Modeling MOR in Norway spruce (Picea abies (L) Karst.) structural lumber with stands and tree characteristics

Modelering av MOR i konstruksjonsvirke av norsk gran (Picea abies (L) Karst.) med bestands og trekarakteristikker

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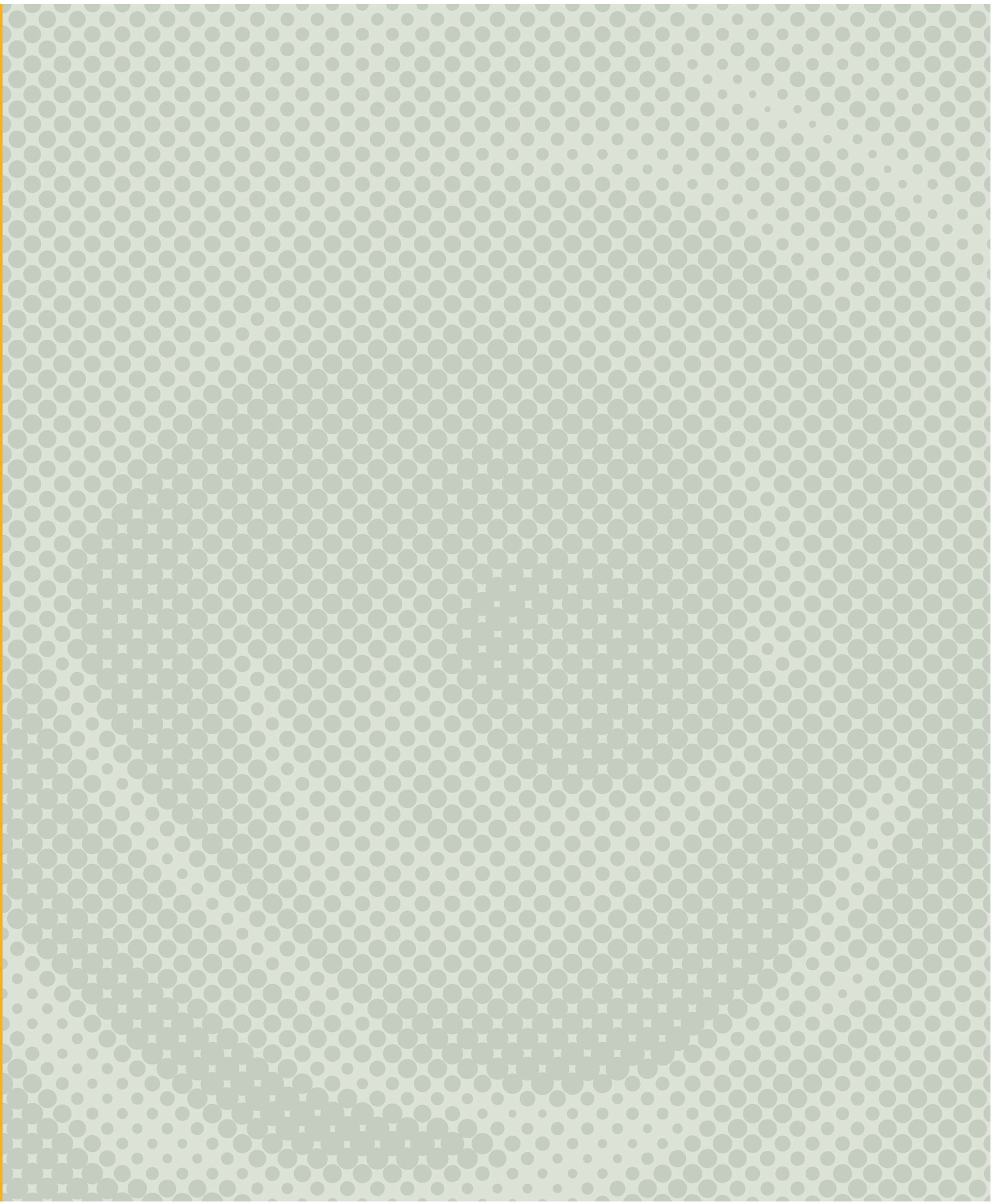

Preface

This article is the final part in my Master's degree in Forest Sciences with the specialization in wood technology at the University of Life Sciences (UMB), Department of Ecology and Natural Resource Management (INA).

My educational background, which consists of a Bachelor in business administration and to be completed Bachelor in forest science (spring 2012), have influenced the choice of topic. The enthusiasm for forestry and especially the technological aspects which create values for the wood based industry, made this topic reasonable.

This thesis is based on the project Tresterk, with the eminent objective to prepare possibilities for producing higher strength classes of graded lumber than performed today. The projects goal is to quantify the effect by strength grading in different phases in the whole production cycle from forest to finished products.

I would like to especially thank my supervisor of this thesis, Professor Olav Høibø, University of Life Sciences, the project manager at Tresterk, PhD. Audun Øvrum, Norsk Treteknisk Institutt and Dr.scient. Geir Isak Vestøl, University of Life Sciences for tapering this article and for giving advices regarding technical questions; and Ove Munthe-Kaas, Kim Lovas and Eirik Henanger for assistance in the laboratory; and Anne Dieset for advises and support during the writing process.

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Abstract

Correct allocation of the raw materials is important to cover the requirements of producers and customers. To achieve this it is crucial to get a precise prediction of the wood properties early in the conversion chain. The modulus of rupture (MOR) is of great importance when using lumber in load bearing structures. An exact determination of the strength properties depends on the accuracy of the measurement systems and the access to significant information related to MOR. The analysis and model development were based on a total of 410 boards of Norway spruce (Picea abies (L.) Karst.), sampled from three different sites in the southern part of Norway. The nominal height and width of the planks tested were 100-200 mm and 50 mm, respectively. The two most common grading systems used in Norway, visual grading after INSTA 142 and grading by resonance vibrations performed with Dynagrade, were evaluated. Both grading systems reduced the MOR residual variance significantly, but they undervalued MOR and the resonance vibrations were somewhat less than the visual. Additionally, stand and tree characteristics were used. Models with IP values and tree and stand variables, managed to reduce the residual variance more ($R^2 = 0.70$) than modulus of elasticity (MOE) measured in the laboratory. The MOE was found to be the best single variable in the reduction of residual variance. The results showed that it might be useful to include stand and tree characteristics in models used to strength grade Norway spruce sawn wood.

Sammendrag

Riktig fordeling av råstoff er viktig for å dekke behovene til kunder og produsenter. Det vil være kritisk å kunne påvise presise egenskaper til tremateriale tidlig i produksjonskjeden. Bøyefastheten (MOR) har stor betydning for bruk av tre i bærende konstruksjoner. Nøyaktigheten til måleutstyret og tilgang til informasjon relatert til MOR er viktig for å kunne påvise disse egenskapene best mulig. Analysene og modellutviklingen er basert på totalt 410 planker av norsk gran (Picea abies (L.) Karst), hentet fra tre bestand i sør Norge. Materialene som ble testet hadde nominell høyde mellom 100 og 200 mm og nominell bredde på 50 mm. To av de mest brukte sorteringssystemene i Norge, visuell styrkesortering etter INSTA 142 og sortering med bruk av resonans vibrasjoner ble evaluert. Begge systemene reduserte signifikant residualvariansen til MOR, men de undervurderte MOR. Resonans vibrasjoner dog noe mindre enn de visuelt bedømte. IP-verdier (Indikatorverdier fra Dynagrade) ga størst bidrag til å redusere residualvariansen til MOR. Sammenhengen mellom plankkvalitet og MOR var best for de gode bonitetene (R^2 = 0.44). Bestands- og tre karakteristikker ble også brukt som forklaringsvariabler. Modeller med IP verdier og bestands- og trevariable reduserte mer av residualvariansen (R^2 = 0.70) enn laboratoriemålt elastisitetsmodul (MOE). MOE var allikevel den enkeltvariabelen som reduserte residualvariansen mest. Resultatene viste det kan være nyttig å inkludere bestands- og trekarakteristikker i modeller som styrkesorterer planker av norsk gran.

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Introduction

In Norway, the annual cut of wood for industrial applications is approximately 8.4 million m^3 (SSB 2012). The gross production of sawn timber is about 2.4 million m^3 and one-third is strength graded (Øvrum 2011). In load bearing wood members, like floor joists, roof trusses and glulam beams it is required to use strength graded wood. The capability to predict and document the strength, thus have a huge influence on the value creation in the wood-based industry. An efficient and accurate grading is important to comply with the new building material standards. Furthermore, a more exact documentation of the strength properties in individual boards increases the competitive power of structural wood in relation to other building materials. However, a precise determination of strength is difficult due to a huge variation in wood properties within and between trees and stands.

The grading system in Norway contains 12 strength classes for general use in structural codes (Standard-Norge 2009)(Appendix I). The system is mainly based on characteristic values of bending strength (MOR). Hence 95 % of the graded pieces have a higher value than the defined class, calculated according to specific standards (Standard-Norge 2004). Additionally, the characteristic value of density and modules of elasticity (MOE) have to meet certain requirements (Standard-Norge 2009).

Concerning safety, bending strength is the most critical property. The grading system is mainly based on bending strength and bending stiffness. Moreover, density is a supplemental property (Hanhijärvi, Ranta-Maunus et al. 2005).

It is easy to measure bending strength by a destructive test. The limitation of this is that the graded piece is no longer usable in structures. An alternative is to load the actual piece to the required limit. When the piece withstands the load, then it is guaranteed to fulfill the requirements of the grading class. The piece may however break if it does not withstand the force. Wood damages can also appear if the load is above the linear elastic stress limit (Kollmann and Côté 1968). Hence, grading is based on non-destructive measurements within the linear elastic range. These methods include uncertainty around measurement errors. Therefore the relationships between non-destructive measurements and strength properties will never be perfectly correlated. To account for this, characteristics values are used.

Measurable characteristics that indicates strength properties

Non-destructive characteristics that influences the strength are called grade indicating properties (Hanhijärvi, Ranta-Maunus et al. 2005).

In general MOE is the best individual predictor of MOR .The advantage of using MOE is that it account for several variables influencing the strength. Such variables are grain angle, knot diameter, density and moisture content (Kollmann and Côté 1968). From previous studies, MOE explains 53 – 72 % of the variation in bending strength (Table I). The relative good correlation between MOE and MOR, and methods measuring MOE, fit well for industry. Still there is a need for even better predictions.

Knots reduce the modulus of rupture considerably, especially if they are located in the tensile zone (Kollmann and Côté 1968). The grain angle found around knots is the most important effect on MOR. They lead to discontinued fiber which create stress concentrations and fracture initiation when sawing logs to boards (Wolfe 2000). Previous investigations have found the relationship between knots and MOR, represented with coefficient of determination (R^2) between 0.16 – 0.27 (Table I). Knot diameter correlate with growing conditions. In general patterns, the knot diameter increases with a decrease in stand density (Høibø 1991). The large spacing increases the breast height diameter (DBH). Høibø found a positive correlation between the size to the knots and the diameter increment in Norway spruce. There exist also longitudinal variations in knot diameter. The knot diameter may increase upwards the stem to the main point/the lower part of the crown and then replaced by decreasing to the top (Flæte and Haartveit 1996; Mäkinen and Colin 1998).

Density depends on the cell wall thickness and the ratio between cell wall and cavity (Kollmann and Côté 1968; Treteknisk 2009). The wood structure makes the thickness of cell wall to bring a strongly influence on MOE and MOR along the grain (Thelandersson and Larsen 2003). For small defect-free wood pieces of Norway spruce (Picea abies (L.) Karst.), 62 % of the variation in MOR can be explained by density (Treteknisk 2006). Several other studies have found density to reduce the residual variance in MOR in the range R^2 = 0.16 – 0.40 (Table I).

The longitudinal variation in density is not uniformly expressed. For mature spruce in southern part of Norway the density was found to be increased slightly upwards the stem (Vadla 2006). Other studies showed a decrease in density upwards the stem towards living crown, but with a considerable variation among trees for stand grown spruce (Olesen 1982); and an increased density in the lower part of the sap wood followed by a slight decrease towards up (Tamminen 1964).

The measurement of density is demanding and thereby impractical to use in MOR models. Still, annual ring width correlate well with density (Hoffmeyer 1995). In general, an increase in ring width reduce the specific gravity of Norway spruce (Kollmann and Côté 1968; Vadla 2006). The effects of ring width to density will be reduced by comparing trees from different climatic regions. To the further north and the higher altitude climate, the less will large ring width decrease the density

(Treteknisk 2009). It is the reduced proportion of latewood in each growth ring that reduce the density due to less temperature sum. The geographic variation in this study was too low to study this effect.

Ring width depends on characteristics such as site fertility and stand density. Models were developed to find the effect of site index on MOR.

Stem taper and diameter at breast height (DBH) are also commonly known properties influencing MOR (Kollmann and Côté 1968; Lei, Zhang et al. 2005; Liu, Zhang et al. 2007). Both variables can be measured by a harvester.

According to Weibull´s weakest link theory, lumber dimension will affect the strength. The probability to get a weak point in a larger board is increasing due to a larger volume of exposed wood. This effect is included in constructional standards with a size-dependent correction factor (Standard-Norge 2004).

Table I Coefficient of determination between non-destructively measured characteristics and bending strength, presented as results from studies by several authors in this field, for European spruce (Picea abies) (Hoffmeyer 1995).

Variable	**R^2**			
	I	**II**	**III**	**IV**
Knots	0.27	0.20	0.16	0.25
Annual ring width	0.21	0.27	0.20	0.44
Density	0.16	0.30	0.16	0.40
MOE, bending or tension	0.72	0.53	0.55	0.56
Knots and annual ring width combined	0.37	0.42	0.39	
Knots and density combined	0.38		0.38	
Knots and MOE	0.73	0.58	0.64	

Table I refers to the following experiments: I (Johansson, Gruber et al. 1992), II (Hoffmeyer 1984), III (Hoffmeyer 1990), IV (Lackner, Foslie et al. 1988)

There are several reasons for grading sawn timber. It is necessary to have standardized products that easily can be compared with similar products regarding utilization potential. Further it is important to set a price on the boards that reflect the specific capacities and meet the customers’ expectations and needs.

There are several methods for grading sawn timber. Visual grading utilizes the effect of knots on the strength properties. Knots are easy to measure and are one of the major degrading characteristics in visual grading of structural lumber. The procedure to measure the knot is specified in INSTA 142 (Standard-Norge 2009), which corresponds to the general requirements for structural graded lumber (Standard-Norge 2005). The size, position and measurement parameters are most important in INSTA 142. Additionally, the standards also include requirements regarding compression wood, grain angle, ring width, deformation, fractures and wanes. In sight of previous studies, combinations of knots and ring width can reduce the residual variance in MOR in the range R^2 = 0.37 – 0.42 (Table I).

The last decade, strength grading using resonance vibrations to detect dynamic MOE has increased considerably. This comes from the strong development of measurements techniques associated with dynamic testing and the use of Fast Fourier Transform algorithm (Thelandersson and Larsen 2003). The accuracy is comparable with the grading results from Computermatic[1] (Omholt 1999), which here in Norway, was the most popular grading machine based on the relationship between bending MOE and MOR before the introduction of dynamic MOE testing. Dynagrade is based on measurements of resonance vibrations. The measuring arrangement to Dynagrade is easy to locate in a transverse conveyor, thus increased grading speed compared to Computermatic. About 80 - 90 % of all strength graded lumber in Norway is done with this technology. Requirements and setting values for machine grading systems has been stated in the Norwegian Standards (Standard-Norge 2005; Standard-Norge 2009). The Dynagrades capability to reduce the variance in MOR is presented in Table II.

Table II Coefficient of determination between actual bending strength- and stiffness, and the predicted values from Dynagrade (Omholt 1999).

	Bending strength (MOR)		Bending stiffness (MOE)	
Dimension (mm)	50*150	50*200	50*150	50*200
R^2	0.61	0.50	0.67	0.48

The long-term goal to this study is to enhance producer’s opportunities to a greater yield of high-classed lumber. Producing stronger lumber may increase the competitive power to forest products. Relationships between stand- and tree variables and board characteristics related to strength properties exist. If the producers of sawn logs can benefit this relation to produce stronger lumber, the market mechanism will make it possible for forest owners to reflect the timber quality in the price. This may be an important improvement to the total supply chain and value creation. Economic adaption might adjust the incentives in silviculture, from volume production to aiming at high-strength timber production. The pricing system in Norway found general timber assortments based on the negotiated price level, to reflect the average quality in the delivered timber. In recent year, the technological advances enables to in detail document the complete production cycle. The general pattern suggests that identification systems have been easier and cheaper to deploy, and their applications have increased substantially. A large EU founded project (Indisputable Key) has been developing a prototype for a complete traceability solution from forest to end-user. This study

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[1] Grading method based on flatwise bending of lumber with constant load. The measured deflection is put into the calculations of bending stiffness.

focused on the improvements to anticipation by including more information to the lumber. The economic and technological requirements for deploying systems that can handle the information are not a part of this study.

Euro code 5, design of timber structures (Standard-Norge 2010) was implemented in Norway April 2010. This standard is the only valid structural code for wood in Norway. By using this standard, wood in general have reduced the design capacities in proportion to the previous standard (Nore/Treteknisk ; Standard-Norge 1999). Consequently, the competitive ability for structural use of lumber can be reduced compared to i.a steel and concrete. Studies have shown the average level of bending strength to be above 50 Nmm^{-2} in Norwegian sawn spruce (Langsethagen 2001; Skyrud and Skaug 2002). Also, a Danish study which evaluated strength grading systems found a typical MOR for structural Nordic timber to be approximately equal to 50 Nmm^{-2} (Hoffmeyer 1995). Concurrently, the highest industrially produced grade of structural timber in Norway is C30 (MOR= 30 Nmm^{-2}). The main reason for the gap between the strength classes in graded lumber and actual MOR is the variation of strength properties in the Norwegian wood base. Thus, the widespread grading machines do not manage to entirely intercept this variation.

In principle, the traditional grading of lumber can be sketched as follows: A randomly received board is graded to fit a strength class based on the measurable characteristics, which assumes to correlate with MOR. The grading systems have no information about stand and tree characteristics that are not visible or measurable at board level. As discussed, relations between such characteristics and MOR exist and involvement of these expects to increase the grading accuracy.

This study is divided into two phases. The first phase was focused on the capabilities of the most common grading systems to grade lumber to fit a strength class. The grading systems evaluated were Dynagrade and visual grading after INSTA 142. The second phase analyzed the possibilities to improve the Dynagrades prediction models by the inclusion of forest inventory variables. The analyses were performed by including easily measurable tree and stand characteristics, in addition to IP values in the models that describe MOR.

Materials and Methods

The material contained 410 boards from 172 logs, from 45 Norwegian spruce trees. It was collected at three different locations in southern part of Norway. All three study sites are located in Østfold County. The different sites were selected to represent most of the range in site indexes. The range in site index (H_{40}[2]) was G11 to G24 according to Tveite (Tveite 1977). Location and site data are presented in Table III.

Diameter at breast height (maximum and minimum under bark), age in root and tree height were recorded for all trees (Table IV). The trees were crosscut to logs with lengths of 4 meter. The logs were ranked, depending to the relative position in proportion to tree height. They were ranked to butt, middle and top logs. The logs were applied with identification numbers that described the unique tree- and log number.

Table III Forest inventory data

Site	Latitude North	Altitude (m)	Site index H_{40} (m)
1. Våler	59.32	102	11
2.Våler	59.32	115	17
3.Skjeberg	59.13	79	24

Table IV Mean values and standard deviation to the tree variables in each site.

Site	N	Age (years)	σ Age (years)	DBH mean (cm)	σ DBH (cm)	H (m)	σ H (m)
1.Våler	15	165	18.7	26.7	6.3	21.8	2.8
2.Våler	15	158	18.3	34.0	8.0	29.9	2.3
3.Skjeberg	15	79	6.7	28.9	5.4	28.5	1.5

Table V Number of logs and boards in the different log types. The yield of boards is separated by nominal dimension.

		N boards of each dimension (mm)		
Log type	N logs	50*100	50*150	50*200
Butt log	43	10	66	74
Middle log	86	35	141	-
Top log	43	84	-	-
Total	172	129	207	74

The logs were sawn into either two or four boards, depending on the small-end diameter. The boards had a nominal width of 50 mm and nominal height at 100, 150 and 200mm (Table V). When the logs were sawn, each individual board was additionally marked with a serial number. It was made

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[2] Average height of the 10 dominant trees per acres, and age in breast height is 40 years.

possible to identify and relate each board with its respective tree and log number. The boards were machine graded with Dynagrade at the mill. Dynagrades mode of operation is as follows. The movement when the lumber arrives to the machine activates a hammer. The hammer taps the longitudinal end side to piece. Microphones will notice the frequency of vibrations in the tested piece. A laser measures the length of the boards. The relation between the length of the board and resonance vibrations is expressed through IP-values. The logs were also graded using the Nordic rules for visual grading (Standard-Norge 2009). The boards were dried in the sawmill to approximately 17 % moisture content and conditioned in a laboratory at 20^{o}C and 65 % relative humidity.

Before testing MOR and MOE, the knots were precisely measured according to the standard (Standard-Norge 2009). In addition knots (k_f) were measured as the smallest diameter of the largest knot in each board. Knot forest (k_f) represents the size of the largest knot like as it appears in a standing tree. This makes it possible to apply the knot variable as a tree characteristic and not a board characteristic in the MOR modeling. The existing stand and tree data did not include any information about knot size.

The MOR and global and local MOE were tested according to the rules for determination of some physical and mechanical properties of structural timber (Standard-Norge 2003) (Table VII). The testing was done using a four-point bending arrangement with an Instron 5800 universal static testing machine. The span, distance between loading points and gauge length for determination of local modulus of elasticity were equal to 18 D, 6 D and 5 D, respectively. The pieces were oriented with the pith side and butt-end in the same direction. This guaranteed every piece was tested in two cross-sectional directions. The lumber were cut based on the Standards (Standard-Norge 2003) requirements for board length (Table VI). All boards were shortened to correct test length in the butt end except boards from butt logs that were shortened in the upper-end. Samples of clear wood were taken closer to the failure point as possible. These samples were weighed and volumes were determined by displacement method. After that they were dried to zero percent moisture content and weighed again. All the sample weights were recorded. These readings were used for density measurements and the moisture content of each tested plank.

Table VI Nominal board dimensions and test arrangement in four-point bending.

Nominal dimension, D (mm)	Board length (cm)	Span (mm)	Distance between loading points (mm)	Gauge length for determination of local modules of elasticity (mm)
50*100	200	1800	600	500
50*150	300	2700	900	750
50*200	400	3600	1200	1000

Table VII Nominal board dimensions and settings used in testing of modules of elasticity and bending strength.

Nominal dimension, (mm)	Lower measure limit, MOE (N)	Higher measure limit, MOE (N)	Velocity used in testing MOE (mm/min)	Velocity for MOR (mm/min)
50*100	400	1500	7	10
50*150	600	2250	10	13
50*200	800	3000	15	20

Actual characteristic values to the tested lumber were calculated with respect of the rules in the standard[3] (Standard-Norge 2004)(Table VIII). Samples that had extraordinary damages such as top breakage and wood damages were excluded from the analysis. MOR, MOE and ρ were adjusted for moisture content that differed from 12 % MC.

The grade yield in the different strength classes were calculated as percent graded boards in each class in proportion to total number of boards.

Table VIII Mean value, standard deviation and characteristic value to bending strength, bending stiffness and density to the lumber, specified at the different site indexes

		G11	G17	G24
MOR (N mm^{-2})	Mean value	64.83	57.77	47.64
	Standard deviation	14.82	13.65	10.44
	Characteristic value	39.10	37.39	31.86
MOE (kN mm^{-2})	Mean value	17.81	15.75	12.78
	Standard deviation	3.22	3.26	2.64
	Characteristic value	20.47	17.79	13.93
ρ(kg m^{-3})	Mean value	568.36	502.62	437.79
	Standard deviation	83.75	83.72	57.46
	Characteristic value	430.17	364.48	342.98

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[3] The characteristic values are not adjusted for dimensions that not correspond to the base, 150 mm nominal height. The values are not adjusted for number of samples; and pieces in the smallest samples. The characteristic value for bending strength that correspond to the 5-percentile is downwards adjusted to an actual test value in cases there the 5-percentile value is not an actual test value. NS-EN 384 requirements in such cases is interpolation between the actual test values.

Table IX Definitions of abbreviation

Symbol	Definition
Variables	
MOE	Modulus of elasticity (N mm^{-2})
MOR	Bending strength (N mm^{-2})
IP	Indicating property value received from Dynagrade
ρ	Density (kg m^{-3})
DBH_{rel}	Relative DBH to the specific tree in proportion to mean DBH of site
DBH_{rel}/Age_r	Relative DBH divided with age of the tree, measured in the root
H_{rel}	Position of the log relatively to tree height
H/Age_r	Total height of the tree divided with age measured in the root
K_f	The smallest possible diameter to the largest knot (mm)
Statistics	
R^2	Coefficient of determination
P-value	Probability to obtain a test statistic at least extreme as the actual observed
RMSE	Root mean square error

Table X Correlation matrix for different variables

	MOE	MOR	ρ	IP	K_f	H_{rel}	DBH_{rel}	DBH_{rel}/Age_r	H/Age_r
MOE	1,00								
MOR	0,82	1,00							
ρ	0,65	0,59	1,00						
IP	0,74	0,74	0,33	1,00					
K_f	-0,33	-0,41	-0,12	-0,44	1,00				
H_{rel}	-0,30	-0,34	-0,09	-0,40	0,50	1,00			
DBH_{rel}	-0,50	-0,58	-0,23	-0,43	0,25	0,11	1,00		
DBH_{rel}/Age_r	-0,66	-0,63	-0,48	-0,58	0,21	0,04	0,45	1,00	
H/Age_r	-0,57	-0,51	-0,50	-0,46	0,13	0,02	0,10	0,90	1,00

Statistics and modeling

The statistical analyses were performed with the program JMP 9.0 (SAS-Institute-Inc 2010).

In the first phase, tests were done using variance analyses whenever there were differences in MOR prediction by grading with INSTA 142 or strength grading with Dynagrade. Tukey-Kramer HSD test was used to identify site indexes that differed in MOR. Also, simple linear regression analyses between the IP and MOR were performed. The evaluation of test and models were based on coefficient of determination (R^2) and root mean square error (RMSE). Variables were rejected when $p<0.05$.

In the second phase, the Base model was a mixed model with tree number as random effect and IP value as fixed effect.

Base model: $Y = \alpha + a_i + \beta IP + e_i$

A random coefficient model was used to study the vertical variation in MOR within trees in addition.

Base model 2: $Y = \alpha + a_i + \beta IP + (\gamma + b_i)H_{rel} + e_i$

Y represents MOR. a_i and b_i represents the random effects that vary between trees. The random element e_i is the residuals not covered by a_i and b_i. The random elements a, b and e are assumed to be normal distributed, indicated by the variance components σ_a^2, σ_b^2 and σ_e^2, respectively.

Forest inventory data as fixed effects were included in a stepwise manner to the base model to reduce the MOR residual variance. In the last model variable IP was excluded from the analysis. A correlation matrix between the fixed effects is presented (Table X).

The mixed models and random coefficient models were calculated with the restricted maximum likelihood (REML) method in the fit model platform of JMP. The random effects were included in the R^2 and RMSE calculations in the mixed model procedures. R^2 and RMSE values without random effects included were also calculated. These values are more useful to evaluate the MOR prediction capability. The calculations were done from the residuals.

Results and discussion

The results and discussion are divided in two parts. Firstly, the relationship between MOR and sawn wood quality according to INSTA 142 (Standard-Norge 2009) and machine stress grading using IP-values from Dynagrade were analysed. The second phase analyzed the possibilities for improving the Dynagrades MOR model.

Relationship between MOR and visual grades and machine stress grading

The lumber was graded in strength classes by Dynagrade and according to INSTA 142. Variance analysis was used to test differences between those methods to explain the variance in MOR. A better relationship was observed between MOR and grades from Dynagrade than by visual grading (Figure I). They were both significant to reduce the residual variance in MOR, and explained 34 and 15 % of the variation respectively, in MOR (Table XI). The strength grading with INSTA 142 was mainly based on size and location of the knots. Narrow face knot and compression wood are essential downgrading factors. Johansson (Johansson 1998) showed that these factors were responsible for 57 and 14 % of Nordic lumber downgrading, respectively. A Norwegian study found knots to be responsible in the range of 70- 99 % of downgrading in Norway spruce (Øvrum 2008). In this manner, the relationship between knots and MOR strongly influenced the visual standards grading capabilities. As discussed in the Introduction, it is expected that knot characteristics may explain the MOR residual variance within the range 0.16-0.27. The visual grading must therefore be conservative to fulfill the characteristic MOR requirements.

The different capabilities to explain MOR will affect the grade yield in the various strength classes. The yield of C30 was higher when graded with Dynagrade, than the yield in the corresponding T3 when they were graded after INSTA 142 (Table XIII).

The characteristic MOR in the different strength classes were calculated according to a standard (Standard-Norge 2004)(Table XII). The characteristic MOR in the grades from both Dynagrade and INSTA 142 was higher than the requirements in the belonging strength classes (Table XII). The characteristic MOR value in the grade classes from Dynagrade corresponded however better to the strength requirements than that present in the grade classes after INSTA 142.

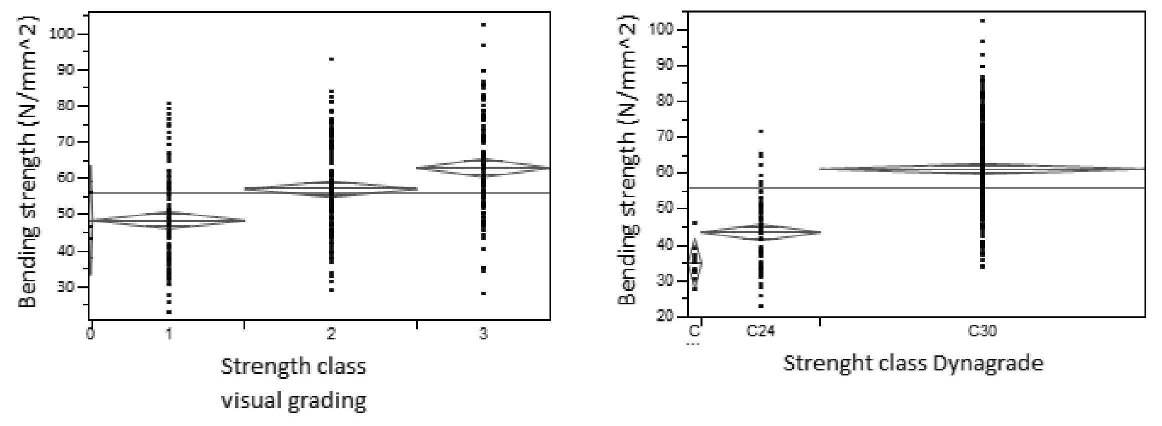

Figure I Variance analysis of MOR and respectively strength classes according to INSTA 142 and grades after Dynagrade

Table XI Statistics for the variance analysis of MOR and strength classes according to INSTA 142 and Dynagrade

	Visual grading	Dynagrade
R^2	0.15	0.34
RMSE	13.29	11.70
p-value	<0.0001	<0.0001

Table XII. Requirements to characteristic MOR for the strength classes. Characteristic MOR in the corresponding grades after INSTA 142 and Dynagrade.

	T0/C14	T1/C18	T2/C24	T3/C30
Minimum characteristic MOR	14	18	24	30
Actual characteristic MOR, in visual grades	43.10[4]	30.91	36.44	41.60
Actual characteristic MOR, in resonance vibration grades	N/A	28.90	28.91	40.73

Note: The characteristic values are not adjusted for number of samples, sample size and dimension.

Table XIII Comparison of yield in the different strength classes, graded visually and by Dynagrade

Strength class	Visual grading (INSTA 142)	Resonance vibrations (Dynagrade)
T0/C14	0.80 %	
T1/C18	32.98 %	2.95 %
T2/C24	37.27 %	26.00 %
T3/C30	28.95 %	71.05 %

A study have found R^2 values from the linear regressions between MOR and IP-values from the Dynagrade in the range from 0.50 - 0.61 (Omholt 1999). This results are not comparable with the previous variance analyze (Table XI). Thus, with respect to the results tabulated in Table XI, there were used strength classes graded with Dynagrade. The Dynagrade assigns the continuous IP-values to each board, which determines the particular strength class. Using the IP-values as an independent variable, a regression model can predict MOR. Table XIV indicates the linear regression between IP and MOR. The value of R^2 increases considerably to 0.54 and seems to be well corresponded to the findings of Omholt (Omholt 1999). The results were anticipated with respect to the individual IP-values. These values are in better correlation with MOR than the strength classes. These classes contain a range of IP-values. Still, there seems to be a notable increase in R^2 with the breakdown of strength classes to individual properties for each board. This might be a potential factor for the adjustment in the setting values to the machine, to fit the grades to the MOR requirements. The sample size in this study was too small to get any basis to adjust the settings.

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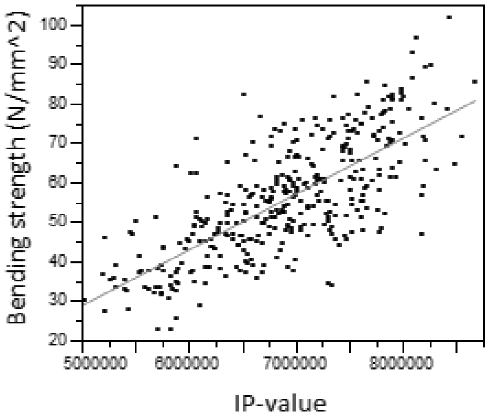
[4] The characteristic value for T0, will not classify as a valid estimate after EN 384 because of it is estimated at only 3 pieces and the value that is presented is the lowest observed bending strength. The characteristic value must be estimated at least 40 pieces to be valid.

Table XIV Regression model as a prediction of MOR with IP as an independent variable. Analysis of variance of the prediction model is presented.



Model	**Function**
1	$\mathrm{MOR} = -41.42 + 0.000014 * \mathrm{IP} - \mathrm{Value}$

Statistics from the regression

R^2	0.54
RMSE	9.78
P-value	<0.0001

The lumber quality may differ because of site index differences. The general patterns showed that the site fertility decreased MOR due to larger ring width. Still, dens stands reduced the diameter increment and the knot diameter in stands growing Norway spruce (Høibø 1991). Correcting for ring width in such cases may give fertile sites greater MOR. Ring width corrections were not performed in this study. The capabilities to detect fertility properties, which make the increase in MOR, were not included in the previous results (Table XI and XIV). Separating lumber from each site index may detect differences in MOR in relation to fertility. Further, the efficiency of grading methods to include those properties was analyzed.

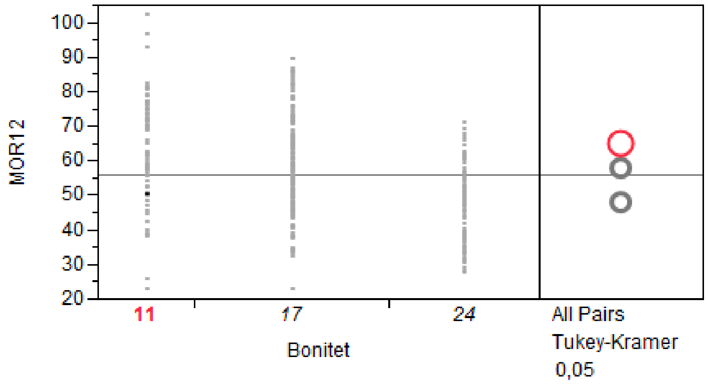
To detect Dynagrades and INSTA 142 inclusion of site differences, the analysis of variance was performed with site index as a nominal variable to describe MOR. The MOR were significant different in all site indexes (Table XV). Increasing site index reduced MOR. The analyses were used for the determination of grading accuracy in different site indexes (Figure II). The differences in visual grading of G11 (P=0.0002) and G17 (P<0.0001) were small (Table XVII). Grading these sites individually reduced some of the residual variance in MOR (Table XV) as compared to the analysis when lumber from all sites were graded together (Table XI). The mean MOR level decreased with fertility (Table XV). Grading lumber from G24, R^2 became very low (0.02), but found to be significant (P=0.02). The R^2 value for grading this site index indicated that knots were poor to provide explanation for low levels of MOR. The relative impact of knots may be less in such cases and could account for some of the effects.

Dynagrade included much of MOR residual variance for all sites than visual grading (Table XVII). However, grading lumber from G24 showed highest levels of R^2 (0.44). Since site fertility in this study decreased MOR, the grade classes from G24 fits well into the Dynagrades underestimation of MOR

(Table XII). The results are not in due to uncertainty concerning IP-values. These are based on the resonance frequency to tested boards. Since reduced strength properties gives low frequency the uncertainty are greatest in such cases (Omholt 1999).

A covariance analysis was performed to test the presence of site-differences in MOR explained by IP-values, or if there was any additional site effect. The test was performed with site index as a nominal variable and IP as a covariate. The effect of site was significant ($p<0.0001$), and for a given IP, the predicted MOR was higher in timber from the low-fertility site (G11) when comparing the two others. The MOR of the timber from this site differed a lot from the timber of the other two (G17 and G24) similar ones (Table XVI). The results showed the accuracy of strength prediction from IP-values that could be improved by the timbers origin.

Table XV Comparison means of MOR in the different site indexes. Statistics from variance analyze and mean levels of MOR are presented.



Statistics

R^2	0.20
RMSE	12.93

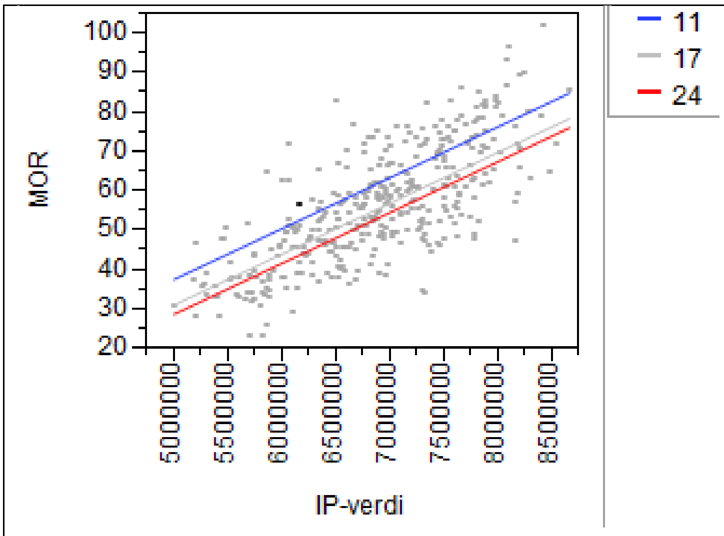
P-value

Site index	<0.0001

Mean MOR (Nmm^{-2})

G11	64.83
G17	57.77
G24	47.64

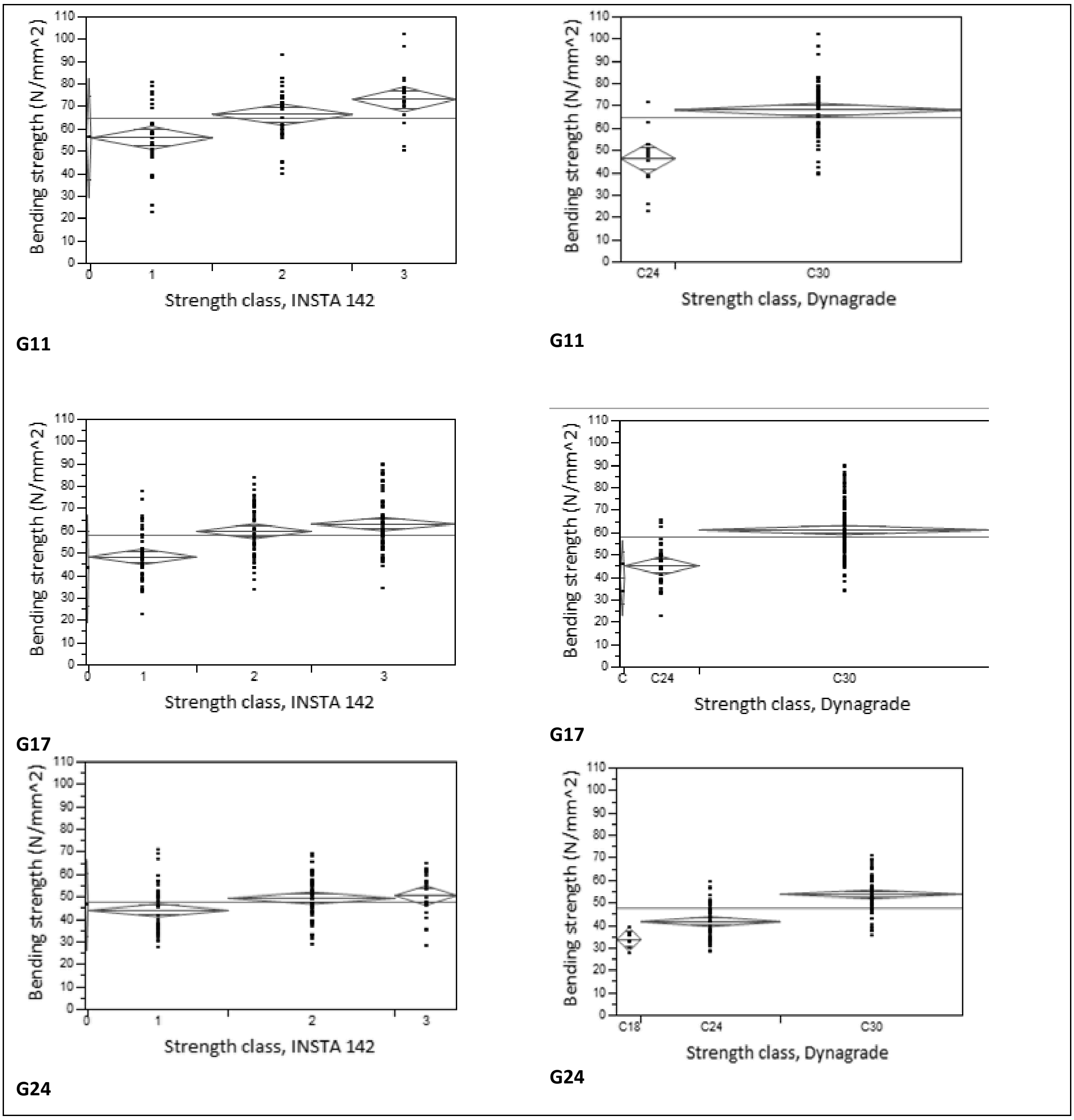
Table XVI Covariance analysis of MOR in different site indexes. P values to variables are presented.



P-values	
IP	<0.0001
Site index	<0.0001

Table XVII Statistics from variance analysis of MOR, by strength classes from visual and resonance vibrations in the different site indexes.

	Visual grading			**Resonance vibrations**		
Site Index	G11	G17	G24	G11	G17	G24
R^2	0.19	0.20	0.05	0.28	0.23	0.44
RMSE	13.36	12.23	10.17	12.55	11.96	7.83
p-value	0.0002	<0.0001	0.02	<0.0001	<0.0001	<0.0001



G11 G11

G17 G17

G24 G24

Figure II Variance analysis of MOR by strength classes graded by INSTA 142 and Dynagrade. The separate grading by different site indexes is presented.

Using the IP values combined with stand and tree characteristics to explain bending strength

The MOR is explained through mixed models and random coefficient models. The discussed statistics to these models are presented in Table XV III. The first model (Model 1_R) includes only IP that provides explanation about MOR. Using additional tree and stand characteristics, the attempt was to reduce the residual variance of MOR. The longitudinal variations in density were also determined by a linear regression using H_{rel} as an independent variable.

The value of R^2 for Model 1_R was 0.54 where only fixed effects were included. In the modeling where random effects were included, R^2 value was 0.78. This represented the best possible fit between the IP and MOR, each tree modeled individually. The model improvement by more fixed effects increased R^2 value up to 0.70. This was the result of a combination among IP and stand- and tree characteristics, without the inclusion of random effects (Model 5_R). The MOE added to Model 5_R raised R^2 value to 0.76. A model with MOE alone as a fixed effect displayed 67 % of the variation in MOR.

In Model 2_R, the fixed effect DBH_{rel}/Age_r was added to the base model. This variable reduced the residual variance in MOR. R^2=0.59 and RMSE = 9.32 N mm^{-2}. When the variable DBH_{rel}/Age_r is high, it indicates that the diameter increment has been greater than average in the site. It is likely that the variable is correlated with stem taper. A report of Lei and Zhang predicted lumber bending MOR and MOE in black spruce based on tree characteristics (Lei, Zhang et al. 2005). They found stem taper as a best explanatory variable to predict MOE (53.49 % of R^2 = 0.56). Furthermore, MOE was the best factor to predict MOR (89.77 % of R^2 = 0.79). The tapers role to explain strength capabilities was introduced by Volkert in 1941 (Kollmann and Côté 1968). It was suggested that the density, and thereby MOR, in the base of a tree could be higher in trees with a cylindrical stem when compared with large fall-off trees. This provides explanation for the significant negative contribution of DBH_{rel}/Age_r to MOR ($P<0.0001$).

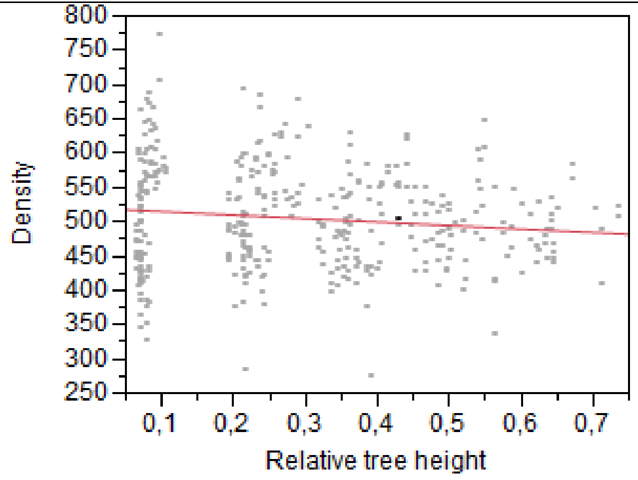
Table XVIII Statistics for the MOR models.

Summary of statistics	Model 1R	Model 2R	Model 3R	Model 4R	Model 5R	Model 6R	Model 7R
Variance components from model step							
σ_a^2	63.47	34.59	36.55	16.73	17.95	10.65	32. 57
σ_b^2	-	-	286.21	263.29	258.13	166.71	181. 79
σ_e^2	51.42	51.66	41.70	42.02	40.65	37.39	44. 38
Summary statistics from model step, including fixed and random effects							
R^2	0.78	0.78	0.83	0.83	0.84	0.85	0.82
RMSE	7.17	7.19	6.46	6.48	6.38	6.12	55.87
Summary statistics from model step, only fixed effects included							
R^2	0.54	0.59	0.63	0.70	0.70	0.76	0.67
RMSE	9.78	9.32	8.84	8.02	8.00	7.17	8.34
p-values for the fixed effects in the different models							
IP	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
DBH_{rel}/Age_r		<0.0001	-	-	-	-	
H_{rel}			0.0022	0.001	0.0131	0.0521	
DBH_{rel}			<0.0001	<0.0001	<0.0001	<0.0001	
H/Age_r				<0.0001	<0.0001	0.0003	
K_f					0.0020	0.0054	
MOE						<0.0001	<0.0001

Models

Model	Equation
Model 1R	$MOR_{12} = -9.78 + 0.01*IP$
Model 2R	$MOR_{12} = 7.92+0.009*IP-1710.44* DBH_{rel}/Age_r$
Model 3R	$MOR_{12} = 25.92 + 0.0086*IP - 11.90* H_{rel} - 25.12* DBH_{rel}$
Model 4R	$MOR_{12} = 41.58+0.0078*IP - 12.63* H_{rel} - 24.21* DBH_{rel} - 4.80* H/Age_r$
Model 5R	$MOR_{12} = 45.73+0.0074*IP - 9.43* H_{rel} - 23.58* DBH_{rel} - 4.83* H/Age_r - 0.15* K_f$
Model 6R	$MOR_{12} = 31.50+0.0046*IP - 6.45* H_{rel} - 18.07* DBH_{rel} - 2.74* H/Age_r - 0.13* K_f + 1.44*MOE$
Model 7R	$MOR_{12} = 18.74 + 2.54*MOE$

Table XIX Linear regression model as a prediction of density with H_{rel} as an independent variable. Analysis of variance of the prediction model and p-value is presented.



Model	**Function**
1 ρ	$\rho = 520.09 - 50.80 * H_{rel}$

Statistics from the regression	
R^2	0.02
RMSE	74.12
P-value	0.016

The fixed effect of DBH_{rel}/Age_r was excluded in Model 3_R. The H_{rel} and DBH_{rel} became the successor effects. The value of R^2 increased to 0.63 and RMSE decreased to 8.84 N mm^{-2}. The variable H_{rel} described the log height in comparison with the total height of the tree. The longitudinal variation in density decreased slightly, but significant upwards the stem with a P-value 0.016 (Table XIX). The density correlate with specific gravity (Thelandersson and Larsen 2003). The decrease in density upwards the stem may decrease MOR. The diameter of the knots will increase with the distance from the ground (Mäkinen and Colin 1998). In general, an increase in knot size will reduce MOR. Therefore, increasing H_{rel} may leads to a significant reduction in MOR (P=0.0022). The properties to density or knot size that most dominates on the effects of H_{rel} is not specifically analyzed. The result corresponded however to the findings by Øvrum (Øvrum 2008). The pronounced effect of increased distance from stump reduced the probability of better strength grades in his study which graded Norway spruce by INSTA 142. Larger DBH_{rel} has a significant negative contribution to MOR (P<0.0001). A study based on Norway spruce from even aged stands in southern part of Norway showed the same relationship (Høibø 1991). A report on modeling bending strength in black spruce stands has suggested that DBH was the best single predictor of MOR (Liu, Zhang et al. 2007). Liu showed a model with the variable DBH alone, where it explained approximately 58 % of the variance in MOR (Liu, Zhang et al. 2007). From the parameter estimate (Table XVIII), it can be suggested that the parameter that provides the strongest reduction in MOR is DBH_{rel}. Since the DBH_{rel} is relative to average DBH in each stand, the variable indicated that a particular tree might have been dominant. The dominance could lead to increased knot size and stem taper and following decreased MOR. The influence of board size was not analyzed. The effect might be influencing MOR due to the weakest link theory. A larger DBH may increase the yield of the boards with 200 mm height and hence greater the volume of exposed wood. A large DBH may show a distribution with a bigger share of outer boards, by more splitting of logs to four boards. This could probably increase MOR in accordance with more mature wood, although this effect was not considered alone.

In Model 4_R, H/Age_r was added to Model 3_R. R^2 increased to 0.70 and RMSE decreased to 8.02 N mm^{-2}. The variance component σ_a^2 decreased from 37 to 17 N mm^{-2}. H/Age_r can be used as an alternative explanatory variable to site indexing. This might explain the substantial decrease of σ_a^2 since site index affect MOR. The negative effect of H/Age_r on MOR was significant (P<0.0001). This corresponds to the previously obtained relationship found between site index and MOR (Table XV). In most cases, the average stand age is registered in the forest management plan, while Age_r (age of the individual tree) is not available. The height of the individual tree may be measured with a harvester. Thus, tree height divided by mean age of the stand as given by the management plan could be a more practical variable to use. This variable will most probably not reduce the MOR residual variance to the same extent as H/Age_r.

In Model 5_R K_f was added to Model 4_R. The value of R^2 seems to be increased marginally from 0.6963 (Model 4_R) to 0.6989. Whereas, RMSE decreased to 8.00 N mm^{-2}. The variable K_f describes the diameter of knots as they appear in the forest. Increased k_f values contributed significantly negative to MOR (P=0.002). This is in accordance with general knowledge (Kollmann and Côté 1968; Wolfe 2000). The inclusion of K_f reduced the significance of the variable H_{rel} (P = 0.0131). As discussed, the effect of H_{rel} is probably influenced by the knot size. This seems to be varied with the ground distance (Flæte and Haartveit 1996; Mäkinen and Colin 1998). Thus, the lower significance to H_{rel} might be explained by K_f that might carry some of the variable effect to MOR. The correlation between these variables was 0.5 (Table X). Collinearity between these variables might be considered.

Model 6_R includes MOE in addition to the tree and stand characteristics. The value of R^2 increased to 0.76. RMSE decreased to 7.17 N mm^{-2}. The random components σ_e^2 were reduced to 37.39 N mm^{-2}. The H_{rel} was no longer significant to explain MOR. The H/Age_r and K_f become less, but still significant. Multicollinearity between MOE and those variables may be considered. The MOE include variables as density, ring width and knots (Kollmann and Côté 1968) which make relations between the variables reasonable. As compared to Model 7_R, which explains MOR by only MOE as a variable, MOE is the single variable that explains much residual variation in MOR (R^2=0.67). This accordance with general knowledge discussed. Nevertheless, combinations of IP and stand and tree characteristics explain much variation in MOR than MOE alone.

The objective of this study was to investigate the grading capabilities to predict MOR by including easily measurable variables for lumber in a model which already included IP-values. We found a smaller effect by adding information about knots. Knots are the most difficult variables for the forest inventory data measurements in this report. Detailed information about knot diameter is therefore not recommended to be included in MOR models. Thus, the effect of knots to reduce MOR has probably been involved in more accessible characteristics in this study, especially by the variable H_{rel}. The H_{rel} could be measured by the harvester. To calculate DBH_{rel} is assumed to have a presumption of the stand average DBH, or it could be calculated afterwards whenever the necessary information exists. Average stand age is normally described in the forest management plan and is easier to implement when compared with Age_r. To describe the height growth for each individual tree, a simplified variable could be given as individual tree height divided by mean stand age from the management plan. All along, the IP-values are included as a part of modeling. They are included to indicate the overall effect of grading with forest inventory data delivered to Dynagrade. Therefore is it not possible to have a conclusion with significant effects using the models to pre-grade lumber without aforesaid values.

The analysis carried out in this study has treated MOR as the only property that determines the strength characteristics of timber. There are also existing requirements to MOE and ρ. The MOR is most important for structures; especially ρ can be a tough requirement for Norwegian timber. Overall, the results might not be used without including these properties.

The model is based on a too limited material in order to be valid for stands from different altitudes and latitudes. However, the material represents a relative large range in growing conditions for Norway spruce trees from lower altitudes in South-east Norway.

Conclusion

Phase one indicates that commonly used grading systems in Norway, both visual grading and machine grading, under estimate the actual bending strength (MOR). However, machine grading with Dynagrade, reduced the residual variance in MOR to a higher extent than visual grading according to INSTA 142. Machine grading with Dynagrade gave a higher yield in the highest strength class (C30) compared to visual grading after INSTA 142. Fertility in sites decreased significant MOR. The IP variable received from Dynagrade reduced much of the residual variance in MOR in the grading of lumber from fertile sites.

Models from the second phase predicted the MOR values better than IP alone. Tree and stand characteristics improved the models. Information about knot characteristics did not give any substantial reduction in the residual variance when IP-values (IP), relative height (H_{rel}) -and DBH (DBH_{rel}) and height divided by total age (H/Age_r) already were included. These variables are easy to measure by a harvester and simple valuations. The best model, with only IP and tree and stand characteristics, explained much variation in MOR than MOE measurements in laboratory. Still, MOE becomes a single variable which has reduced the residual variance in MOR to a higher level.

The results might be used to add essential information to lumber, before they are sawn. If the information can be followed until the grading machine, an increase in grade yield of stronger lumber can be anticipated. Overall, the limited geographic area and the small number of sites that covers this report restrict the applications of the models.

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Appendix 1

Strength class	**C14**	**C16**	**C18**	**C20**	**C22**	**C24**	**C27**	**C30**	**C35**	**C40**	**C45**	**C50**
Characteristics bending strength (N mm^{-2})	14	16	18	20	22	24	27	30	35	40	45	50
Mean characteristic value of modules of elasticity (kN mm^{-2})	7	8	9	9,5	10	11	11,5	12	13	14	15	16
Characteristics density (kg m^{-3})	290	310	320	330	340	350	370	380	400	420	440	460