_{dyn} (Freq. & Dens.))
- combination of E_{dyn} (Freq. & Dens.) and density, i.e. taking the NDT-measured density along as a separate predictor to increase the prediction accuracy of density as grade determining property
- knot area ratio KAR measured manually
- INSTA T class measured by industrial scanning or KAR combined with global density.

The motivation of analysing these methods was:

1. E_{dyn} (Freq. & Dens.) corresponds closely to E_{stat}, which is a well established grading method but not under vigorous development any more, and was used as reference case. Also Ultrasonic and board X-ray could be alternatives and probably give similar results.
2. Density (clear wood density) was combined with E_{dyn} (Freq. & Dens.) to see the effect of improved correlation of density as a grade determining parameter itself. Both a combined grading parameter (regression equation) and a set of two parallel parameters were used.
3. Because correlation between knot parameters and strength of pine is relatively high, the effectiveness of grading based on knots only and on knots combined with density measured by weighing of planks were analysed. Again, a combined grading parameter and a dual parameter model were used.

The results given in Table 16 are obtained by simultaneous grading to three grades C40, C30 and C18. Yield in case of optimum grading, mean value of yields and standard deviation are given. When settings are determined according to EN 14081, mean values of four samples can be used, and accordingly, the standard deviation of yields will be divided by two.

Table 16 contains also two grading quality parameters. The first one is deviation of the 5-percentile value of strength in each grade from the code value, e.g. 40, 30 or 18, respectively. 5-percentiles are calculated based on nonparametric method. Second, the form of lower tail of strength is analysed and expressed in the form of the ratio of 0.5-percentile to 5-percentile value.

Results for generated spruce values show that average yield of E_{dyn} (Freq. & Dens.) to C40 would be raised from 19,4% to 20,1% or 21,8% by combining density as distinct grading parameter, depending on how the combination of two parameters is made. Separate settings for E_{dyn} and density seem to give best yield to the highest grade and lowest number of rejects. In practical grading this small advantage cannot be witnessed because of the random effects in determination of settings.

Visual grading of spruce is known to have quite weak correlation to strength. Therefore, combination of INSTA T class determined by machine vision and global density, gives surprisingly good yield to C40, 16.8% when optimum yield is 32.6%, and low number of rejects, 3.7%.

Results for pine show yield 33.5% to C40 for E_{dyn} (Freq. & Dens.) alone, nearly same numbers when combined with density measurements. Dual criteria model gives practically identical result with E_{dyn} (Freq. & Dens.) alone for yields to all grades. A combined model, regression line, would give higher yield to C30 and more rejects, which would result in a more acceptable 5-percentile of strength.

The most important result of these simulations is that a knot criterion combined with density information can work as well as established machine grading methods for pine.

Yield to C40 can be 30% when yield in optimum grading is 55%. Number of rejects will be higher than in case of spruce.

Simulations show that 5-percentile of bending strength used in design of structures will be exceeded in most cases, and in some cases more than 20%. In a few cases the mean value of 5-percentiles is below the code value. This is observed for pine C18, when KAR or E_{dyn} (Freq. & Dens.) is used in grading.

The ratio of 0.5-percentile to 5-percentile value is in most cases between 0.7 and 0.8 for C40 and C30. For C18 this ratio is below 0.6. Exact values for C18 in Table 16 maybe influenced by the data generation procedure which is based on normal distribution and gives on average 13 negative strength values in a sample of 10 000 pines.

For comparison, some simulation results with old spruce data are included in Table 16 ("spruce 150 mm"). This spruce material is more representative to Finnish forest, and gives 63% yield to C40 in optimum grading and 35% by using E_{dyn} (Freq. & Dens.) measurement.

Table 16. Yield to C40, C30 and C18 when graded simultaneously, quality of grading in terms of deviation of 5 percentile value from code characteristic value and ratio of 0.5 percentile to 5 percentile value, on average. E_{dyn} refers to E_{dyn} (Freq. & Dens.) Yield in optimum grading means the best possible yield percentages, if the grade determining properties were known deterministicly.

Data base of grade determining properties	Indicating property	Yield [%] mean ± standard deviation (yield in optimum grading)				$f_{0.05}$ vs. characteristic value, mean of difference [%]			$\frac{f_{0.005}}{f_{0.05}}$		
		C40	C30	C18	reject	C40	C30	C18	C40	C30	C18
"spruce 150 mm"	Table A/19 in Turk et al (2003)	35,7±9,3 (63,1)	49,1±12,5 (27.8)	12,8±6 (9,0)	(0,1)	+1.4	–0.8	+0.7	0.82	0.75	0.61
	E_{dyn}	34,2±10,6	50,6±13,1	12,8±6,5	2,4±3,8	+3,2	–0,1	+7,5	0,81	0,74	0,64
	E_{dyn} & density	34,7±9,7	50,2±13,5	12,7±6,6	2,4±4,0	+0,7	–1,9	+8,0	0,82	0,73	0,64
"spruce combigrade"	E_{dyn}	19,4±6,4 (32,6)	33,7±10,3 (27,6)	46,1±6,4 (39,8)	0,8±0,6 (0,5)	+6,2	+10,0	+11,1	0,74	0,78	0,56
	E_{dyn} & density	21,8±6,2	30,1±10,1	47,3±6,4	0,8±0,7	+3,3	+9,3	+11,8	0,77	0,78	0,56
	E_{dyn} + density	20,1±8,5	32,9±13,6	44,1±8,0	2,9±4,3	+1,9	+9,7	+15,7	0,70	0,78	0,58
	KAR & density	4,5±6,4	31,0±11,0	57,6±13,1	6,9±9,8	–	+12	+22,4	–	0,75	0,56
	KAR + density	11,1±7,0	21,3±10,7	63,2±9,6	4,4±6,1	–	+19,0	+26,2	–	0,78	0,56
	T class + density	16,8±7,4	21,9±11,6	57,5±13	3,7±6,2	–1,8	+13,9	+21,2	0,76	0,77	0,56

"pine combigrade"	E_{dyn}	33,5±6,7 (54,9)	22,7±11,6 (13,4)	39,9±10,2 (29,6)	3,9±2,1 (2,2)	+4,4	+3,9	–8,6	0,76	0,72	0,35
	E_{dyn} & density	33,8±6,6	22,1±11,0	40,4±9,6	3,7±2,1	+4,0	+3,7	–9,0	0,76	0,72	0,32
	E_{dyn} + density	33,6±10,4	26,4±13,0	32,3±8,5	7,7±6,0	+4,4	+1,5	–2,0	0,71	0,73	0,40
	KAR	23,7±11,5	27,9±12,4	44,7±12,0	3,8±6,2	+3,3	+0,1	–15,7	0,73	0,61	-
	KAR & density	32,1±7,5	25,1±8,4	35,1±9,8	7,7±6,3	+1,6	–3,8	–8,3	0,74	0,69	0,35
	KAR + density	26,8±9,1	15,8±10,5	49,5±11,0	7,8±6,6	+11,4	+18,1	+9,1	0,74	0,75	0,47
	T class + density	29,6±9,1	18,1±11,1	44,6±10,8	7,7±6,7	+7,1	+10,9	+6,3	0,72	0,72	0,43

Note: In combinations of indicating properties:

"&" refers to consideration of 2 indicating properties separately.

"+" refers to using one combined indicating property using linear regression model.

Data base "spruce 150 mm" refers to data of 600 specimens intended to represent spruce grown in Finland.

Other data bases are not representative and have wider deviation of strength properties than representative data.

All test results and simulations concern a single size of sawn timber, having width about 150 mm. As a general comment it can be said that there is a considerable random component in European "machine control" strength grading systems. As an example, when settings of E_{dyn} (Freq. & Dens.) method are based on testing of 4 × 250 randomly sampled specimens, average yield to C40 falls between 26 and 44% in 95% of cases. In practice there will be other factors which increase the variability of results.

5.6 Future research

This project has dealt with the potential of different NDT-methods to predict the grade-determining properties of sawn timber. In one sense, this project is to be seen as a preliminary study, because the sample size was too small to allow the actual development of strength grading procedures. In addition, only one cross-section dimension was used. A proper continuation of the work should include a larger project in which larger samples of several sawn timber dimensions should be investigated. Obviously, the results obtained now do give a good foundation for continuation, since at least a rough picture of the potential of non-destructive methods is available.

6. Summary

6.1 General

The quality of a strength grading system is determined principally by two factors: the ability of the measured parameter(s) to predict strength and the measurement error of the predictor parameter(s). The former can be quantified by regression analysis (the obtained coefficient of determination, r^2) and the latter by the coefficient of variation V of the measurement error. If the regression analysis is based on measurements made in the same conditions and the same apparatus that is used in the strength grading machine, the effect of the measurement error and V is already included in the r^2 value directly. Otherwise, if the measurements are made in laboratory conditions, the effect of measurement error should be considered separately, when evaluating the effectiveness of a certain strength grading system.

In the present study, various non-destructive test (NDT) methods were applied to a sample of approx. 100 spruce and 100 pine specimens with cross section dimensions 46 mm x 146 mm. From these measurements almost 40 NDT-parameters were extracted. After the NDT-measurements the specimens were tested in destructive loading to obtain the bending strength, stiffness and density values of each specimen. All these three properties are grade determining properties in the European system of timber strength classes. Based on regression analyses, the r^2-values of the single NDT-parameters and their combinations were obtained in regard to all three grade determining properties. These values were used to estimate the potential of different strength grading methods by simulation.

The sample size used was rather small, which inevitably brings in the possibility of chance to influence the obtained results. Furthermore, the different measurements were not made in similar conditions. Some of them were made in laboratory conditions and some in true industrial conditions (the conditions of each measurement are explained in Sections 3.2.1–3.2.15). Thus, the results presented should not be used as definitive ranking of the methods. Nevertheless, the indication of the potential of different methods and their combinations has been obtained.

6.2 Evaluation of different methods

It should be emphasized that the r^2 values of the correlations given above for the different methods must be considered as indicative, because uncertainty is linked with them due to the small sample size. *Small differences of r^2 values should not be used as indication of superiority of a certain method compared to another.*

Out of the three grade determining properties, the bending strength is in most cases the critical one. Therefore, in the following outline only correlations with respect to it are considered.

According to the present experimental results, the best single parameter predictors of bending strength are the stiffness parameters (modulus of elasticity [MOE]) measured by either static method, vibration method or by ultrasonic method. X-ray scanning of boards reaches the same level. As single predicting methods of strength these can reach r^2 values of 0.5–0.6 for spruce and 0.7–0.8 for pine. It is difficult to improve significantly their r^2 values with auxiliary measurements. However, combining stiffness parameters with knot or density measurements or X-ray measurement with stiffness parameters does improve the result.

Density as measured by different methods (direct weighing, X-ray or gamma-ray irradiation) can reach r^2 values 0.3–0.4 for spruce and 0.5–0.6 for pine; density in general is a much better predictor of the strength of pine than of spruce. Combination to knot measurement increases the r^2 values to above 0.5 for spruce and to 0.7 for pine.

The ability of knots to predict strength is greatly different for spruce and pine having correlations with r^2-values of approx. 0.2–0.3 and approx. 0.5–0.6, respectively. If knot measurement is supplemented by density or annual ring width measurement, r^2 values show clearly higher results: above 0.5 for spruce and 0.6–0.7 for pine.

Annual ring width is roughly as good predictor of the strength of spruce as density (r^2 value approx. 0.35). For pine it has r^2 value of similar magnitude but is not as good as density for strength prediction. Combination of annual ring width, density and knot measurement can reach r^2 of 0.6 for spruce and 0.7 for pine.

The log measurements showed surprisingly high correlations to strength and, as their development for strength grading is very preliminary so far, seem to have potential in this respect. The log X-ray could reach an r^2 value of 0.47 for spruce strength and 0.69 for pine strength. Log frequency and log acoustic tomography could reach r^2 values of approx. 0.25–0.35.

When considering the fitness of a strength grading system to a certain application, the evaluation of the prediction accuracy in terms of r^2 and V is not adequate alone. Obviously, the price of the system, its fitness to production line and target strength classes are other important factors.

6.3 Potential yield to different strength classes

Yield to different strength classes depends obviously on the quality of timber material to be graded (the yields in the optimum grading) and on the effectiveness of the grading method. When European "machine control" method is used in accordance with prEN 14081, there seems to be also a considerable random factor related to the method of determination of settings. If settings would be determined twice based on appropriate, fully representative sampling in both cases, the two settings obtained could easily produce different yields to the best grade. As an example, yield can vary between 24 and 44% (95% probability to fall between these limits) just because of random effects, when no mistakes are made in the determination of settings or in the grading. This random effect can be limited by using more effective grading and larger sample sizes. However, in nearly all calculated cases the 5-percentile value of strength exceeds 40 N/mm^2 in C40 and exceeds 30 N/mm^2 in C30. Variation of 5-percentile value of C18 is larger, and it can also fall below 18 N/mm^2.

Most grading methods give higher coefficient of determination with strength of pine than strength of spruce. It has to be noticed that in general this does not indicate that yield with grading of pine would be better than with spruce. Larger knot sizes of pine result in larger portion of material belonging to low strength classes.

Combining density with E_{dyn} (Freq. & Dens.) as a second distinct parameter results only in an improved r^2 value for density. This seems not to have any remarkable and consistent effect on yield or strength of graded timber. The effect of combining a knot measure to E_{dyn} (Freq. & Dens.) on yield was not studied yet.

Combination of density and knot measurement has practically same r^2 values for grade determining properties as E_{dyn} (Freq. & Dens.) alone. It was simulated how these methods would compare in terms of yield to C40 and rejects. In both cases (spruce and pine) used in this project, E_{dyn} (Freq. & ens.) gives a bit higher yield to C40 and lower number of rejects, than the combinations of density and knot measure used. These combinations have, however, potential to be further developed.

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Appendix A: Results of destructive results

Destructive test results of spruce.

Rank	h, mm	b, mm	MOR, N/mm^2	MOE-Local, N/mm^2	MOE-Global, N/mm^2	Dens. R_u, kg/m^3	Dens. R_0, kg/m^3	MC, %
1	146.6	45.6	18.6	6100	5900	385	347	11.0
2	146.7	45.6	20.2	8500	8100	403	363	11.0
3	146.8	45.8	20.5	5900	7900	427	384	11.4
4	146.9	45.7	22.4	9700	9500	413	372	11.1
5	146.6	45.9	22.7	8000	7700	391	351	11.3
6	146.8	45.7	22.9	7400	8200	391	351	11.1
7	147.1	45.7	23.0	9200	10200	382	344	11.1
8	146.6	45.7	24.1	9500	8800	368	331	11.1
9	147.4	45.7	25.4	8300	8700	378	340	11.2
10	146.4	45.7	26.2	10600	9500	419	376	11.5
11	146.6	46.0	26.5	8600	7800	356	321	11.1
12	146.4	45.7	27.7	6000	5600	336	302	11.2
13	146.7	45.9	27.9	7900	7900	351	316	11.3
14	146.9	45.8	28.2	10200	11100	441	397	11.1
15	146.7	45.6	28.4	11000	10800	383	344	11.4
16	146.9	45.6	29.0	7800	7100	354	319	11.0
17	146.4	45.7	29.0	10200	10800	418	375	11.5
18	146.4	45.9	29.6	8600	8600	383	344	11.1
19	147.0	45.8	29.8	8500	8400	383	345	11.1
20	145.7	45.7	30.3	9700	9700	428	388	10.5
21	146.9	45.7	30.4	9100	8800	371	333	11.3
22	146.8	45.7	30.4	9500	9800	424	381	11.3
23	146.7	45.6	30.6	9100	8600	335	302	11.0
24	146.8	45.7	31.4	10800	10400	381	343	11.1
25	146.8	45.7	31.4	9200	9700	399	359	11.0
26	146.5	45.9	31.5	9400	8600	392	353	11.2
27	146.9	45.7	32.3	7300	7900	432	389	11.3
28	146.9	45.9	32.6	13100	11400	425	383	11.1
29	146.8	45.8	33.2	8000	8800	404	362	11.6
30	146.9	45.8	34.1	9500	8700	413	370	11.6
31	146.8	45.7	34.3	11800	11600	480	430	11.7
32	146.9	45.9	34.3	8600	8900	414	372	11.5
33	146.7	45.7	34.4	9300	9300	380	341	11.5
34	146.9	45.6	34.6	7800	7700	397	356	11.4
35	146.6	45.5	34.9	9300	9100	394	354	11.3

Rank	h, mm	b, mm	MOR, N/mm^2	MOE-Local, N/mm^2	MOE-Global, N/mm^2	Dens. R_u, kg/m^3	Dens. R_0, kg/m^3	MC, %
36	146.0	45.6	35.6	12500	12600	534	477	11.9
37	146.8	45.9	35.7	11000	10400	366	329	11.2
38	146.9	45.9	35.8	8900	10300	433	388	11.5
39	146.9	45.6	36.5	12000	11700	474	425	11.4
40	146.7	45.8	36.7	8300	9600	438	393	11.5
41	146.8	45.9	36.8	13900	12200	444	399	11.4
42	146.8	45.8	37.1	12700	11700	421	378	11.4
43	146.7	45.8	38.5	10300	9400	385	346	11.1
44	146.7	45.8	38.7	10800	10900	392	353	11.2
45	146.6	45.6	39.1	10000	9600	422	378	11.6
46	147.1	45.7	40.2	9200	8700	412	370	11.3
47	146.7	45.8	40.4	12100	10600	424	381	11.3
48	146.3	45.7	40.4	12300	12000	400	359	11.4
49	145.1	45.8	40.8	10900	11700	409	368	11.2
50	146.7	45.8	40.8	12500	11700	469	421	11.3
51	146.8	45.8	41.2	12000	11100	399	359	11.3
52	146.6	45.8	43.3	14700	14800	517	463	11.7
53	146.2	45.8	44.0	12200	12100	440	395	11.4
54	146.5	45.8	44.0	14300	13200	469	421	11.4
55	146.6	45.7	44.2	14400	13400	449	404	11.2
56	146.4	45.7	44.5	15500	14000	466	417	11.8
57	146.9	45.6	44.9	10600	9900	414	372	11.2
58	146.7	45.7	45.7	12100	11400	443	398	11.3
59	146.6	45.8	45.7	10900	10500	410	368	11.4
60	146.5	45.7	46.0	10700	10500	372	335	11.2
61	147.5	45.8	46.2	12600	12800	490	439	11.7
62	146.4	45.7	46.3	10700	10700	417	375	11.4
63	146.5	45.7	46.8	11500	10800	454	407	11.6
64	146.7	45.8	47.0	12700	11700	454	408	11.4
65	146.8	45.8	47.0	12800	11200	436	391	11.3
66	146.7	45.8	47.5	12300	11500	371	334	11.2
67	146.6	45.8	47.7	13000	12400	436	393	11.0
68	146.6	45.6	48.3	10600	10500	463	415	11.6
69	146.3	46.1	48.4	13700	13000	426	381	11.6
70	146.9	45.7	48.8	12500	12100	418	377	11.1
71	146.4	45.8	48.8	12400	12400	434	389	11.6
72	146.0	45.6	48.9	12900	13200	439	393	11.5
73	146.7	45.5	49.0	9500	9200	465	417	11.5
74	146.5	45.7	49.1	11600	11300	418	375	11.3
75	146.5	45.6	49.4	11700	11400	407	365	11.3

Rank	h, mm	b, mm	MOR, N/mm^2	MOE-Local, N/mm^2	MOE-Global, N/mm^2	Dens. R_u, kg/m^3	Dens. R_0, kg/m^3	MC, %
76	146.7	45.7	49.4	11500	11400	401	361	11.2
77	147.0	45.6	49.5	11200	10900	394	354	11.2
78	146.4	45.7	49.6	9900	9700	396	355	11.6
79	146.8	45.7	49.7	12800	12400	455	409	11.3
80	146.7	45.8	49.9	13900	12900	457	410	11.4
81	146.6	45.8	51.4	12000	11400	441	395	11.5
82	146.9	45.6	51.5	13700	12900	425	382	11.3
83	146.7	45.7	52.1	13400	12500	459	411	11.5
84	146.5	45.8	52.3	12500	12300	390	350	11.5
85	146.2	45.7	52.6	12300	12500	444	399	11.4
86	146.7	45.6	53.1	14300	11700	480	430	11.6
87	146.5	45.6	53.7	10900	12200	489	439	11.4
88	146.8	45.7	53.7	13600	13400	460	413	11.5
89	146.9	45.6	54.5	11300	12000	423	379	11.6
90	147.1	45.7	54.7	11500	11200	401	361	11.0
91	146.4	45.8	54.7	12800	11800	437	393	11.3
92	146.7	45.8	54.9	12600	12200	455	409	11.5
93	146.2	45.6	56.3	13900	13700	529	476	11.2
94	146.7	45.7	56.8	12600	12000	433	388	11.6
95	146.6	46.0	57.3	13400	13300	445	399	11.5
96	146.5	45.8	57.6	13000	12500	465	416	11.8
97	146.7	45.8	58.1	15400	14000	495	443	11.6
98	146.2	45.8	58.4	12100	12100	437	392	11.5
99	146.7	45.7	58.6	14600	13800	429	385	11.5
100	146.8	46.3	58.9	15400	14300	463	415	11.6
101	147.0	45.7	59.0	13800	13900	473	424	11.5
102	146.8	45.8	59.9	13100	12300	420	378	11.2
103	146.3	45.7	61.0	14700	15000	516	462	11.6
104	146.9	45.8	61.0	13400	12600	431	388	11.1
105	146.3	45.7	64.2	13700	12900	434	391	11.1
106	147.0	45.7	64.5	13600	13500	493	443	11.5
107	146.5	45.7	64.5	15000	14300	461	414	11.2
108	146.6	45.8	64.7	14900	15700	502	450	11.6
109	146.5	45.7	66.9	17700	16900	549	491	11.8
110	146.0	45.8	68.1	17300	15300	528	472	11.9
111	146.6	45.5	68.9	16000	15000	471	422	11.5

Destructive test results of pine.

Rank	h, mm	b, mm	MOR, N/mm^2	MOE-Local, N/mm^2	MOE-Global, N/mm^2	Dens. R_u, kg/m^3	Dens. R_0, kg/m^3	MC, %
1	146.9	45.8	16.2	8400	7500	369	333	10.8
2	146.1	45.6	17.2	6600	7700	407	370	10.1
3	146.8	45.9	18.2	6000	7200	388	351	10.7
4	146.5	46.0	18.5	6600	6800	377	341	10.7
5	146.7	45.9	19.0	8000	7300	401	362	10.5
6	146.8	45.7	20.8	6900	7500	438	395	10.8
7	146.8	46.0	22.1	8600	9200	451	406	11.1
8	146.1	46.0	22.2	7600	9900	484	436	11.2
9	146.9	45.7	22.6	6700	8400	466	422	10.5
10	146.2	45.6	22.9	7600	7900	421	378	11.2
11	146.3	45.7	23.4	7800	7900	410	369	11.2
12	146.8	45.8	25.1	13400	11500	490	442	10.9
13	146.5	45.8	25.1	10500	10900	516	468	10.1
14	146.7	46.0	25.4	9600	8600	407	366	10.9
15	146.7	45.7	25.8	9100	8900	430	388	11.0
16	146.8	45.8	26.2	9700	9100	410	371	10.5
17	146.7	45.6	26.3	8400	9100	416	375	10.7
18	145.3	45.7	27.4	9900	9500	450	406	11.0
19	146.4	45.7	27.4	9100	9900	483	435	10.9
20	146.6	45.7	28.0	8300	8200	423	383	10.5
21	146.6	45.7	28.0	7100	8500	417	377	10.7
22	146.6	45.7	28.1	10200	10000	432	391	10.5
23	146.6	45.8	28.7	11200	10600	454	410	10.8
24	146.6	45.5	28.8	9900	10800	472	427	10.6
25	146.6	45.6	29.9	12800	11500	437	393	11.3
26	146.4	45.6	30.5	12300	11000	446	402	11.0
27	146.4	45.6	30.6	10900	10600	453	409	10.9
28	146.5	45.6	31.2	9600	10000	406	367	10.6
29	146.3	45.7	31.5	9500	10100	444	398	11.3
30	146.6	45.7	31.5	9800	9700	421	381	10.6
31	146.7	45.7	31.7	9300	9200	405	367	10.3
32	146.3	45.7	32.0	8500	10300	459	412	11.2
33	146.5	45.7	32.4	11600	11600	497	448	10.9
34	146.7	45.6	32.5	12300	11500	541	487	11.1
35	146.7	45.8	32.7	10800	11500	497	448	11.0
36	146.1	45.6	33.1	9800	9000	414	375	10.6
37	146.4	45.7	33.7	8100	7400	435	392	10.8
38	146.7	45.7	34.8	9700	10000	463	416	11.3

39	146.9	45.9	35.9	11200	9900	478	431	10.8
40	146.8	45.8	37.1	9900	10400	424	382	10.8
41	146.9	45.9	37.3	10200	9600	416	377	10.3
42	146.7	45.6	37.4	11500	11300	479	432	10.9
43	146.7	45.8	37.9	14000	12900	489	441	10.9
44	146.4	45.2	38.5	10800	10600	454	410	10.7
45	145.8	45.6	38.9	12500	11600	445	403	10.6
46	146.8	45.8	40.3	10800	10500	456	412	10.7
47	146.8	45.6	40.8	11500	12800	502	453	11.0
48	146.8	45.7	41.1	14000	13300	498	450	10.6
49	146.7	45.7	41.1	10900	11100	488	438	11.2
50	146.7	45.7	41.4	11800	10800	439	396	11.0
51	146.2	45.7	42.2	9300	10300	469	423	10.9
52	146.9	45.6	42.3	10000	10300	470	426	10.5
53	146.3	45.6	43.1	14400	13600	526	472	11.5
54	146.7	45.6	43.2	13400	13000	438	394	11.3
55	146.6	45.8	44.4	11600	11100	449	406	10.7
56	146.6	45.5	44.6	12500	12900	516	464	11.2
57	146.4	45.7	45.1	14000	12800	539	483	11.6
58	146.6	45.6	46.3	12800	12000	472	427	10.7
59	146.2	45.7	46.6	12700	11700	493	445	10.8
60	146.8	45.6	47.1	13100	12000	434	391	11.1
61	146.3	45.9	47.8	12900	12700	505	453	11.4
62	146.4	45.4	48.4	14800	13900	511	461	10.9
63	146.8	45.9	48.7	11200	11000	440	396	11.1
64	146.6	45.7	48.9	12100	11300	485	435	11.4
65	145.9	45.8	49.7	12100	11200	489	442	10.7
66	146.4	45.6	49.7	12600	11700	460	415	10.8
67	146.3	45.9	51.8	14500	13800	505	455	11.1
68	144.5	45.7	52.1	15100	14200	577	520	11.1
69	146.7	45.6	52.4	14200	13200	529	477	11.0
70	145.1	45.5	53.7	10800	11100	495	446	11.0
71	146.5	45.7	54.1	16400	16100	547	491	11.4
72	146.7	45.8	54.5	14500	13400	574	514	11.7
73	145.5	45.6	54.7	10500	10200	426	384	11.1
74	145.5	45.8	56.4	17000	16000	591	529	11.5
75	147.0	45.8	56.4	14500	13400	499	452	10.4
76	146.7	45.8	56.5	10600	10500	449	406	10.7
77	146.6	45.6	56.7	10400	10500	507	456	11.2
78	146.4	45.6	58.3	14400	14200	518	466	11.2
79	145.5	45.5	58.4	15000	14300	530	476	11.3
80	146.6	45.7	58.4	16200	15800	534	481	11.0
81	145.5	46.0	58.9	13700	12600	503	454	10.9

82	146.6	45.7	59.7	14600	14200	488	438	11.6
83	144.7	45.6	59.8	16400	16500	604	542	11.3
84	146.3	45.8	60.8	15000	14500	478	430	11.1
85	145.6	45.8	61.4	11300	11500	526	473	11.2
86	146.6	45.8	62.8	17000	16300	560	503	11.3
87	146.2	45.7	62.9	15300	14300	501	452	10.8
88	147.0	45.6	63.3	10500	10200	475	428	11.0
89	146.4	45.6	63.7	18000	17000	572	515	11.2
90	146.3	45.7	63.8	13300	12900	583	523	11.6
91	146.6	45.7	63.8	16200	15700	480	432	11.1
92	145.6	45.5	63.9	12800	12300	478	433	10.4
93	146.7	45.7	65.5	18800	17600	619	556	11.3
94	146.2	45.4	65.8	14100	13600	582	519	12.1
95	146.0	45.6	66.2	14800	13800	554	499	11.0
96	146.8	45.6	66.6	14000	12900	492	441	11.5
97	146.1	46.0	66.8	17500	16000	566	507	11.6
98	146.6	45.6	67.7	13600	12600	487	439	10.8
99	146.4	45.7	68.0	17000	16200	560	502	11.6
100	145.6	45.4	68.9	15400	15000	573	513	11.7
101	145.6	45.7	69.2	14600	14100	547	492	11.1
102	146.1	45.5	70.0	15300	14300	571	511	11.7
103	146.2	45.6	70.6	13000	12400	567	507	11.8
104	145.8	45.6	71.1	15700	14800	521	468	11.2
105	145.7	45.8	72.2	15900	14400	538	482	11.6
106	145.0	45.6	73.5	16300	15600	565	508	11.2
107	144.5	45.6	75.2	16900	16100	545	490	11.3
108	146.2	45.6	78.3	15800	15200	639	570	12.0

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Title

Potential of strength grading of timber with combined measurement techniques

Report of the Combigrade-project – phase 1

Abstract

About 100 pieces of both spruce (*Picea abies*) logs and pine (*Pinus sylvestris*) logs were sampled and sawn timber produced. Non-destructive measurements of logs and sawn timber were made by 15 organisations producing 40 different measured quantities for each test piece. Finally, test material was loaded to failure in bending, and grade determining properties (modulus of elasticity, bending strength and density) were measured.

Degrees of determination were calculated between non-destructively measured indicators and grade determining properties. Also strength grading procedure determined by prEN 14081 was simulated numerically, and effectiveness of some potential grading methods was analysed.

It was concluded that the coefficient of determination between strength and most non-destructive indicators was remarkably higher with pine than spruce. Especially knot size and density are potential grading parameters for pine but not for spruce. This does not, however, indicate that yield to high grades would be in general better with pine than spruce, but it indicates that pine has larger variability of knot sizes and density, and consequently higher variability of strength. Log scanning can also produce strength indicators which are on the level of some existing grading methods.

Simulation of European machine grading procedure indicated that there is a random factor which affects the yield to different grades. It can be counteracted by increasing the sample size when determining the settings for grading.

Keywords
sawn timber, strength grading, combined measurement, measuring methods, non-destructive testing, x-ray scanning, acoustic measurement, density measurement, stiffness, gamma rays

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This report documents the results of the first part of "Combigrade"-project. 100 pieces of both spruce (Picea abies) logs and pine (Pinus sylvestris) logs were sampled and sawn timber produced. Non-destructive measurements of logs and sawn timber were made by 15 organisations producing 40 different measured quantities for each test piece. Finally, test material was loaded to failure in bending, and grade determining properties (modulus of elasticity, bending strength and density) were measured. Coefficients of determination were calculated between non-destructively measured indicators and grade determining properties. Also strength grading procedure determined by prEN 14081 was simulated numerically, and effectiveness of some potential grading methods was analysed.

Part 1 of the project is planned to be followed by a larger testing programme enabling the determination of settings for new and combined grading methods in accordance with the up-coming European standard.

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