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Modeling Density and Mechanical Properties in Norway Spruce (Picea abies (L.) Karst) by Forest Inventory Data

Modellering av densitet og mekaniske egenskaper til trelast av gran ved bruk av skoglige data

Runa Stenhammer Aanerød

Preface

This master's thesis marks the end of my Master's degree in Forest Sciences with the specialization in wood technology at the Norwegian University of Life Sciences (NMBU), Department of Ecology and Natural Resource Management (INA). During the years at NMBU, my interest and knowledge for wood technology has grown and I was therefore very grateful when I could write a thesis within strength grading of structural timber.

The thesis is based on the project Tresterk, with the main goal to develop systems for the production of timber with higher strength and stiffness, to increase the timber's competitiveness compared to other building materials. It has been motivating to work on such a concrete project, where several participants look at different aspects of the concept. Hopefully, my thesis can be a useful contribution in the research of better grading of timber.

Since my educational background consists of a Bachelor in Forest Sciences, I have focused on the aspects regarding the effect of forest inventory data on density, modulus of elasticity (MOE) and modulus of rupture (MOR) and how forest inventory data can contribute to improve strength grading of timber. The modelling in JMP has sometimes been difficult and frustrating, but I feel that I have learned a lot these past four months. Professor Geir Isak Vestøl, Professor Olav Albert Høibø and PhD candidate Carolin Fischer have been helpful through the entire thesis process and increased my understanding for modelling and strength grading of timber. I would also like to thank the participants of the project Tresterk that has formed the basis for the data material used in this thesis.

In addition, I would like to thank my professors in wood technology at the Norwegian University of Life Sciences for introducing me to the field of wood technology and for having encouraged me to immerse myself in this topic I would also like to thank Jonas Skaare Amundsen for support, encouragement and assistance during this last months, and my fellow students and friends for making my years at Ås unforgettable.Finally, I wish to give a special thanks to my supervisor professor Geir Isak Vestøl, Norwegian University of Life Sciences, for giving me an interesting problem to work with. He has contributed greatly to the thesis work by giving very concrete guidance and through his natural positivity. This has motivated me to do my best when working with and writing this thesis.

Runa Stenhammer Aanerød,

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Abstract

The properties of Norwegian timber varies greatly, but no quality sorting is done before the logs are sawn to boards at the sawmills. This means that large amounts of timber with wide variation in quality pass through the grading system, resulting in a smaller yield in the higher strength classes.

The requirements for structural timber are getting higher due to stricter safety margins in new standards. Still, forest owners are only rewarded by the volume the timber contains, and not based upon the strength of the timber. Thus, forest owners don't focus on which strength classes the timber belongs to during harvesting which causes a grading loss in higher strength classes.

To meet the requirements from producers and customers, a more correct description of the timber is of importance. To achieve this, an earlier sorting and a more precise prediction of the wood properties is necessary. In this study, the timber properties are predicted by forest inventory data to investigate the potential of presorting by the use of variable at site, tree and log level.

Density, modulus of elasticity (MOE) and modulus of rupture (MOR) were measured on 1206 boards from 205 Norway spruce (*Picea abies* (L.) Karst.) trees, sampled from 14 sites in south-eastern Norway. The variability of the properties was analyzed in linear mixed models where the random variance was divided into site variance, tree variance and residual variance. Variables at stand level, tree level, log level and board level were treated as fixed effects, and added as covariates to the model.

For density, relative log height in tree (H_{rel}), expressed as the ratio of the position of one log to the total tree height, was the most important fixed effect, and density increased with increasing relative log height. For MOE, both the H/D-ratio, defined as the ratio of tree height to DBH of each selected tree, DBH and the interaction between H_{rel} and DBH were important fixed effects. MOE increased with increasing H/D-ratio and interaction between H_{rel} and DBH, while it decreased with increasing DBH. For MOR, DBH was the most important fixed effect, and MOR decreased with increasing DBH.

Variance due to site accounts for a smaller proportion of the total variance in MOE and MOR than in density, while the within-tree variance accounts for a larger proportion of the variance in MOE and MOR than in density. Density is better explained than MOE and MOR at stand level, while this difference is much smaller, and partly opposite when also tree and log variables are included. This is probably because the density varies quite a lot at stand level, while MOE and MOR are also influenced by knots and other defects which may vary between trees and within trees. Since the strength properties are explained differently on stand, tree and log level, this means that the potential for sorting at different levels are not equal for density, MOE and MOR.

For density, variables at stand, tree and log level reduced the site and tree variance to a greater extent than IP-value from Dynagrade. For MOE and MOR, variables at stand, tree and log level alone did not reduce the site and tree variance to a greater extent than IP-value, but the contribution from these variables improved the grading in combination with Dynagrade.

Presorting using forest inventory data has the potential of improving the grading yield, but an implementation in the forest industry will require great effort and a desire from the entire value chain to be feasible.

Sammendrag

Egenskapene til norsk tømmer varierer sterkt, men kvalitetssortering gjøres først etter oppdeling ved sagbrukene. Dette betyr at store mengder tømmer med store kvalitetsvariasjoner går gjennom det samme sorteringssystemet, med den konsekvens at det blir mindre utbytte i de høyeste fasthetsklassene.

Kravene til konstruksjonsvirke blir stadig strengere, mens skogeierne kun belønnes av volum. Dette skaper en motsetning mellom tilbud og etterspørsel.

En mer korrekt fordeling av virket er viktig for å tilfredsstille kravene fra produsenter og kunder. For å oppnå dette må sortering på et tidligere tidspunkt gjennomføres, og nøyaktigheten til sorteringsmaskiner må forbedres. I denne oppgaven er egenskapene til tømmer predikert ved hjelp av skoglige data for å undersøke potensialet for en forsortering på henholdsvis bestandsnivå, trenivå og stokknivå.

Densitet, elastisitetsmodulus (MOE) og bøyefastet (MOR) ble målt på 1206 planker fra 205 trær av norsk gran (Picea abies (L.) Karst.), som ble samlet inn fra 14 forskjellige steder i Sørøst-Norge. Variasjonen i egenskapene ble analysert med lineære modeller hvor den tilfeldige variasjonen ble delt inn i bestandsvariasjon, trevariasjon og residualvariasjon. Variabler på bestandsnivå, trenivå, stokknivå og plankenivå ble behandlet som faste effekter, og ble lagt til modellen som kovariabler.

For densitet var relativ stokkhøyde i treet (H_{rel}), uttrykt som forholdet mellom posisjonen til en stokk og den totale høyden på treet, den viktigste faste effekten, og densiteten økte med økende relativ stokkhøyde. For MOE var både H/D-forholdet, definert som forholdet mellom treets høyde og DBH, og interaksjonen mellom H_{rel} og DBH signifikante faste effekter. De faste variablene påvirket MOE ulikt. MOE økte med økende H/D-forhold og interaksjon mellom H_{rel} og DBH, mens en økning i DBH redusert MOE. For MOR var DBH den viktigste effekten, og MOR avtok med økende DBH.

Variasjon mellom bestand utgjør en mindre andel av den totale variasjonen i MOE og MOR enn den gjør for densitet, mens variasjon innen trær utgjør mer av variasjonen i MOE og MOR enn for densitet. Densitet forklares bedre enn MOE og MOR på bestandsnivå, mens denne forskjellen er mye mindre, og dels motsatt når også tre- og stokkvariabler er inkludert i modellene. Dette skyldes trolig at densitet varierer ganske mye på bestandsnivå, mens MOE og MOR er også påvirket av kvist og andre feil som kan variere mellom trær og innen trær. Siden densitet, MOE og MOR er forklart ulikt avhengig av nivå betyr dette at potensialet for sortering på ulike nivåer er forskjellige for de ulike egenskapene.

Variabler på bestand-, tre- og stokknivået reduserte bestands- og trevariasjonen i densitet i større grad enn IP-verdi fra Dynagrade. Variabler på bestand-, tre- og stokknivå alene reduserte ikke bestands- og trevariasjonen i MOE og MOR bedre enn IP-verdien fra Dynagrade, men bidro til å øke forklaringen sammen med IP-verdi.

Forsortering ved hjelp av skoglige data har potensiale til å forbedre sorteringsutbyttet, men innføring av forsortering er ikke gjennomførbart uten at hele sektoren har et ønske om dette. I tillegg vil en forsortering være krevende å gjennomføre, da det krever flere endringer fra dagens praksis.

Content

Nomenclature

a	distance between a loading position and the nearest support in a bending test, in millimeters;
b	width of cross section in a bending test, or the smaller dimension of the cross section, in millimeters;
$E_{m,l}$	local modulus of elasticity in bending, in N/mm^2;
F	load, in N;
F_{max}	maximum load, in N;
$F_{max,est}$	estimated maximum load, in N;
f_m	modulus of rupture, in N/mm^2;
(F_2-F_1)	increment of load in N on the regression line with a correlation coefficient of 0.99 or better
$(\frac{F_2 - F_1}{w_2 - w_1})$	k-value
h	depth of cross section in a bending test, or the larger dimension of the cross section, or the test piece height in perpendicular to grain and shear tests, in millimeters;
I	second moment of area, in millimeters to the fourth power;
ℓ	span in bending, or length of test piece between the testing machine grips in compression and tension, in millimeters;
ℓ_1	gauge length for the determination of modulus of elasticity or shear modulus, in millimeters
ℓ_2	Distance between the supports and gauge length in torsion, in millimeters;
m_w	mass of test piece with the moisture content at the time of testing;
$m_{12\,\%}$	mass of test piece before drying;
m_0	mass of test piece after drying;
n	number of observations;
N	Newton;
R^2	coefficient of determination;
RSS	residual sum of squares;
TSS	total sum of squares;
V_w	volume of test piece with the moisture content at the time of testing, in cubic meters;
w	deformation or displacement, in millimeters;
w_2-w_1	increment of deformation in millimeters corresponding to F_2-F_1;
$W_{\%}$	moisture content, in percent;
ρ_w	density at the time of testing;
ρ_{12}	density adjusted to 12 % moisture content

Abbreviations

Symbol	Definition
Age	Tree age at stump height
AICc	Corrected Akaike Information Criterion value, which is a measure of model fit that is helpful when comparing different models.
ALT	Altitude
BA	Basal area
DBH	Mean diameter at breast height
DBH_{rel}	Relative diameter, expressed as the ratio of DBH of the sample trees in relationship to the mean DBH of the stand
Density	Wood density; ratio of mass to volume
F-ratio	Lists the F-statistic for testing that the effect is zero. It is the ratio of the mean square for the effect divided by the mean square for error. The mean square for the effect is the sum of squares for the effect divided by its degrees of freedom.
H	Total tree height
H/D-ratio	Slenderness of tree, expressed as the ratio of total tree height in relationship to the mean DBH of each selected tree
H_{log}	Longitudinal log height in tree, measured from butt end of the tree to midway between butt end and top end of the log
H_{rel}	Relative longitudinal log position in the tree, expressed as the relationship between the position of one log and the total tree height; H_{log}/H
H_{180}	Height to the whorl at which the living crown covered half of the circumference
H_{360}	Height to the whorl at which the living crown covered the whole circumference
IP-value	Indicating property value received from Dynagrade
LAT	Latitude
LCR	Crown ratio, expressed as the length of the living crown in relationship to total tree height
Mechanical properties	The strength and the resistance to deformation.
MOE	Modulus of elasticity. Measure of the resistance to bending, that is, directly related to the stiffness of a beam; also a factor in the strength of a long column
MOR	Modulus of rupture. Breaking strength, determines the load a beam will carry
p-value	Lists the p-value for the test. Values of 0.05 or less are often considered evidence that there is at least one significant effect in the model
R^2	Coefficient of determination. Estimates the proportion of variation in the response that can be attributed to the model rather than to random error. An R^2 closer to 1 indicates a better fit. An R^2 closer to 0 indicates that the fit predicts the response no better than the overall response mean
RMSE	Root mean square error. Estimates the standard deviation of the random error
SI	Site index, dominant height at age 40 years (Tveite 1977)
VIF	Shows the variance inflation factors. High VIFs indicate a collinearity problem

1 Introduction

In Norway, just below 8.8 million m^3 roundwood is removed for sale per year, of which approximately 3.2 million m^3 is sawlogs (SSB 2012). According to unofficial estimates from the Norwegian timber control (Norsk trelastkontroll), about one-third of the sawn timber is strength graded (Øvrum 2011). Strength graded timber constitute a substantial income for many sawmills and planing mills, and the capability to predict and document the strength thus have a major importance (Øvrum 2011).

The implementation of Eurocode 5 constitutes a challenge for the timber industry. Eurocode 5 was implemented in Norway in April 2010, and is today the only current engineering standard for timber structures (Nore 2011). Eurocode 5 allows lower tension perpendicular to the fiber direction than calculations done by the former standard NS 3470 (Nore 2011). This means that in some constructions, timber is no longer capable of competing with other building materials, causing a negative effect on the entire value chain from forest to finished buildings (Nore 2011). One way to counteract this effect is to develop systems for production of timber with higher strength and stiffness (Nore 2011; Øvrum 2011).

Density, modulus of elasticity (MOE), and modulus of rupture (MOR) are the most important properties for structural timber (Høibø et al. 2014; Lei et al. 2005). MOE and MOR are correlated both with physical properties of the wood, such as density, and with other wood characteristics which are considered as defects in visual grading (Vestøl et al. 2012).

Because of large variation in strength properties in timber, strength grading into different strength classes is required in order for timber to be used in load-bearing structures, such as joists, glulam, trusses and roof trusses (Hanhijärvi et al. 2005; Øvrum 2011). The strength class system consists of 12 classes (Table 1). This system has been adopted to ensure structural timber to achieve its purpose (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008). The variation in Norwegian timber is large (Chrestin 2000; Stapel & Denzler 2010; Øvrum 2011), and the strength properties of Norway spruce (*Picea abies* (L.) Karst.) vary widely within regions and among trees (Chrestin 2000; Nagoda 1985; Shmulsky & Jones 2011). The strength grading is done on kiln-dry timber, either visually after the Nordic standard INSTA 142 (Nordic-standard 2009), or by strength grading machines approved by the European standard EN 14081-1-4 (Standard-Norge 2009b) (Øvrum 2011).

Table 1: Strength classes in NS-EN 338 with corresponding characteristic modulus of rupture (MOR), modulus of elasticity (MOE) and density (Standard-Norge 2009a).

	Strength class NS-EN 338								
Grade determining properties	**C14**	**C16**	**C18**	**C22**	**C24**	**C27**	**C30**	**C35**	**C40**
Characteristic modulus of rupture (N/mm^2)	14	16	18	22	24	27	30	35	40
Characteristic modulus of elasticity (kN/mm^2)	7	8	9	10	11	12	12	13	14
Characteristic density (kg/m^3)	290	310	320	340	350	370	380	400	420

Of the pieces graded, 5 % may have a lower strength value than indicated by the strength class (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008; Myhra 1999). To ensure that the few weak pieces will not fail, an additional material safety factor of 1.3 is used (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008). Both modulus of rupture, modulus of elasticity and density must satisfy the values in Table 1 in order to fulfil the requirements of the strength classes (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008; Myhra 1999).

Earlier, visual grading was the most common strength grading method. Visual grading is based on strength-reducing characteristics like grain deviation, knots, reaction wood and other visual characteristics with significance for strength (Høibø et al. 2014; Shmulsky & Jones 2011). Visual grading is relatively inaccurate, but the accuracy has been improved by using mechanical grading (Høibø et al. 2014). In Norway, Dynagrade is by far the most commonly used strength grading machine (Høibø et al. 2014; Øvrum 2013), and approximately 80-90 % of the sawn timber is graded by this machine (Øvrum 2011).

Dynagrade measures the resonance vibration of the timber. The vibration is initiated by a strike from a metal hammer, and is captured by microphones at the end of the board. In combination with the length of the board, which is measured by a laser, Dynagrade calculates an indicating property (IP-value) (Dynalyse-AB 2014; Høibø et al. 2014; Øvrum 2013). The IP-value is correlated with the strength of the boards with an R^2-value of about 0.5 for Norway spruce (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008; Hoffmeyer 1995; Larsson et al. 1998; Olsson et al. 2012; Ranta-Maunus 2012). The resonance vibration is dependent of the ratio of MOE to density, which in turn depends on knots and other defects in the timber.

The highest strength class sorted in Norway today is C30, with the characteristic modulus of rupture of 30 N/mm^2 (Table 1) (Øvrum 2011). This is lower than the average strength of sawn timber from Norway, which is well above 40 N/mm^2 (Fjeld 2012; Langsethagen 2001; Myhre & Lilleslett 2003; Skyrud & Skaug 2002; Slotnæs & Værnes 2000). Unfortunately, the grading systems are not accurate enough to detect the large variation in Norwegian timber (Øvrum 2011). This leads to an inability to produce large enough volumes in higher strength classes that is commercially viable for sawmills (Øvrum 2011). In addition, the grading is done after primary or secondary processing with limited focus on what end product the various log qualities are suitable for (Vestøl et al. 2012).

To increase the grade yield, one can adapt sawing according to data measured on the logs (Vestøl et al. 2012). Such adaptions can be based on acoustic velocity in logs (Carter et al. 2006; Dickson et al. 2003; Jones & Emms 2010; Tsehaye et al. 2000a; Tsehaye et al. 2000b), external log shape (Jappinen & Beauregard 2000), or X-ray scanning of logs (Brannstrom et al. 2007; Oja et al. 2001; Oja et al. 2005). Another possibility is to predict the bending properties even earlier in the conversion chain (Vestøl et al. 2012). A third possibility is to predict bending properties of sawn timber based on forest inventory data (Vestøl et al. 2012). Such models have been developed for Black spruce (Lei et al. 2005; Liu, C. et al. 2007; Liu, C. M. et al. 2007), and Norway spruce (Høibø et al. 2014; Vestøl et al. 2012). Predicting bending properties from forest inventory data might give a better basis for further grading and a higher yield from the timber resource (Vestøl et al. 2012).

Due to their high frequency and strong effects, knots are known to be one of the key factors defining strength (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008; Kollmann & Côté 1968; Shmulsky & Jones 2011; Øvrum et al. 2009), and are among the most important characteristics in visual grading (Vestøl et al. 2012). It is mainly the changed fiber direction around a knot that causes the weak point (Hanhijärvi et al. 2005; Øvrum & Skaug 2007). The larger the size of a knot, the more severe, but also the location of a knot is of importance. When bending stresses occur, the maximum stress is located on the top and bottom edge of a beam. Also, knots on the lower edge of a beam are more severe than those on the upper, because knots have a more harmful effect in tension than compression (Shmulsky & Jones 2011).

Surveys have shown that the knot diameter increases towards the living crown, before it decreases towards the top (Haartveit & Flæte 2002; Høibø 1991; Makinen & Colin 1998; Øvrum et al. 2008; Øvrum & Vestøl 2009). The knot diameter is also correlated with different variables describing tree growth (Vestøl et al. 2012). Makinen and Colin (1998) found that branch diameter increased with increasing diameter at breast height and crown length in Scots pine, Maguire et al. (1999) found a similar result for Douglas fir, and Høibø (1991) and Vestøl and Høibø (2001) found positive correlation between knot diameter and diameter growth in Norway spruce.

By adding density to grading machines that measure resonance frequencies, the grading will be more accurate (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008; Ranta-Maunus 2009; Ranta-Maunus 2010). Density is defined as the ratio of mass (weight) and volume (Treteknisk 2009). Density is mainly governed by the amount of latewood compared to earlywood (Skaug 2007).The density will vary within a tree species, between stands, between trees inside the same stand, and within the same tree (Treteknisk 2009).

Density is influenced by many factors, especially those affecting the diameter growth. In general, factors reducing the diameter growth, increases the density; a decreased annual ring width provides an increment in the ratio between latewood and earlywood (Hundhausen 2010). Earlywood has thinner cell walls, thus lower density than latewood; and the greater amount of latewood, the higher density (Treteknisk 2009). The ratio between earlywood and latewood is given by growth rate and growth area (Hanhijärvi et al. 2005; Kvaalen et al. 2008; Treteknisk 2009; Øvrum & Skaug 2007). In the same geographical growth area, the thickness of latewood will be almost constant (Hanhijärvi et al. 2005; Kvaalen et al. 2008; Treteknisk 2009; Øvrum & Skaug 2007). The annual ring width, however, will increase with an increasing nutrient content in the soil and with silviculture that reduce competition between trees (Høibø 1991; Jyske et al. 2008; Kollmann & Côté 1968; Kvaalen et al. 2008; Skaug 2007; Treteknisk 2009; Øvrum & Skaug 2007; Øvrum 2013). The increment in annual ring width will happen in the earlywood, causing the density to decrease, since the proportion of latewood is reduced (Treteknisk 2009). Regarding genetic effect, a so-called genetic correlation is present between growth and density. This means that trees that have the facility to grow rapidly also have facilities for low density, meaning that the choice of plant material can influence the density (Kvaalen et al. 2008).

If timber from the same growth area is compared, the smaller annual ring width will provide greater density (Treteknisk 2009). A less favorable climate for growth will reduce the thickness of the latewood because the growth season comes to an end at an earlier time (Treteknisk 2009). In general, this means that at the same annual ring width, conifers grown further north or at higher altitudes have a lower density than conifers grown more south or at lower altitudes (Treteknisk 2009). In addition, an increased age will normally contribute positively to density, because older trees has a reduced diameter growth (Hundhausen 2010; Sonderegger et al. 2008).

The longitudinal variation in density in Norway spruce is not uniformly expressed. Kucera (1994) and Vadla (2006) reported a slightly increasing density upwards in the stem, Olesen (1982) found a decrease in density upwards the stem, while Repola (2006) and Sonderegger et al. (2008) found small differences in wood density between different heights in the stem. The radial density profile also varies (Høibø et al. 2014). Density is positively correlated with MOE, crushing strength and tensile strength (Vestøl et al. 2012).

An increasing dominance of trees is expected to influence the bending properties through their negative correlations with both knot size and density (Hundhausen 2010; Vestøl et al. 2012). A longitudinal decrease in bending properties may be expected due to increased knot size and increased knot diameter to log diameter ratio (Vestøl et al. 2012). According to Weibull's weakest link theory, an increase in dimension increases the probability of defects in the timber, causing an expected decrease in larger boards. However, upwards the stem, the amount of knots increase, causing a negative impact on the strength from smaller dimensions (Vestøl et al. 2012). Any longitudinal variation in density will also have an effect on bending properties (Vestøl et al. 2012). The importance of density and knot size may differ between strength and stiffness properties (Vestøl et al. 2012).

Several investigators have examined the possibility of modelling bending properties, and several variables have been found to have significance for MOE and MOR:

- site quality (Watt et al. 2006; Øvrum et al. 2009),
- stand density (Høibø 1991; Lei et al. 2005; Liu, C. et al. 2007),
- mean annual ring width (Haartveit & Flæte 2002),
- DBH (Haartveit & Flæte 2002; Lei et al. 2005; Liu, C. et al. 2007),
- tree height (Watt et al. 2006; Øvrum 2013),
- stem slenderness (Haartveit & Flæte 2002; Kijidani et al. 2010; Langsethagen 2001; Lei et al. 2005; Lindstrom et al. 2009; Liu, C. et al. 2007; Liu, C. M. et al. 2007; Skyrud & Skaug 2002; Watt et al. 2006; Øvrum 2013),
- knot diameter (Haartveit & Flæte 2002; Lei et al. 2005),
- log position in the stem (Hanhijärvi et al. 2005; Vestøl et al. 2012; Øvrum et al. 2009),
- crown length (Haartveit & Flæte 2002; Lei et al. 2005; Liu, C. et al. 2007) and
- crown width (Lei et al. 2005; Liu, C. et al. 2007).

In addition, mean annual air temperature (Watt et al. 2006) have been found to have significance for MOE. When modelling MOR, several investigators have found MOE to be the most important variable (Fewell 1982; Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008; Lei et al. 2005; Liu, C. et al. 2007).

Both MOR and MOE are dependent on density (Bramming et al. 2006; Haartveit & Flæte 2002; Liu, C. et al. 2007; Watt et al. 2006), but the relationship between MOR and MOE varies because knot size has a greater effect on MOR than on MOE (Vestøl et al. 2012).

1.1 Aim of thesis

Several studies have been done to achieve more efficient and accurate grading of sawn timber, but still the mechanical properties exhibit great variation within the grading classes (Vestøl et al. 2012). This is a challenge when using wood compared to other building materials that are more precisely described (Vestøl et al. 2012). An important question is how the mechanical properties are related to the growth of the trees, and if it is possible to use this knowledge to improve the industrial utilization of wood (Vestøl et al. 2012). In addition to enabling a more optimal raw material disposition, such knowledge may also give valuable feedback to forest management (Vestøl et al. 2012)

The first aim of this thesis has been to analyze the variability of density, MOE and MOR of structural Norway spruce timber, and to model the variability based on information at stand, tree and log level. The second aim has been to analyze if such information can be used to improve the accuracy of strength grading.

2 Materials and methods

The material was collected from 14 different sites in south-eastern Norway (Figure 1). The geographical data and inventory data for the sites are presented in Table 2.

The sites represented a large variety in latitude and altitude to investigate the effect of latitude and altitude alone and in combination. Most of the stands were scheduled for harvesting. The data included a longitudinal gradient of sites at relatively low altitude from Agder to Trøndelag, and an altitudinal gradient of sites from 150 meter to 845 meter at 60 – 61° northern latitude. In Trøndelag, the objective was to obtain a variation in site quality; however, only relatively low site indices were achieved.

It was desired to have sites with typical site indices for the areas, and in some cases it was asked for specific site indices to contribute to this variation (Stange, Toten, Birkeland and Froland). The sample was too small to be representative for each area, and the aim was rather to obtain the best possible dispersion, as described earlier. To a certain extent, the stands were chosen randomly, even though it was up to the forestry managers to identify appropriate fields.

Figure 1: Sample sites.

Table 2: Stand data.

Site	Latitude (°N)	Longitude (°E)	Altitude (m)	Site index (H40)	Basal area (m^2/ha)
Birkenes	58.29	8.20	170	11	44
Froland	58.53	8.46	210	20	45
Hurum	59.64	10.45	150	23	60
Lier	59.86	10.33	380	14	35
Veggli	60.04	9.11	700	8	21
Rødberg	60.26	8.94	800	8	32
Stange	60.53	11.37	370	14	47
Begnadalen	60.64	9.80	544	8	39
Toten	60.66	10.89	220	20	44
Etnedal	61.06	9.54	845	11	42
Tretten	61.31	10.24	630	14	45
Ulsberg	62.75	9.99	470	11	45
Trondheim	63.35	10.25	150	11	41
Frosta	63.65	10.91	100	11	34

The site indices, defined as dominant height at age 40 years (Tveite 1977), ranged from 8 to 23, and the basal area were ranging from 21 m^2/ha to 60 m^2/ha (Table 2)

In a selected area at each site, diameter at breast height (DBH) was recorded for 100-150 trees. In order to saw timber with dimension at least 50 by 100 mm from the butt logs, the trees to be selected were required to have DBH of at least 20 cm. The trees with a DBH larger than 20 cm were stratified in five groups with an equal number of trees in each group. From each group, three trees were randomly chosen. This resulted in a sample of 15 trees that was representative of the diameter distribution for trees with DBH larger than 20 cm, and at the same time secured the variation in the data. By a completely random selection without stratifying the trees, there is a risk of having all the trees grouped together in the middle, reducing the variability of the material. Trees with decay or visible defects such as top breakage, splay knots or too much crook were avoided.

The tree level variables measured on each sample tree were average of maximum and minimum diameter over bark at breast height (DBH), age at stump height (age), total tree height (H), height to the whorl where the living crown covered half of the circumference (H_{180}), and height to the whorl where the living crown covered the whole circumference (H_{360}). Mean values of the sampled trees from each site are presented in Table 3.

The relative diameter (DBH_{rel}), defined as the ratio of DBH of the sample trees to the mean DBH of the stand, and the H/D-ratio, defined as the ratio of H to DBH of each selected tree were calculated. The variable DBH_{rel} was based on the mean diameter of trees with DBH larger than 20 cm, i.e. those trees that were considered for the study. This means that it describes the relative diameter among trees sampled from each site, and also among trees that are large enough to yield saw logs.

Table 3: Tree data.

Site	No of trees (n)	DBH (mm)	DBH_{rel}	Age	Height (dm)	H_{360} (dm)	H_{180} (dm)	LCR	H/D
Begnadalen	15	263	1.02	108	201	108	81	0.60	0.78
Birkenes	13	330	1.05	138	232	162	117	0.49	0.72
Etnedal	14	292	0.99	91	190	112	81	0.58	0.68
Froland	15	299	0.98	66	237	130	103	0.56	0.81
Frosta	15	282	1.01	125	233	146	104	0.55	0.84
Hurum	15	269	0.97	49	256	177	156	0.39	0.97
Lier	15	279	1.00	76	218	141	105	0.51	0.80
Rødberg	14	266	1.00	124	175	96	70	0.60	0.66
Stange	15	240	1.00	58	187	88	67	0.64	0.79
Toten	15	290	0.98	104	257	160	118	0.54	0.90
Tretten	15	294	1.00	120	240	158	130	0.46	0.83
Trondheim	15	316	1.00	119	250	184	147	0.41	0.83
Ulsberg	15	276	1.59	128	211	132	106	0.49	0.78
Veggli	14	332	1.06	153	213	114	80	0.62	0.65

The logs were cut into lengths of 3.6, 4.2 or 4.6 meters. The butt logs were in general cut to 4.2 meters, while the top logs were cut to 3.6 meters. Several of the top logs were cut to 3.6 if this made room for an additional log. At least 4 meters is required for testing a 200 mm plank width, while the limit for the sawmills was 3.6 meters.

The log position (H_{log}), expressed as the log height in the tree, measured from butt end of the tree to midway between butt end and top end of the log, was registered. In addition, the relative log position within the tree (H_{rel}), expressed as the relationship between the position of one log and the total tree height was calculated. The material consisted of 445 butt logs, 444 middle logs and 348 top logs. Each log was sawn into two or four boards depending on the small-end diameter.

The dimension of the boards depended on the small-end diameter, and when sawing, it was attempted to make the saw-pattern as normal as possible. The dimension of the boards where restricted to the dimensions presented in Table 4.

The material contained 15 trees from each of the 14 sites, but because an entire timber package disappeared in the ordinary production at Soknabruket, the data from five trees is missing and the study is based on data from the remaining 205 trees. The missing trees were from Birkenes, Etnedal, Rødberg and Veggli (Table 3). In total, the material contained 1206 boards by the time the modelling started. The number of logs and boards from each site are presented in Table 4.

The board were dried in an industrial kiln and conditioned at 65 % relative humidity (RH) and 20 °C before testing.

Table 4: Sample tested divided by dimension and stand.

	Number of boards of each dimension					
Site	38 x 100 mm	50 x 100 mm	50 x 150 mm	50 x 200 mm	50 x 225 mm	Total
Begnadalen	5	29	27	2	0	63
Birkenes	0	27	47	18	0	92
Etnedal	2	28	0	19	0	49
Froland	0	30	56	14	0	100
Frosta	10	30	34	6	8	88
Hurum	0	41	61	2	0	104
Lier	0	41	42	7	0	90
Rødberg	0	26	21	4	0	51
Stange	5	27	10	4	0	46
Toten	2	29	58	31	0	120
Tretten	0	29	58	25	0	112
Trondheim	13	29	38	18	19	117
Ulsberg	19	22	32	4	4	81
Veggli	0	26	47	20	0	93
Total	56	414	531	174	31	1206

Since the processing of the boards happened at Begna, Sokna and Steinkjer, the boards where dried in industrial kilns and graded with Dynagrade machines at three different sawmills. All boards were graded in a Dynagrade at the sawmills, and an IP-value as defined in EN 14081-2 (Standard-Norge 2010b) was recorded for each board (mean values for each site are presented in Table 5).

The mean moisture content during sawing was 14 %, 16 % and 19 % for each of the three sawmills. A description of the correction of IP-value to 12 % moisture content is found in chapter 2.4 Determination of moisture content. Also, the density, MOE and MOR for each board was calculated, and the mean values for each site are presented in Table 5.

Table 5: Board variables.

Site	Number of boards (n)	IP-value	Density (kg/mm^3)	MOE (kN/mm^2)	MOR (N/mm^2)
Begnadalen	63	6.68	463	13.1	50.9
Birkenes	92	7.22	508	15.6	55.6
Etnedal	49	5.90	422	10.4	40.8
Froland	100	6.79	461	13.2	48.2
Frosta	88	7.25	479	14.3	55.4
Hurum	104	6.45	409	11.5	40.7
Lier	90	6.58	448	12.6	45.7
Rødberg	51	6.42	437	11.8	44.3
Stange	46	6.92	451	12.8	49.9
Toten	120	7.67	461	14.5	54.2
Tretten	112	6.85	434	12.0	47.7
Trondheim	117	6.93	440	12.5	46.4
Ulsberg	81	7.09	454	12.8	49.2
Veggli	93	6.73	449	12.5	47.7

2.1 Local modulus of elasticity (MOE)

The local modulus of elasticity (MOE) was tested in accordance to the rules for determination of some physical and mechanical properties of structural timber described in NS-EN 408:2010 (Standard-Norge 2010c).

The testing was done using a four-point bending arrangement, where the test pieces were symmetrically loaded and the cross section at the mid-span between the loading points were used for calculations (Figure 2). The test pieces were oriented the same way each time with the pith side facing east and butt-end facing south, to avoid knots or other defects in boards from the same log to systematically end up on either the tensile side or the compression side. This reduced the dependency of boards from the same log.

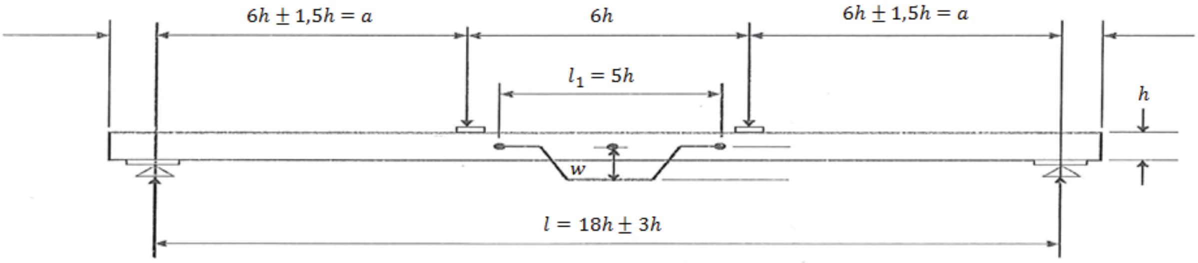


Figure 2: Test arrangement for measuring modulus of elasticity (MOE) and modulus of rupture (MOR).

The local MOE was calculated by the formula shown in Equation 1.

$$E_{m,l} = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)} \qquad \textbf{Equation 1}$$

where

a = distance between a loading position and the nearest support in a bending test, in millimeters

b = width of cross section in a bending test, in millimeters

$E_{m,l}$ = the local MOE, in N/mm^2

F_2-F_1 = an increment of load in N on the regression line with a correlation coefficient of 0.99 or better

h = depth of cross section in a bending test, in millimeters

I = $\frac{b \times h^3}{12}$

ℓ = distance between the two loading positions, in millimeters

ℓ_1 = distance between the measuring instrument anchor point, in millimeters

w = deformation, in millimeters

w_2-w_1 = the increment of deformation in millimeters corresponding to F$_2$-F$_1$

$\frac{F_2 - F_1}{w_2 - w_1}$ = k-value

Depending on the dimension, the load was applied at different speed (Table 6). Also the maximum load applied depended on the dimension (Table 6). According to the standard, the test speed shall not exceed a certain rate because the faster the test runs, the higher values are obtained. When measuring MOE, the load shall be applied within 30 seconds. The lower failure load was estimated to 20-30 N/mm^2, and the intension was to load 20 % of the lower failure load.

Table 6: Estimated and measured upper and lower limit.

	Load cycles		Load range for data recording		
Dimension (mm)	**Upper load (N)**	**Lower load (N)**	**Upper limit (N)**	**Lower limit (N)**	**Speed (mm/min)**
38x100	1400	400	1300	500	5
50x100	1800	500	1700	600	5
50x150	2700	2800	2600	900	5
50x200	3500	1000	3400	1200	10
50x225	3900	1200	3800	1300	10

2.2 Modulus of rupture parallel to grain (MOR)

The modulus of rupture (MOR) was tested in accordance to NS-EN 408:2010 (Standard-Norge 2010c), and the testing was done in a similar arrangement as MOE (Figure 2). The load was applied at a constant rate, and failure occurred within 3-5 minutes (Table 7).

Table 7: Test speed MOR.

Dimension (mm)	Speed (mm/min)
38x100	10
50x100	10
50x150	10
50x200	15
50x225	15

To calculate the modulus of rupture, Equation 2 was used.

$$f_m = \frac{3Fa}{bh^2}$$

Equation 2

where

a = distance between a loading position and the nearest support in a bending test, in millimeters

b = width of cross section in a bending test, in millimeters

F = load, in N

f_m = modulus of rupture, in N/mm^2

h = depth of cross section in a bending test, in millimeters

2.3 Determination of density

The density was measured from samples covering the whole cross section, taken as close to the failure point as possible.

The density was determined in accordance with ISO 3131 (International-Standard 1975b). The density was determined at the moisture content at the time of test, and corrected to 12% moisture content according to NS-EN 384:2010 (Standard-Norge 2010a). The volume and weight of the test pieces was measured, before the test pieces were lowered in water and the mass of the test pieces were noted. The density at the moisture content, W, at the time of the test is given in kilograms per cubic meter by Equation 3.

$$\rho_W = \frac{m_W}{V_W}$$

Equation 3

where

ρ_W = the density at the time of the test

m_W = the mass of the test piece with the moisture content at the time of testing

V_W = the volume of the test piece with the moisture content at the time of testing, in cubic meters

The results are expressed in kg/m^3 at an accuracy of 5 kg/m^3.

2.4 Determination of moisture content

The moisture content was measured from samples covering the whole cross section, taken as close to the failure point as possible.

The moisture content was determined by weighing and drying in accordance to ISO 3130 (International-Standard 1975a). The mass of the test samples was weighed before drying in 103 °C until the mass of the test piece was constant. After the test pieces were cooled, they were weighed again. The moisture content was calculated by the formula shown in Equation 4.

$$W_{\%} = \frac{m_W - m_0}{m_0} \times 100$$

Equation 4

where

m_W = the mass of the test piece before drying

m_0 = the mass of the test piece after drying

$W_{\%}$ = the moisture content in percent

The moisture content ranged from 8.9 % to 16.2 %, with an average of 13.6 %.

Table **8** presents the range in moisture content divided by the different dimensions.

Table 8: Range in moisture content divided by dimensions.

Dimension	N	Minimum	Maximum	Mean
38x100	56	12.9	13.8	13.5
50x100	414	8.9	14.5	13.3
50x150	531	11.9	16.2	13.7
50x200	174	11.9	15.2	13.6
50x225	31	13.5	15.1	14.3

2.4.1 IP-value

The moisture content during grading differed between sawmills, and the IP-values were adjusted to 12 % moisture content by the formula given in Equation 5 below.

$$IP_{\%} = \frac{IP_w}{\left(1 - 0.0123 \cdot (w - 12)\right)} \qquad \textbf{Equation 5}$$

where

$IP_{\%}$ = the adjusted IP-value

IP_W = the IP-value of the board when wet

w = the moisture content in the boards

2.4.2 MOE and MOR

The local MOE was adjusted by 1 percent for each percentage point deviation from 12 % moisture content, as prescribed by NS-EN 384:2010 (Standard-Norge 2010a), except that corrections were made on individual values instead of characteristic values. The adjustment formula is given in Equation 6.

$$MOE = E_{m,l} \times \left(1 + 0.01(W_{\%} - 12)\right) \qquad \textbf{Equation 6}$$

where

$E_{m,l}$ = local modulus of elasticity in bending, in N/mm^2

$W_{\%}$ = the moisture content in percent

MOR-values were adjusted by 1 % for each percentage point deviation from 12 % moisture content, even though NS-EN 384 does not prescribe any corrections for moisture content on MOR. The formula is given in Equation 7.

$$MOR = f_m \times \left(1 + 0{,}01 \times (W_{\%} - 12)\right) \qquad \textbf{Equation 7}$$

where

f_m = modulus of rupture, in N/mm^2

2.4.3 Density

In accordance with NS-EN 384:2010 (Standard-Norge 2010a); if the moisture content deviates from 12 %, the density is to be adjusted by 0.5 % for every percentage point difference in moisture content. The adjustment formula is given in Equation 8.

$$\rho_{12} = \rho_W \times \left(1 - 0{,}005 \times (W_{\%} - 12)\right)$$ **Equation 8**

where

ρ_{12} = the density adjusted to 12 % moisture content

ρ_W = the density at the time of the test

$W_{\%}$ = the moisture content in percent

2.5 Model development

Variation in density, MOE and MOR were analyzed in linear mixed models using the fit model platform in the JMP software, version 10.0 (SAS-Insitute-Inc. 2012), where the random variance was divided into site variance, tree variance and residual variance (Equation 9). The tree variance was nested under site, since not all tree numbers were unique. The effect of variables at stand level, tree level, log level and board level were treated as fixed effects in the analysis. The variable definitions of the fixed effects, divided in different levels, are presented in Table 9.

$$Y = \mu + f(A, B, \ldots) + S_i + T_j(S_i) + e$$ **Equation 9**

where

Y = density (ρ), MOE or MOR.

μ = the intercept (or mean for variance component models).

$f(A, B, \ldots)$ = the different fixed effects to be tested, the variable estimates. The variable definitions are given in Table 9.

S_i = the random site effects; i.e. variance due to site.

$T_j(S_i)$ = the random tree effects; i.e. variance due to tree.

e = the residual variance; i.e. within-tree variance.

Table 9: Variable definitions.

Variables	Abbreviation	Unit
Stand level		
Site index, dominant height at age 40 years (Tveite 1977)	SI	m
Altitude	ALT	m
Latitude	LAT	°N
Basal area	BA	m^2/ha
Tree level		
Mean diameter at breast height over bark	DBH	mm
Relative diameter, defined as the ratio of DBH of the sample trees to the mean DBH of the stand; DBH_{tree}/DBH	DBH_{rel}	
Tree age at stump height	Age	year
Tree height	H	dm
Height to the whorl at which the living crown covered half of the circumference	H_{180}	dm
Height to the whorl at which the living crown covered the whole circumference	H_{360}	dm
Crown ratio, the length of living crown in relationship to total tree height: $(H – H_{180})/H$	LCR	
H/D-ratio, defined as the ratio of tree height to DBH of each selected tree	H/D	dm/mm
Log level		
Log height in tree, measured from butt end of the tree to midway between butt end and top end of the log	H_{log}	dm
Relative log height in tree, expressed as the relationship between the position of one log and the tree height; H_{log}/H	H_{rel}	
Board level		
IP-value; indicting property value received from Dynagrade	IP	
Wood density	ρ	kg/mm^3
Modulus of elasticity	MOE	kN/mm^2
Modulus of rupture	MOR	N/mm^2

The random elements, S_i, $T_j(S_i)$ and e were assumed to be normally distributed and given by the variance components σ_S^2, σ_T^2 and σ_e^2. The fixed effects were entered into the models by starting with variables at stand level, then variables at stand- and tree level, further variables at stand, tree and log level, and finally, variables at stand, tree and log level in combination with IP-value. In addition, models based on IP-value from Dynagrade were estimated.

The variables were required to have a significance level at 0.05 or less to be included in the model.

The models were evaluated by the means of R^2- and RMSE-values of the fixed effects model, and the reduction of site, tree and residual variances described the parts of the random variance that were explained by different models. R^2- and RMSE-values from the JMP modelling output included the contribution from both fixed and random effects. R^2- and RMSE-values without random effects included were calculated from residuals of the fixed effects parts of the models. Linear regressions were performed between measured density-, MOE- and MOR-values and the predicted model formulas. The regressions were forced through zero with an incline of 1. R^2- and RMSE-values were based on the residuals from these regressions and on the total variance of the measured response values (density-, MOE- and MOR-values). The equation to calculate R^2- and RMSE-values is found in Equation 10.

$$R^2 = 1 - \frac{RSS}{TSS}$$

Equation 10

Where
R^2 = coefficient of determination
RSS = residual sum of squares
TSS = total sum of squares

Akaike information criterion (AICc) was included to assess the relative goodness of fit of the models.

Several of the variables used in the models are correlated to a certain degree. Collinearity has therefore been considered, but after calculating a variance inflation factor (VIF) for each variable, it does not seem like the severity of multicollinearity is serious. A correlation matrix between the different fixed effects variables used in the different models, separated in levels, are presented in Table 10 (stand level), Table 11 (tree level), and Table 12 (board level).

Table 10: Correlation matrix for fixed effect variables at stand level.

	SI	ALT	LAT	BA
SI	1.00			
ALT	-0.61	1.00		
LAT	-0.32	-0.04	1.00	
BA	0.72	-0.43	-0.13	1.00

Table 11: Correlation matrix for fixed effect variables at tree level.

	DBH	DBHrel	Age	H	H180	H360	LCR	H/D
DBH	1.00							
DBHrel	0.70	1.00						
Age	0.37	0.31	1.00					
H	0.58	0.32	0.05	1.00				
H180	0.09	-0.04	-0.04	0.59	1.00			
H360	0.18	-0.02	0.06	0.62	0.84	1.00		
LCR	0.21	0.21	0.05	-0.18	-0.89	-0.69	1.00	
H/D	-0.65	-0.56	-0.38	0.22	0.46	0.38	-0.45	1.00

Table 12: Correlation matrix for fixed effect variables at board level.

	IP	Density	MOE	MOR
IP	1.00			
Density	0.40	1.00		
MOE	0.68	0.67	1.00	
MOR	0.60	0.55	0.80	1.00

3 Results

Mean values, standard deviation and coefficient of variation for density, MOE and MOR are presented in Table 13. The mean value of density was 450 kg/m^3, the mean value of MOE was 12.8 kN/mm^2 and the mean value of MOR was 47.3 N/mm^2 (Table 13). Density had the smallest coefficient of variation, followed by MOE and MOR, with the values 9.4 %, 19.5 % and 24.7 %, respectively (Table 13). For density, the largest variation was found in tree variance, followed by site and residual (Table 13). For MOE and MOR, the largest variation was found in the residual, followed by tree and site variance (Table 13). This is also shown graphically in Figure 19 on page 43.

Table 13: Mean value, standard deviation and coefficient of variation of density, bending stiffness (MOE) and modulus of rupture (MOR) for the material. Also, the variation component of site, tree and residual divided in value and percent for density, MOE and MOR.

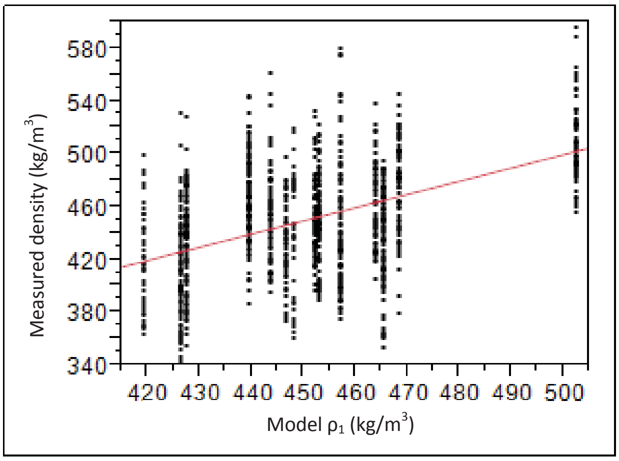
	Density, ρ (kg/m^3)		MOE (kN/mm^2)		MOR (N/mm^2)	
Mean value	450		12.8		47.3	
Standard deviation	42		2.5		11.7	
Coefficient of variation (%)	9.4		19.5		24.7	
	Var Component	**%**	**Var Component**	**%**	**Var Component**	**%**
Site, S_i	521	28.8	1.5	23.8	16.7	12.0
Tree, $T_j(S_i)$	787	43.4	2.2	35.4	52.2	37.5
Residual, e	505	27.9	2.6	40.8	70.3	50.5
Total	1814	100	6.3	100	139.2	100

3.1 Density, ρ

3.1.1 Model ρ_1 – using variables at stand level

Model ρ_1 describes density using only variables at stand level (Table 14). The model includes altitude, latitude and SI as fixed effects, and it has an R^2 of 0.212 and RMSE is 37.50 kg/m^3. The site variance was reduced from 521 (Table 13) to 132 (Table 14), while the tree variance and the residual variance were not affected. Interactions between altitude and latitude, and between latitude and SI were not significant ($p = 0.3024$ and $p = 0.3516$, respectively). Interaction between altitude and SI was neither significant ($p = 0.2210$), unless altitude was removed from the model ($p = 0.0278$).

In model ρ_1, an increase in the variables SI, altitude and latitude causes a decrease in density. Altitude is the most important variable, by means of the highest F-ratio, closely followed by SI, while the effect of latitude is smaller (Table 14). A simple regression model between density and the predicted values from the fixed effects part of model ρ_1 is presented in Figure 3, which shows the regression line forced through zero with an incline of 1.

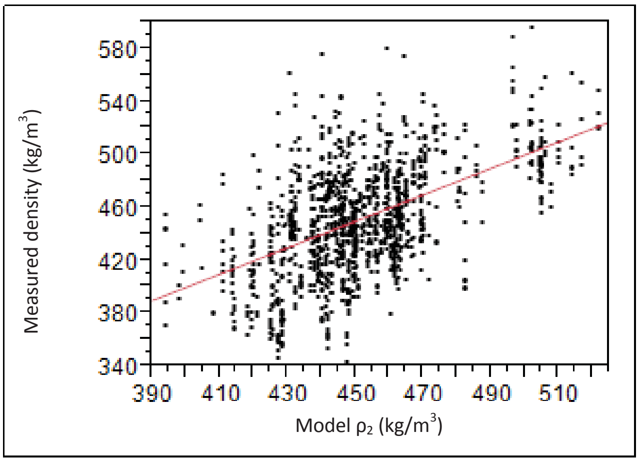


—— Regression line forced through zero with an incline of 1.

Figure 3: Regression model as a prediction of the measured density and the predicted model ρ_1.

3.1.2 Model ρ_2 – using variables at stand and tree level

Model ρ_2 describes density, using variables at stand- and tree level (Table 14). The model includes SI, altitude, latitude, age and H/D as fixed effects, and it has an R^2 of 0.284 and RMSE is 35.73 kg/m^3. The site variance was reduced to 146, the tree variance was reduced to 704, while the residual variance remained unchained (Table 14). An increase in the variables SI, altitude and latitude caused a decrease in density, while an increase in age and H/D gave an increase in density (Table 14). H/D and altitude were the fixed effects that explained the most in model ρ_2, followed by SI and latitude, while age explained the least in the model (Table 14). A simple regression model between density and the predicted values from the fixed effects part of model ρ_2 is presented in Figure 4, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

Figure 4: Regression model as prediction of measured density and the predicted model ρ_2.

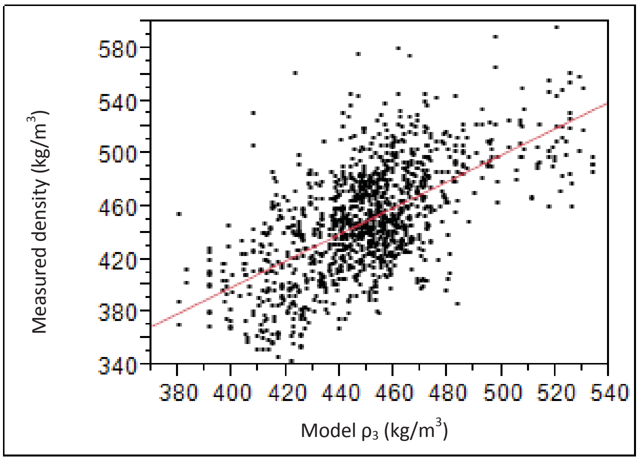
When an interaction between SI and age was added to the model ρ_2, the fixed effect SI was no longer significant ($p = 0.1266$), and the AICc-level increased from 11383.7 to 11384.1. The interaction between altitude and latitude did not contribute significantly to model ρ_2 ($p = 0.4088$), and therefore not included in the model.

As an alternative model to ρ_2, a model with SI, altitude, latitude, DBH, age and interaction between SI and age was considered. The fixed effect SI was not significant ($p = 0.4346$). The model reduced the site variation with 92.3 %, to 40 and the tree variation with 15.1 %, to 668. The residual variation was not affected. Unfortunately, the AICc-level was higher (AICc = 11386.9).

The fixed effects H, H_{180}, H_{360}, and LCR were not significant as single variables.

3.1.3 Model ρ_3 – using variables at stand, tree and log level

Model ρ_3 (Table 14) describes density using stand, tree and log variables. The fixed effects were SI, altitude, latitude, DBH, age, H_{rel}, interaction between SI and age, and interaction between H_{rel} and DBH (Table 14). The interaction between DBH and age was not significant (p = 0.4131) and therefore not included in the model. Increases in SI, altitude, latitude and DBH decrease the density, while increases in age, H_{rel}, the interaction between SI and age, and the interaction between H_{rel} and DBH increase the density. The model has an R^2 of 0.387 and RMSE is 33.07 kg/m^3. Compared with the variance component analysis, the model reduced the site variance with 92.7 %, the variance due to trees with 11.9 %, and the residual variance with 15.5 % (Table 13 and Table 14). H_{rel} was by far the most important single variable (F = 99.65, p = <0.0001, see Table 14), followed by the interaction between H_{rel} and DBH, altitude, latitude, DBH, age and interaction between SI and age (Table 14). The fixed effect SI was not significant (p = 0.3523). A simple regression model between density and predicted values from the fixed effects part model ρ_3 is presented in Figure 5, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

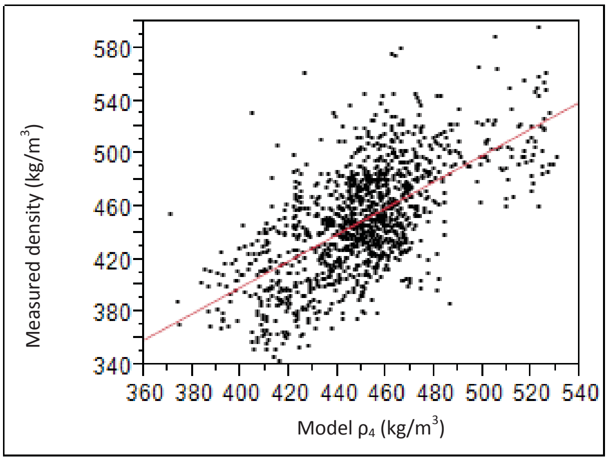
Figure 5: Regression model as prediction of measured density and the predicted model ρ_3.

An alternative to the model ρ_3, a model with SI, altitude, latitude, age, H/D, H_{rel}, and an interaction between SI and age as fixed effect, was considered. The model explained less of the variance due to site, trees and residual and had a higher AICc-level (AICc = 11249.5).

3.1.4 Model ρ_4 – using variables at stand, tree, log and board level

Model ρ_4 in Table 14 describes density using variables at stand, tree, log, and board level. The model includes SI, altitude, latitude, DBH, age, H_{rel}, interaction between SI and age, interaction between H_{rel} and DBH, and IP-value as fixed effects, and has an R^2 of 0.414 and RMSE is 32.35 kg/m^3 (Table 14). The site variance was reduced with 92.9 %, to 37, the tree variance was reduced with 17.4 %, to 650, and the residual variance was reduced with 16.0 %, to 424 (Table 13 and Table 14). H_{rel} was the most important variable (F = 105.72, p = <0.0001, see Table 14). Further, the interaction between H_{rel} and DBH, altitude and latitude followed before DBH, IP-value, age and the interaction between SI and age (Table 14). The fixed effect SI was not significant and contributed little (F = 1.63, p = 0.2304) (Table

14). The interaction between DBH and age was not significant (p = 0.4704), and therefore not included in the model. Increases in SI, altitude, latitude and DBH cause a decrease in density (Table 14). Increase in age, H_{rel}, interaction between SI and age, interaction between H_{rel} and DBH, and IP-value cause an increase in density (Table 14). A simple regression model between density and the predicted values from the fixed effects part of model ρ_4 is presented in Figure 6, which shows the regression line forced through zero with an incline of 1.



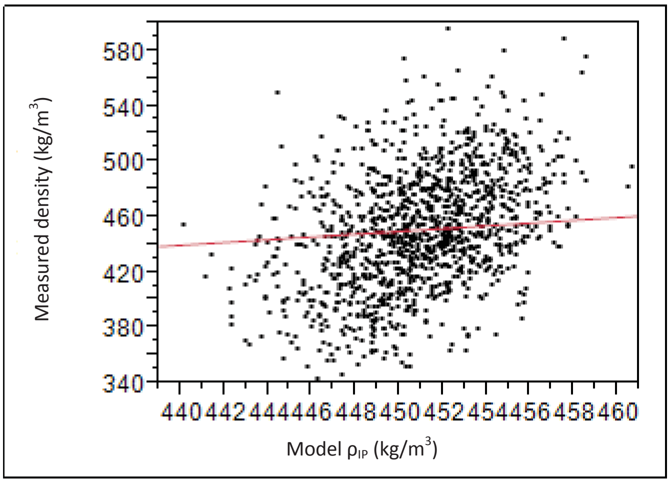
—— Regression line forced through zero with an incline of 1.

Figure 6: Regression model as prediction of measured density and the predicted model ρ_4.

An alternative model to ρ_4 was made, with SI, altitude, latitude, age, H/D, H_{rel}, interaction between SI and age and IP-value was made. The model explained less of the variation due to site, trees and residual, and had a higher AICc-level (AICc = 11237.1).

3.1.5 Model ρ_{IP} – using IP-value

Model ρ_{IP} describes a significant positive correlation between density and IP-value (F = 8.47, p = 0.0037), but the R^2 is only 0.054 and RMSE is 41.08 kg/m^3 (Table 14). The fixed effects model left major unexplained variance both due to site, tree and residual (Table 14). A simple regression model between measured density and the IP-values from Dynagrade is presented in Figure 7.



—— Regression line forced through zero with an incline of 1.

Figure 7: Regression model as prediction of measured density and the predicted model ρ_{IP}.

Table 14: Statistics for density (ρ) models.

Summary of statistics:										
	Model ρ_1		Model ρ_2		Model ρ_3		Model ρ_4		Model ρ_{IP}	
Variance component from model step										
		%		%		%		%		%
S_i	132	74.7	146	72.0	38	92.7	37	92.9	472	9.4
$T_j(S_i)$	787	0.0	704	10.5	693	11.9	650	17.4	737	6.4
e	505	0.0	505	0.0	427	15.5	424	16.0	508	+ 0.5
Total	1424	21.5	1355	25.3	1158	36.2	1112	38.7	1717	5.3
Summary statistics from model step, only fixed effects included										
R^2	0.212		0.284		0.387		0.414		0.054	
RMSE (kg/mm^3)	37.50		35.73		33.07		32.35		41.08	
Akaike Information criterion value										
AICc	11404.8		11383.7		11222.7		11203.2		11406.8	
F-ratio and p-values for the fixed effects in the different models										
	F-ratio	p-value	F-ratio	p-value	F-ratio	p-value	F-ratio	p-value	F-ratio	p-value
SI	22.34	0.0007	12.12	0.0034	0.95	0.3523[1]	1.63	0.2304[1]		
ALT	25.07	0.0004	16.24	0.0022	34.36	0.0003	30.80	0.0004		
LAT	8.15	0.0165	11.88	0.0060	29.92	0.0005	30.12	0.0005		
DBH					29.30	<0.0001	22.34	<0.0001		
Age			6.35	0.0139	24.38	<0.0001	19.16	0.0002		
H/D			17.56	<0.0001						
H_{rel}					99.65	<0.0001	105.72	<0.0001		
(SI·Age)					9.46	0.0113	7.79	0.0188		
(H_{rel} · DBH)					35.31	<0.0001	43.21	<0.0001		
IP-value							19.42	<0.0001	8.47	0.0037
Models:										
Model	Equation									
Model ρ_1	$1039.1 – 5.64 \cdot SI – 0.100 \cdot ALT – 7.66 \cdot LAT$									
Model ρ_2	$1044.9 – 5.02 \cdot SI – 0.084 \cdot ALT – 9.58 \cdot LAT + 0.303 \cdot Age + 80.9 \cdot (H/D)$									
Model ρ_3	$1128.7 – 1.26 \cdot SI – 0.086 \cdot ALT – 10.41 \cdot LAT – 0.200 \cdot DBH + 0.590 \cdot Age + 38.07 \cdot H_{rel} + 0.065 \cdot (SI \cdot Age) + 0.364 \cdot (H_{rel} \cdot DBH)$									
Model ρ_4	$1079.2 – 1.62 \cdot SI – 0.080 \cdot ALT – 10.23 \cdot LAT – 0.173 \cdot DBH + 0.516 \cdot Age + 39.15 \cdot H_{rel} + 0.058 \cdot (SI \cdot Age) + 0.406 \cdot (H_{rel} \cdot DBH) + 5.807 \cdot IP$									
Model ρ_{IP}	$423.1 + 4.063 \cdot IP$									

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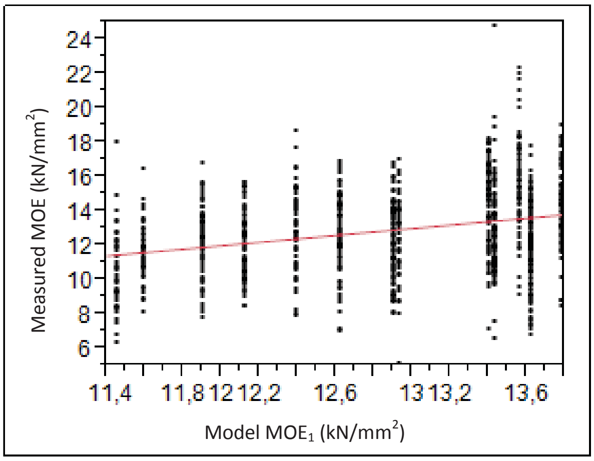
[1] Not significant

3.2 MOE

3.2.1 Model MOE_1 – using variables at stand level

When modelling the MOE only using variables at stand level, a model with altitude as the only fixed effect gave the best model (Table 15). Model MOE_1 has an R^2 of 0.068 and the RMSE is 2.41 kN/mm^2 (Table 15). The site variance was reduced from 1.5 (Table 13) to 1.0 Table 15, while the tree variance and the residual variance not were effected (Table 15). An increase in altitude causes a decrease in MOE, and the fixed effect has an F-ratio of 7.35 and a p-value of 0.0186 (Table 15). A simple regression model between MOE and the predicted values from the fixed effect part of model MOE_1 is presented in Figure 8, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

Figure 8: Regression model as prediction of measured MOE and the predicted model MOE_1.

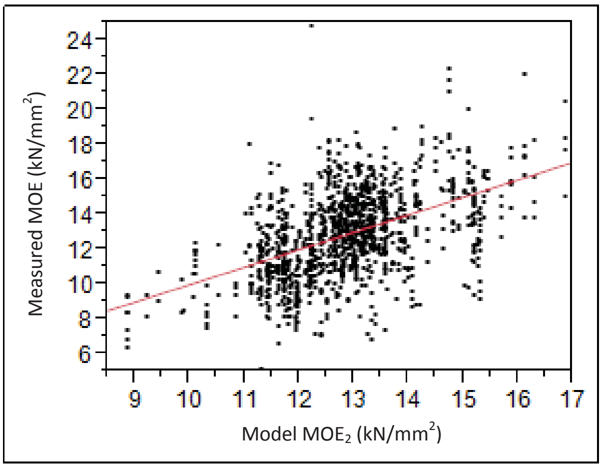
An alternative model to model MOE_1 is a model made with altitude, latitude and SI. Altitude and SI were significant ($p = 0.0007$ and $p = 0.0111$, respectively), while latitude was not ($p = 0.0627$). The interaction between altitude and latitude and between SI and latitude were not significant ($p = 0.5860$and $p =0.0897$, respectively), and therefore not included in the model. In a model with the fixed effects altitude, SI and interaction between altitude and SI only altitude was significant ($p = 0.0496$), and only if altitude and SI were removed from the model, the interaction was significant ($p = 0.0346$).

3.2.2 Model MOE_2 – using variables at stand and tree level

Model MOE_2 was the best model for predicting MOE, only including variables at stand and tree level. The model is found in Table 15 and is made with the fixed effects SI, altitude, latitude, age and H/D. The model has an R^2 of 0.246 and the RMSE is 2.16 kN/mm^2 (Table 15). The interaction between altitude and latitude was not significant ($p = 0.6797$), and therefore not included in the model. The interaction between SI and age was significant ($p = 0.0121$), but still it was not included to the model since the fixed effect SI turned out to be not significant ($p = 0.2689$), and the AICc-level increased (AICc = 4935.1).

As compared with the variance component analysis, the model MOE_2 reduced the site variance with 74.7 %, to 0.4, the tree variance with 21.1 %, to 1.8, and the residual variance with 0.4 %, to 2.6 (Table 13 and Table 15). Increases in the variables SI, altitude and latitude cause a decrease in the MOE, while an increase in age and H/D gives an increase in the MOE (Table 15). By means of the F-ratio, H/D was the fixed effect that explained the most in the model MOE_2, followed by altitude, latitude, SI and age.

A simple regression model between MOE and the predicted values from the fixed effects part of model MOE_2 is presented in Figure 4, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

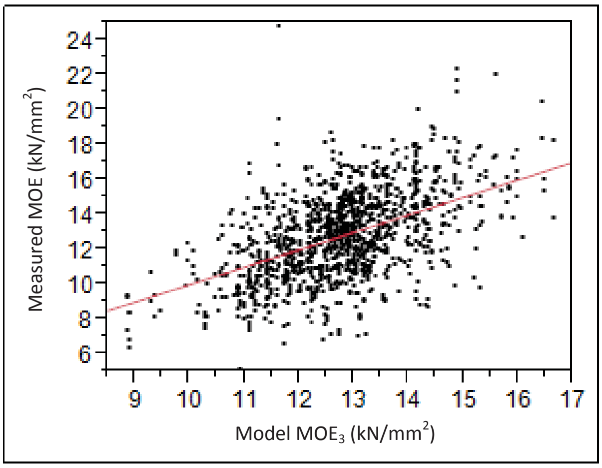
Figure 9: Regression model as prediction of measured MOE and the predicted model MOE_2.

An alternative to model MOE_2 was a model made with altitude, latitude, DBH and age as fixed effects. The model explained more of the variance due to site and trees, it had a higher R^2 than model MOE_2 ($R^2 = 0.271$), but the AICc-level increased (AICc = 4930.6). When SI and interaction between SI and age was added to the model, the interaction was significant ($p = 0.0012$), while SI was not ($p = 0.3297$). When SI and H were added separately to the model, the fixed effects were not significant ($p = 0.1975$ and $p = 0.1339$). When SI and H were added simultaneously to the model, H was significant ($p = 0.0341$), while SI was not ($p = 0.0512$).

When H was modelled alone or with altitude, the effect on the MOE was negative, while the effect of H on the MOE, when modelled with DBH is positive. The fixed effects H_{180}, H_{360} and LCR are not significant.

3.2.3 Model MOE_3 – using variables at stand, tree and log level

Model MOE_3 was the best model with stand, tree and log variables, and the fixed effects were altitude, latitude, DBH, age, H_{rel}, and interaction between H_{rel} and DBH (Table 15). The MOE decreased with increasing altitude, latitude, DBH and H_{rel}, and increased with increasing age and interaction between H_{rel} and DBH (Table 15). The model's R^2 is 0.275 and the RMSE is 2.13 kN/mm^2 (Table 15). Model MOE_3 reduced the site variance with 82.0 %, the variance due to trees with 22.9 %, and the residual variance with 2.3 % (Table 13 and Table 15). DBH was the most important single variable, closely followed by altitude, age and H_{rel} (Table 15). Further, interaction between H_{rel} and DBH, and latitude, followed. A simple regression model between MOE and the predicted values from the fixed effects part of model MOE_3 is presented in Figure 10, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

Figure 10: Regression model as prediction of measured MOE and the predicted model MOE$_3$.

The interaction between altitude and latitude was tested, but did not give significant ($p = 0.8855$) effect to the model and was therefore not included. Also the AICc-level of the model increased (AICc = 4926.0) with this interaction in the model. When interaction between DBH and age was added, the interaction was not significant ($p = 0.4302$). Also an alternative model was considered, with the fixed effects altitude, latitude, age, H, H/D and H_{rel}. This model reduced the variance due to site, trees and residual with the same amount as in model MOE$_3$, but it had a higher AICc-level (AICc = 4915.3). When the fixed effect SI was added to this model, it was not significant ($p = 0.0619$), and the AICc-level increased further (AICc = 4916.8).

3.2.4 Model MOE$_4$ – using variables at stand, tree, log and board level

Model MOE$_4$ in Table 15 describes MOE using variables at stand, tree, log, and board level. The best model was with SI, altitude, latitude, DBH, age, H_{rel}, interaction between H_{rel} and DBH, and IP-value, and the R^2 was 0.546, and the RMSE is 1.68 (Table 15). As compared with the variance component, the site variance was reduced with 96.0 %, to 0.1, the variance due to trees was reduced with 62.8 % to 0.8, and the residual variance was reduced with 22.2 % to 2.0 (Table 13 and Table 15). When SI and interaction between SI and age were added to the model, the model explained almost all the site variance, with a remaining site variance of 0.02. The fixed effect SI was not significant ($p = 0.3637$) and the AICc-level increased (AICc = 4606.1). The interaction between altitude and latitude did not give any significant contribution to model MOE$_4$ ($p = 0.8197$). Neither did the interaction between DBH and age ($p = 0.6506$).

In model MOE$_4$, IP-value was the most important variable, followed by the interaction between H_{rel} and DBH. Then followed altitude, latitude, H_{rel} and DBH, while SI and age were the least important variables (Table 15). MOE decreased with increasing SI, altitude, latitude, DBH and H_{rel}, and increases with increasing age, interaction between H_{rel} and DBH, and IP-value. A simple regression model between MOE and the predicted values from the fixed effects part of model MOE4is presented in **Figure 11**, which shows the regression line forced through zero with an incline of 1.

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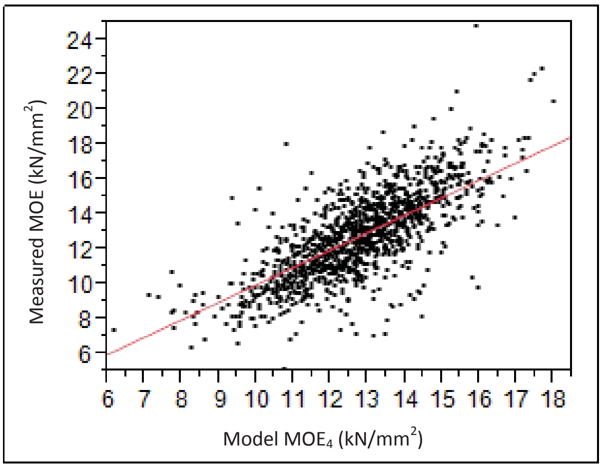


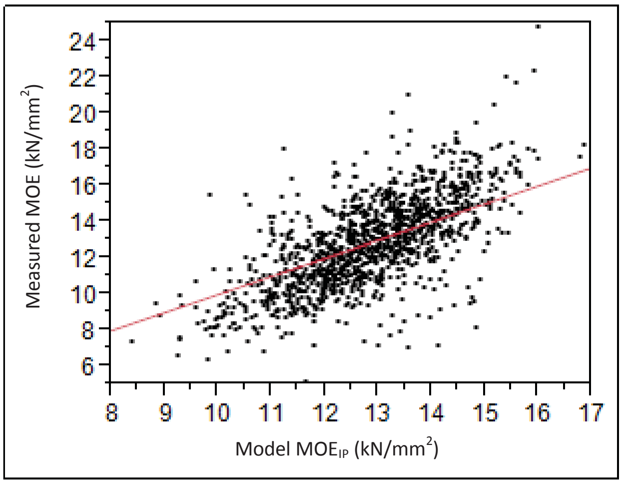
—— Regression line forced through zero with an incline of 1.

Figure 11: Regression model as prediction of measured MOE and the predicted model MOE$_4$.

An alternative model with SI, altitude, latitude, H/D, H_{rel} and IP-value explained almost the same amount as the model MOE$_4$, with a remaining site variance of 0.1, tree variance of 1.0 and residual variance of 2.1. The model had a higher AICc-level (AICc = 4614.0).

3.2.5 Model MOE$_{IP}$ – using IP-value

Model MOE$_{IP}$ describes a significantly positive correlation between MOE and IP-value (F = 413.70, p = <0.0001), but the R^2 is only 0.440 and the RMSE is 1.87 kN/mm^2 (Table 15). The site variance was reduced with 67.4 %, to 0.5, the tree variance was reduced with 58.7 %, to 0.9, while the residual variance was reduced with 16.7 % to 2.1 (Table 14). A simple regression model between the measured MOE and the IP-values from Dynagrade is presented in Figure 12, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

Figure 12: Regression model as prediction of measured MOE and the predicted model MOE$_{IP}$.

Table 15: Statistics for modulus of elasticity (MOE) models.

Summary of statistics:										
	Model MOE_1		Model MOE_2		Model MOE_3		Model MOE_4		Model MOE_{IP}	
Variance component from model step										
		%		%		%		%		%
S_i	1.0	36.7	0.4	74.7	0.3	82.0	0.1	96.0	0.5	64.7
$T_j(S_i)$	2.2	0.0	1.8	21.1	1.7	22.9	0.8	62.8	0.9	58.7
e	2.6	0.0	2.6	0.4	2.5	2.3	2.0	22.2	2.1	16.7
Total	5.8	8.7	4.7	25.4	4.5	28.6	2.9	54.1	3.6	43.0
Summary statistics from model step, only fixed effects included										
R^2	0.068		0.246		0.279		0.546		0.440	
RMSE (kN/mm^2)	2.41		2.16		2.12		1.68		1.87	
Akaike Information criterion value										
AICc	4958.1		4929.5		4911.3		4598.4		4625.8	
F-ratio and p-values for the fixed effects in the different models										
			F-ratio	p-value	F-ratio	p-value	F-ratio	p-value	F-ratio	p-value
SI			8.96	0.0088			6.72	0.0217		
ALT	7.35	0.0186	17.94	0.0014	33.54	<0.0001	29.77	0.0002		
LAT			11.60	0.0061	7.73	0.0180	25.76	0.0006		
DBH					49.01	<0.0001	15.31	0.0001		
Age			6.58	0.0124	30.81	<0.0001	5.99	0.0180		
H/D			42.07	<0.0001						
H_{rel}					29.66	<0.0001	23.03	<0.0001		
($H_{rel} \cdot$ DBH)					11.24	0.0008	41.18	<0.0001		
IP-value							386.43	<0.0001	413.70	<0.0001

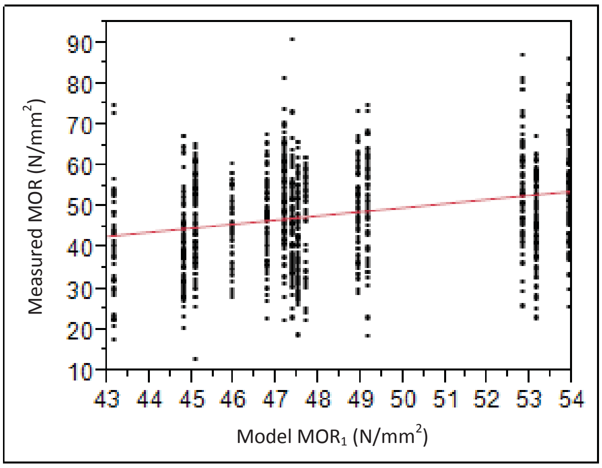
Models:

Model	Equation
Model MOE_1	$14.1 - 0.003 \cdot ALT$
Model MOE_2	$40.7 - 0.005 \cdot ALT - 0.49 \cdot LAT - 0.224 \cdot SI + 0.016 \cdot Age + 6.642 \cdot (H/D)$
Model MOE_3	$36.0 - 0.004 \cdot ALT - 0.33 \cdot LAT - 0.014 \cdot DBH + 0.030 \cdot Age - 1.574 \cdot H_{rel} + 0.016 \cdot (H_{rel} \cdot DBH)$
Model MOE_4	$28.1 - 0.003 \cdot ALT - 0.37 \cdot LAT - 0.109 \cdot SI - 0.006 \cdot DBH + 0.011 \cdot Age - 1.248 \cdot H_{rel} + 0.027 \cdot (H_{rel} \cdot DBH) + 1.635 \cdot IP$
Model MOE_{IP}	$1.4 + 1.676 \cdot IP$

3.3 MOR

3.3.1 Model MOR_1 – using variables at stand level

When modeling MOR using only variables at stand level, SI and altitude gave the best model. This model is presented as model MOR_1 in Table 16, and it has an R^2 of 0.047 and RMSE is 11.42 N/mm^2. The site variance was reduced from 16.7 (Table 13) to 8.5 (Table 16), while the tree variance was reduced with scarce 0.2 % (Table 13 and Table 16). The residual variance was not affected (Table 16). In model MOR_1, an increase in the variables SI and altitude causes a decrease in MOR. By means of the highest F-ratio, both variables had approximately the same importance, with altitude as the most important (Table 16). A simple regression model between MOR and the predicted values from the fixed effects part of model MOR_1 is presented in Figure 13, which shows the regression line forced through zero with an incline of 1.



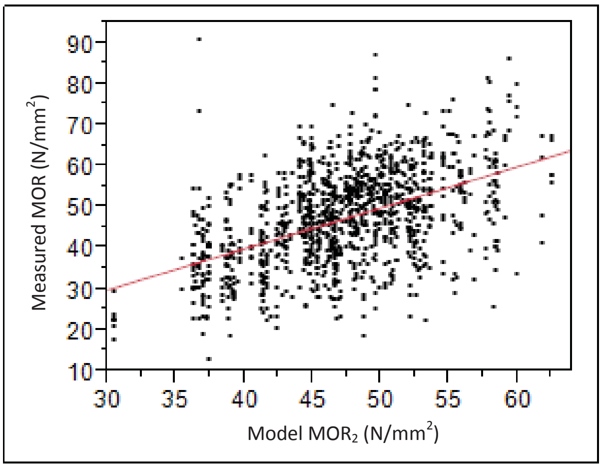
—— Regression line forced through zero with an incline of 1.

Figure 13: Regression model as prediction of measured MOR and the predicted model MOR_1.

If the interaction between SI and altitude was added to the model, none of the fixed effects were significant (SI = 0.1657; altitude: p =0.1711; interaction SI and altitude: p = 0.4401). Latitude did not give a significant contribution to the model MOR_1 (p = 0.4775). None of the interactions between SI, altitude and latitude were significant. The interaction between SI and altitude was significant if the fixed effect altitude was removed from the model (p = 0.0202).

3.3.2 Model MOR_2 – using variables at stand and tree level

Model MOR_2 describes MOR, using variables at stand- and tree level. The model includes altitude, DBH and age as fixed effects, and it has an R^2 of 0.236 and the RMSE is 10.22 N/mm^2 (Table 16). The site variance was reduced 16.7 to 7.4 (Table 13 and Table 16, respectively), and the tree variance was reduced from 52.2 to 28.7 (Table 13 and Table 16, respectively), while the residual variance was scarcely affected, with 0.2 % (Table 13 and Table 16). Increases in the variables altitude and DBH cause a decrease in MOR, while an increase in DBH causes an increase in MOR (Table 16). DBH is the most important variable, by means of a much higher F-value than the other fixed effects in the model (F = 114.98, p = <0.0001, see Table 16). Age is the second most important variable (Table 16), while altitude is the least important (Table 16). An interaction between DBH and age was tested, but the interaction was not significant (p = 0.4740), and therefore not included in the model. A simple regression model between MOR and the predicted values from the fixed effects part of model MOR_2 is presented in Figure 14, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

Figure 14: Regression model as prediction of measured MOR and the predicted model MOR$_2$.

An alternative model with SI, altitude, DBH and H explained less of the variance and the AICc-level was higher (AICc = 8845.9). Also another model with SI, altitude, H and H/D was considered, but the AICc-level was higher (AICc = 8839.8). A model with altitude, age, H and H/D was also considered, but the AICc-level was higher (AICc = 8837.8).

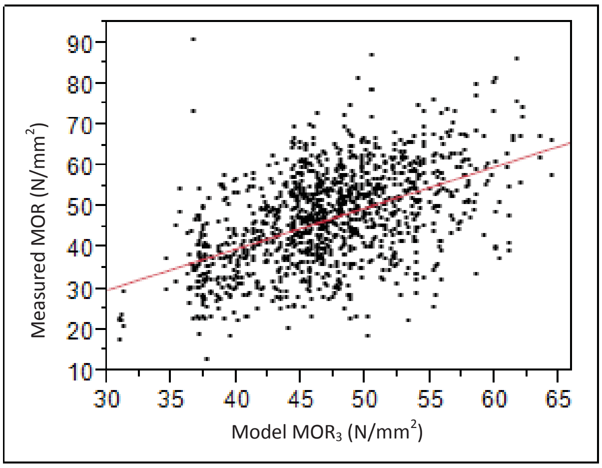
When MOR was modeled with H alone or H and altitude, the effect of H on MOR was negative, while the effect of H in combination with DBH was positive. When MOR was modeled with H_{180}, H_{360} and LCR, the fixed effects were not significant.

3.3.3 Model MOR$_3$ – using variables at stand, tree and log level

Model MOR$_3$ (Table 16) describes MOR using stand, tree and log variables. The fixed effects were altitude, DBH, age, H_{rel} and interaction between H_{rel} and DBH (Table 16). The site variance was reduced with 55.1 %, to 7.5, the tree variance was reduced with 44.8 %, to 28.8 and the residual variance was reduced with 2.9 %, to 68.2 (Table 13 and Table 16). Model MOR$_3$ has an R^2 of 0.248 and the RMSE is 10.14 N/mm^2 (Table 16). DBH is the most important variable, with a considerably higher F-value than the other variables (F = 105.27, p = <0.0001, see Table 16). Further, H_{rel} and age followed, before altitude and interaction between H_{rel} and DBH (Table 16). Increase in the variables altitude, DBH and H_{rel} cause a decrease in MOR, while increases in the variables age and interaction between H_{rel} and DBH cause an increase in MOR (Table 16).

Neither SI (p = 0.7565) nor latitude (p =0.1616) gave any significant contribution to the model, and therefore these effects were not included. The interaction between altitude and latitude was not significant (p = 0.5719), nor was the interaction between DBH and age (p = 0.5791), and therefore none of these were included in the model.

A simple regression model between MOR and the predicted values from the fixed effects part of model MOR$_3$ is presented in Figure 15, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

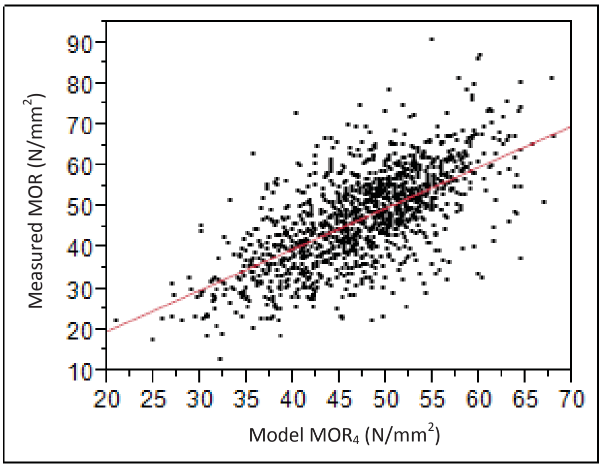
Figure 15: Regression model as prediction of measured MOR and the predicted model MOR$_3$.

An alternative model with the fixed effects SI, altitude, latitude, age, H, H/D, H_{rel} and interaction between SI and age was considered, but the model explained less of the variance and had a higher AICc-level than model MOR$_3$ (AICc = 8819.1). In addition, the fixed effect SI was not significant (p = 0.8170).

3.3.4 Model MOR$_4$ – using variables at stand, tree, log and board level

Model MOR$_4$ in Table 16 describes MOR using variables at stand, tree, log, and board level. The fixed effects were DBH, age, H_{rel}, interaction between H_{rel} and DBH, and IP-value (Table 16). When the fixed effects SI, altitude and latitude were added, the fixed effects altitude and latitude were significant, while the fixed effect SI was not (p = 0.0667). The interaction between SI and age was not significant (p =0.0587), and therefore not included in the model. Nor the interaction between DBH and age was added since it did not give significant contribution to the model (p = 0.8458). Increases in the variables DBH and H_{rel} cause a decrease in MOR, while increases in the variable age, interaction between H_{rel} and DBH, and IP-value cause an increase in MOR (Table 16). The site variance was reduced with 76.0 %, to 4.0, the variance due to trees was reduced with 70.9 %, to 15.2, and the residual variance was reduced with 15.3 %, to 59.5 (Table 16). The model has an R^2 of 0.443 and the RMSE is 8.73 N/mm^2 (Table 16). IP-value was the most important variable, followed by DBH (Table 16). Further, the interaction between H_{rel} and DBH followed, while the variables H_{rel} and age were least important.

A simple regression model between MOR and the predicted values from the fixed effects part of model MOR$_4$ is presented in Figure 16, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

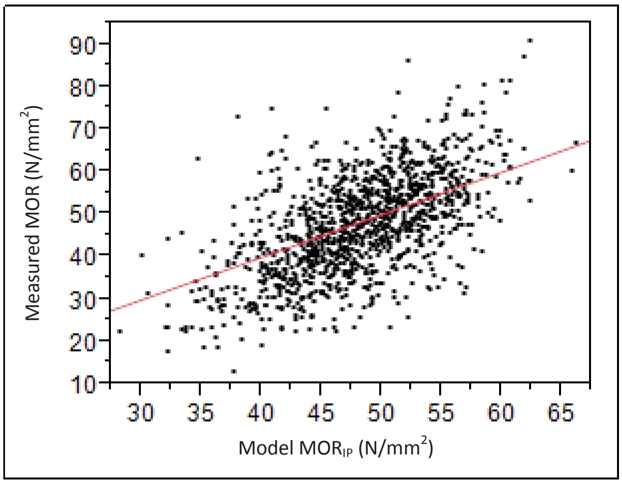
Figure 16: Regression model as prediction of measured MOR and the predicted model MOR$_4$.

An alternative model with the fixed effects SI, altitude, latitude, DBH, age and IP-value (Table 16) was considered. The site variance was reduced with 91.0 %, to 1.5, the variance due to trees was reduced with 70.7 %, to 15.4, and the residual variance was reduced with 43.5 %, to 61.8 (Table 13 and Table 16). The model has an R^2 0.443 and the RMSE is 8.73 N/mm^2 (Table 16), but the AICc-level is higher (AICc = 8619.7).

Another alternative model with the fixed effects SI, altitude, latitude, H, H/D, H_{rel} and IP-value was also considered. The model explained more of the site variance (2.3), but less of the tree variance and residual variance (17.0 and 61.2, respectively). The model had a higher AICc-level (AICc = 8608.0).

3.3.5 Model MOR$_{IP}$ – using IP-value

Model MOR$_{IP}$ describes a significant positive correlation between MOR and IP-value (F = 301.04, p = <0.0001), and the R^2 is 0.350 and the RMSE is 9.43 N/mm^2 (Table 16). The site variance was reduced with 79.0 %, to 3.5, the tree variance was reduced with 51.3 %, to 25.4, and the residual variance was reduced with 11.7 % to 62.0 (Table 13 and Table 16). A simple regression model between measured MOR and the IP-values is presented in Figure 17, which shows the regression line forced through zero with an incline of 1.



—— Regression line forced through zero with an incline of 1.

Figure 17: Regression model as prediction of measured MOR and the predicted model MOR$_{IP}$.

Table 16: Statistics for modulus of rupture (MOR) models.

Summary of statistics:										
	Model MOR_1		Model MOR_2		Model MOR_3		Model MOR_4		Model MOR_{IP}	
Variance component from model step										
		%		%		%		%		%
S_i	8.5	48.9	7.4	56.0	7.5	55.1	4.0	76.0	3.5	79.0
$T_j(S_i)$	52.1	0.2	28.7	45.1	28.8	44.8	15.2	70.9	25.4	51.3
E	70.3	0.0	70.1	0.2	68.2	2.9	59.5	15.3	62.0	11.7
Total	130.9	5.9	106.1	23.7	104.5	24.9	78.7	43.5	91.0	34.7
Summary statistics from model step, only fixed effects included										
R^2	0.047		0.236		0.248		0.443		0.350	
RMSE (N/mm^2)	11.42		10.22		10.14		8.73		9.43	
Akaike information criterion value										
AICc	8909.0		8835.2		8811.4		8573.4		8657.5	
F-ratio and p-values for the fixed effects in the different models										
	F-ratio	p-value	F-ratio	p-value	F-ratio	p-value	F-ratio	p-value	F-ratio	p-value
SI	6.28	0.0290								
ALT	9.71	0.0092	12.56	0.0038	11.85	0.0047				
LAT										
DBH			114.98	<0.0001	105.27	<0.0001	62.04	<0.0001		
Age			24.35	<0.0001	22.51	<0.0001	8.25	0.0069		
H_{rel}					26.67	<0.0001	21.98	<0.0001		
($H_{rel} \cdot$ DBH)					11.76	0.0006	35.32	<0.0001		
IP-value							276.88	<0.0001	301.04	<0.0001
Models:										

Model	Equation
Model MOR_1	$64.5 - 0.015 \cdot ALT - 0.700 \cdot SI$
Model MOR_2	$67.5 - 0.013 \cdot ALT - 0.091 \cdot DBH + 0.118 \cdot Age$
Model MOR_3	$68.7 - 0.012 \cdot ALT - 0.087 \cdot DBH + 0.114 \cdot Age - 7.76 \cdot H_{rel} + 0.083 \cdot (H_{rel} \cdot DBH)$
Model MOR_4	$11.7 - 0.054 \cdot DBH + 0.052 \cdot Age - 6.548 \cdot H_{rel} + 0.134 \cdot (H_{rel} \cdot DBH) + 7.096 \cdot IP$
Model MOR_{IP}	$-3.5 + 7.528 \cdot IP$

4 Discussion

When selecting stands, one aim was to achieve a gradient in latitude with representative stands from the lowland in each region, and representative variation of site quality in each region. In addition, it was an aim to obtain an altitudinal gradient in south-eastern Norway. The stands, from Birkenes in the south, to Frosta in the north, has satisfying north-south gradient. The stands at the same latitude in eastern Norway have a satisfying altitude gradient, while in Trøndelag, the aim was to achieve a gradient in site quality, but only relatively low site qualities were achieved. The SI-variation in the south was satisfying, though a little difficult to achieve, because the forestry managers were asked to contribute with stands. In some cases, the selection of stand was controlled to achieve variety. Still, Froland was younger than expected and Begnadalen older than expected. Overall, there was a great amount of old stands and site index G11, and this may have influenced the results.

4.1 Variable contribution on density, MOE and MOR

4.1.1 Variables not included in the models

Other investigators have found an effect of basal area (BA), but it had no significance for density, MOE or MOR in this study. Basal area expresses the current situation in a stand, and less about the competition present in the stand during its lifetime. The properties of wood are more dependent on the competitive conditions during the stands lifetime, and this effect is expressed better by other fixed effects, like DBH.

In this study, DBH_{rel} was calculated on the trees with a DBH above 20 cm, causing the variable to contribute almost similar as DBH. Since DBH_{rel} not contain information about the suppressed trees, the variable contributes with less information about the growth conditions in the stand. This was the reason why the variable was excluded from the models.

In simple regression, H had a negative impact on MOE and MOR, while it contributed positively in multiple models together with DHB. This is plausible since DBH and H contribute with information about the tree volume and the slenderness of the trees. Watt et al. (2006) reported that for trees with high growth competition, rapid height growth was important in the competition with neighbors. However, this strategy gives a negative effect on diameter increment. Øvrum (2013) found tree height to be a good predictor for MOR, but thought it to be a very inconsistent variable because it is dependent on tree age and SI. This is the reason this variable was excluded from the models.

4.1.2 Latitude and altitude

For all the density models (Table 14), the fixed effects altitude and latitude contributed negatively to density, which is expected since an increase in these geographical variables causes a decrease in growth conditions, by means of colder climate. For all the MOE models (Table 15), and for the MOR models MOR_1, MOR_2 and MOR_3 (Table 16), the effect of altitude on MOE and MOR was negative. Also for the MOE models MOE_1, MOE_2 and MOE_3 (Table 15), the effect of latitude on MOE was negative. The negative effect of higher altitudes and latitudes on MOE and MOR is in accordance with the findings in Høibø and Vestøl (2010). Higher altitudes and latitudes provide shorter growth periods because of lower temperature sums, which contribute negatively to the thickness of the latewood (Treteknisk 2009), which again is negative for the relationship between density and annual ring width (Watt et al. 2006; Wilhelmsson et al. 2002).

In model ρ_1 (Table 14), latitude had a relative small impact on density compared with SI and altitude. Also for model MOE_2 and MOE_3 (Table 15), the contribution from latitude was less than the other fixed effects. This may be proper for Norwegian geography, or it may be a sampling effect in the material. Unfortunately, the variability of SI and altitude among the northernmost sites was limited, and probably not representative for the area. This may have influenced the results, and particularly the effect of latitude. Still, latitude had negative effect on both density, MOE and MOR, even when corrected for SI and altitude. The interaction between latitude and altitude and between latitude and SI was not significant at any level.

4.1.3 Site index

In all the density models (Table 14), the MOE models MOE_1 and MOE_2 (Table 15) and model MOR_1 (Table 16), SI contributed negatively on density, MOE and MOR. The impact of SI on MOE and MOR have earlier been reported with conflicting results, e.g. Fjeld (2012) and Watt et al. (2006) have reported a negative impact, Liu, C. et al. (2007) found no impact, and Høibø and Vestøl (2010) found a positive impact. The explanation why SI contributes negatively is that a higher site quality often leads to a greater diameter growth, yielding larger annual year rings and lower density (Haartveit & Flæte 2002). Nevertheless, if the stand is dense, this will yield smaller annual year rings and knots, and higher wood density, thus providing higher MOR values (Høibø 1991). If the trees grow in a dense stand, the effect of SI is likely to be reduced, while a sparse stand likely provides lower densities, and thereby lower MOE and MOR values.

The site quality may influence by means of two factors; climatic conditions and the nutrition in the soil. To investigate this relationship, the interaction between SI and altitude was looked upon. In this thesis, the interaction between SI and altitude when predicting density, MOE and MOR at stand level (model ρ_1, MOE_1 and MOR_1), was not significant, unless the fixed effect altitude was removed from the models. This suggests that the SI was depending on nutrition in the soil, rather than climatic factors.

Also the interaction between SI and age was looked upon, and this variable was only significant for density (model ρ_3 and ρ_4). The interaction had a relatively small positive impact on density, and can be looked upon as an adjustment of the negative impact from SI.

4.1.4 DBH and age (mean annual ring width)

Mean annual ring width at breast height have been reported an important variable for reducing MOE and MOR (Haartveit & Flæte 2002; Høibø & Vestøl 2010; Høibø 1991; Maguire et al. 1999; Makinen & Colin 1998). The negative impact of increased mean annual ring width on MOE and MOR can be explained by the effect on proportions of earlywood and latewood. Earlywood has thinner cell walls than latewood and thus lower density, and the greater amount of earlywood, the lower the density .

During forest inventory, the mean annual ring width is more difficult to measure than age and DBH. The age and DBH can be used as a substitute to this variable, since they together provide information about the annual ring width. Therefore, these two variables should be considered together.

DBH had a negative impact, while age had a positive impact on density, MOE and MOR at all levels. In other words, the negative impact from an increased DBH is likely to be compensated some by an increase in age. The findings of a negative impact on density, MOE and MOR from an increasing DBH is in accordance with several other investigations (Haartveit & Flæte 2002; Høibø & Vestøl 2010; Liu,

C. et al. 2007; Vestøl et al. 2012; Wang et al. 2004). A large DBH indicates rapid growth, and rapid growth produces wide annual rings, large knots and large values of taper, which are likely to affect bending stiffness of Norway spruce negatively (Haartveit & Flæte 2002). In addition, stem diameter growth is positively correlated with knot diameter (Høibø 1991; Maguire et al. 1999; Makinen & Colin 1998; Vestøl & Høibø 2001), which again is negatively correlated with MOR (Kollmann & Côté 1968).

Liu, C. et al. (2007) found that DBH was the best single predictor of MOR, explaining approximately 58 % of the variance in MOR. In this study, DBH was the most important fixed effect when modelling MOE and MOR at stand, tree, log and board level. For density, DBH had a substantial role, but not to the same extent as for MOE and MOR. The impact of age on density, MOE and MOR is in contrast to what Høibø and Vestøl (2010) found. Høibø and Vestøl (2010) did not investigate the impact of age on MOE and MOR in combination with DBH, but with tree height and mean annual ring width, and found a negative impact from age on MOE and MOR. If tree height is held constant, and age increases , this means lower SI according to the site quality curves from Tveite (1977). This could explain why Høibø and Vestøl (2010) found a negative impact of age on MOE and MOR.

In this study, none of the interactions between DBH and age were significant and have not been included in any of the models. In total, the negative effect from DBH and the positive impact from age combined give a negative impact from annual ring width.

4.1.5 H/D-ratio (slenderness)

Several investigations have demonstrated that slenderness of trees is an effective predictor of timber strength (Haartveit & Flæte 2002; Høibø & Vestøl 2010; Kijidani et al. 2010; Langsethagen 2001; Lei et al. 2005; Lindstrom et al. 2009; Liu, C. et al. 2007; Liu, C. M. et al. 2007; Skyrud & Skaug 2002; Watt et al. 2006; Øvrum 2013). Slenderness of trees can be expressed as a H/D-ratio, i.e. the tree height divided by the diameter at breast height (Øvrum 2013). In this study, an increasing H/D-ratio was positively correlated with density in model ρ_2, and MOE in model MOE_2, and this is in accordance with Liu, C. et al. (2007); Haartveit and Flæte (2002) and Høibø and Vestøl (2010). A high H/D-ratio indicates long and slender trees, which again indicate that the trees come from denser plantations. An increase in plant density has a positive effect on the mechanical properties of timber; providing smaller annual ring widths, less knots, and higher wood densities (Høibø 1991; Kijidani et al. 2010).

4.1.6 H_{rel}

H_{rel} has a positive impact on density, but a negative impact on MOE and MOR. H_{rel} is expressed as the single log height in a tree divided by total tree height, meaning the relative longitudinal log position in the tree. The negative impact from H_{rel} on MOR can be explained by the increment of branches and knot size upwards toward the lower part of the living crown. In general, an increase in knot size will reduce MOR. Høibø and Vestøl (2010) found a negative impact of log height in pine trees on MOE and MOR. Høibø and Vestøl (2010) explained the negative impact due to characteristics such as knot diameter, which increases with increasing distance from the ground (Makinen & Colin 1998), and density which decreases with increasing distance from the ground (Wilhelmsson et al. 2002). For Norway spruce, the longitudinal variation in density is not uniformly expressed (Kucera 1994; Olesen 1982; Repola 2006; Sonderegger et al. 2008; Vadla 2006). In spruce, it looks like the density increases with increasing height above the ground when the SI is high, and when the SI is low, the opposite seems to be the case (Høibø et al. 2014). In this study, H_{rel} had a positive impact on density in the models ρ_3 and ρ_4, indicating that density increased with distance from the ground, which is in accordance with what Høibø et al. (2014) found.

4.1.7 Interaction between H_{rel} and DBH

The interactions between H_{rel} and DBH in the models ρ_3, ρ_4, MOE_3, MOE_4, MOR_3 and MOR_4, all had a positive impact on density, MOE and MOR, respectively. This indicates that the upwards increase in density, MOE and MOR is greater in trees with a larger DBH than trees with smaller DBH. H_{rel} and DBH both had negative impact on MOE and MOR in the models MOE_2, MOE_3, MOR_2, MOR_3 and MOR_4, indicating that MOE and MOR decrease upwards the trees because of an increase in knot diameter. H_{rel} had a positive impact on density, indicating that density increase upwards the trees. An increase in density will reduce the negative effect from DBH and H_{rel} on MOE and MOR, and this could explain why the interaction between H_{rel} and DBH had a positive impact on MOE and MOR.

4.1.8 Magnitude of effects

Figure 18 below shows how much the log level models (model ρ_3, MOE_3 and MOR_3) predict density, MOE and MOR to vary within the range of each fixed effect. To calculate each effect, the density, MOE and MOR model was calculated, and the different fixed effects were separately chosen as the lowest and highest value measured in the data material. The changes in density, MOE and MOR were calculated in percent (Figure 18).

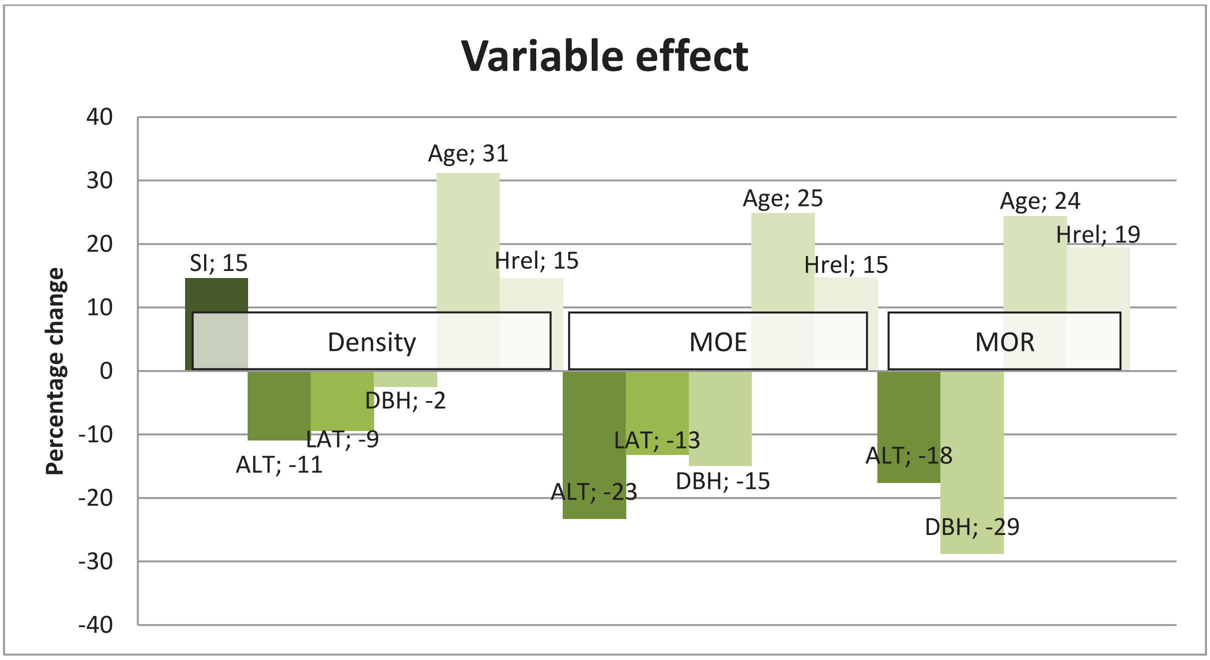


Figure 18: The percentage change in density, MOE and MOR by increase in SI, altitude, latitude, DBH, age and H_{rel}.

Figure 18 shows that an increase from the lowest to the highest values in the variables SI, age and H_{rel} increase the density with 15 %, 31 % and 15 %, respectively, while an increase from the lowest to the highest values in the variables altitude, latitude and DBH decrease the density with 11 %, 9 % and 2 %, respectively. For MOE, an increase in the variables age and H_{rel}, causes an increase in MOE with 25 % and 15 %, respectively, while an increase in the variables altitude, latitude and DBH decreases MOE with 23 %, 13 % and 15 %, respectively. For MOR, an increase from the lowest to the highest values in the variables age and H_{rel}, causes an increase in MOR with 24 % and 19 %, respectively, while an increase from the lowest to the highest values in the variables altitude and DBH causes a decrease in MOR with 18 % and 29 %, respectively.

As presented in Figure 18 the fixed effects at tree level have less importance for density than for MOE and MOR, and the effect of tree size is smaller for density than for MOE and MOR. This is in accordance with what Vestøl et al. (2012) found. The effect of age is almost similar for the different properties, and this can be explained by the effect of increasing age to annual ring width, as discussed earlier under the variable contribution to the models.

When looking at the variable effects in Figure 18, it looks like the strength properties are higher at low altitudes, low latitudes and higher SI, in trees with smaller DBH, at older age, and not in the butt log closest to the ground. Some of these findings seem logical, for instance the effect due to growth and climatic condition. Altitude and latitude affect the relationship between latewood and earlywood, while smaller DBH and higher age leads to narrower annual ring width with the consequence of higher densities. A longitudinal increase in height normally causes a decrease in MOE and MOR because of greater knot diameters, but as discussed under the chapter Variable contribution on density, MOE and MOR, the smaller trees had a greater variation upwards the stem than the larger trees. Normally in spruce, more dominant trees have greater height-variation in knot diameter with distance from the ground than suppressed trees, which is in contrast to the findings in this study. For density, the longitudinal variation in smaller trees compared to larger, and the longitudinal variation due to SI is not clearly expressed.

4.2 Models at stand, tree and log levels

According to the variance component analysis (Table 13, and Figure 19 below), variance due to site accounts for less of the total variance for MOR and MOE than density, while within-tree variance accounts for less of the total variance for density than for MOE and MOR. The variance due to trees is more similar between the three properties (Figure 19). When comparing the models with inventory data at different levels, it is clear that density is explained to a greater extent than MOE and MOR at stand level, while this difference is much smaller, and partly opposite when tree and log variables are included. This is probably because the density varies quite a lot at stand level, while MOE and MOR is also influenced by knots and other defects which may vary between trees and within trees. Since the density, MOE and MOR are explained differently depending on levels, this means that the potential for sorting at different levels are different for density, MOE and MOR.

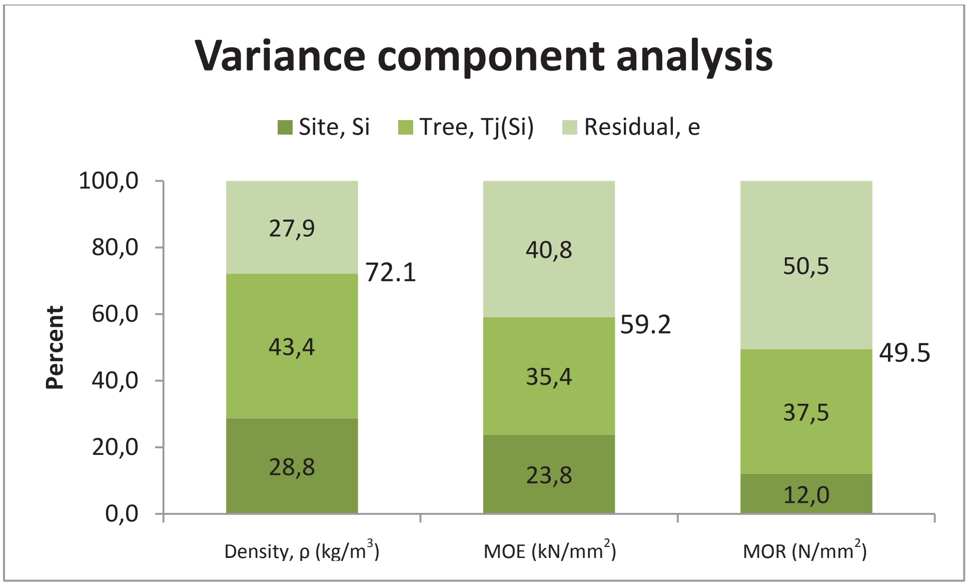


Figure 19: Variance component analysis. The potential explanatory power at stand level, tree level and residual.

As presented in Figure 19, the potential of explaining the variance in the material varies for density, MOE and MOR. Density has a potential explanatory power of 72.1 % when modelling at stand, tree and log level. MOE and MOR has a much smaller amount of variation due to site, which explain the low R^2-values obtained by the models MOE_1 and MOR_1. In the material, over half of the variation is related to within-tree variance (residual, *e*) and this helps to explain the relatively low R^2-value obtained in model MOR_3.

4.3 IP and the potential improvement by presorting

Currently in Norway, Dynagrade is by far the most common grading machine (Høibø et al. 2014; Øvrum 2013), and the models with IP-value as the only fixed effect (ρ_{IP}, MOE_{IP} and MOR_{IP}) represents the grade yield with the current practice. In several studies, the IP-value is correlated with the strength of the boards with an R^2-value of about 0.5 (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008; Hoffmeyer 1995; Larsson et al. 1998; Olsson et al. 2012; Ranta-Maunus 2012). In this study, the R^2-value in model MOR_{IP} (Table 16) was only 0.35 and the RMSE was 9.43 N/mm^2, while the R^2-value in model MOE_{IP} (Table 15) was only 0.44 and the RMSE was 1.87 kN/mm^2. For the density model ρ_{IP} (Table 14), the R^2-value was miniscule 0.054, and the RMSE was 41.08 kg/m^3. The RMSE-values found for MOR and MOE in this study is more in accordance with the findings done by Høibø et al. (2014), who found RMSE-values of 2.6 kN/mm^2 for MOE, and of 10.5 N/mm^2 for MOR.

For MOE and MOR, the models with information about the stand, stand and tree, and stand, tree and log level explained less than the models with IP-value alone. Looking at the variance component analysis, the variables at stand, tree and log level still contain information the IP-value does not account for, and this is clearly expressed by the model combining IP-value and inventory data (the models ρ_4, MOE_4 and MOR_4). The MOE model with inventory data and IP-value had an R^2-value of 0.546 and the RMSE was 1.68 kN/mm^2. The MOR model with the same combination had an R^2-value of 0.443 and the RMSE was 8.73 N/mm^2.

Naturally, the IP-value contributed positively to density, MOE and MOR. When Fjeld (2012) modelled MOR in his thesis, he found that the IP-value obtained from Dynagrade reduced much of the residual variance in MOR in the grading of lumber from fertile sites. Also in this study, the IP-value reduced the residual in MOE and MOR (Table 15 and Table 16) to a greater extent than the variables at stand, tree and log level. For density, the explanation of IP-value was relatively low (Table 14) and this may be due to the fact that the resonance frequency is determined by the relationship between MOE and density, and that the formulas for IP-value take MOE more into account than density. The formulas for IP-value are not known. MOE is affected more by knots and other defects, and then the relationship between MOE and density will not remain constant.

For density, the models at stand level, tree level and log level were all better models than the one with only IP-value. This visualizes the potential of sorting density using inventory data. The poor yield when sorting density using IP-value shows that not all properties of importance for structural timber can be measured at the sawmills by using Dynagrade, and a presorting of the density must be done differently. Measuring density is challenging, but a presorting for density is desirable because it may help reduce process cost and may increase productivity. Hundhausen (2010) claimed that if the density varied greatly, the production of cladding by splitting boards in dry condition caused different surface structures which again increased the process cost. The drying process is an energy-intensive step in the production of timber, and an increase in density affects the drying process considerably. According to Hundhausen (2010), surveys have shown that the drying process possibly can be reduced with 4 % only by presorting in low and high density .

4.4 Implementation

Sorting at stand, tree and log level alone cannot replace the current practice of grading lumber with IP-values obtained from Dynagrade, but the variables at the different levels contains information that have the potential of improving the sorting. This is also found by Høibø et al. (2014).

As a consequence of the implementation of Eurocode 5, presorting is of great importance. The improvement in R^2 found in this study by combining forest inventory data and IP-value shows the potential of improving the strength grading through presorting. The potential of increasing the grade yield have also been found by Øvrum et al. (2009), who showed that simply dividing forest stands in three quality degrees (good, medium, and bad) produced substantial differences in yield in machine strength grading. In the survey from Øvrum et al. (2009), the definition of stands was based on the occurrence of splay knots and crook caused by top breakage, variables not considered in this study. Still, the findings in this study contain information about the potential in presorting.

Introduction of presorting is not easily done. It will require concerted effort from the entire value chain, including forest owners, workers with forest inventory, timber drivers, sawmills and timber buyers. The negative consequences with presorting is the likely increase in cost for transport in and from the forest (Øvrum 2013). In addition, when stands or batches of timber are selected for grading or not, there is a potential loss of some high strength timber, because also in stands with lower mean strength, the presence of some high timber will naturally also occur (Øvrum 2013). This does not have to be only negative, because stands yielding timber with lower mean strength will not be excluded from strength grading, but simply sorted in more accurate piles where the potential of the timber is better utilized, for instance, like the standard grade for the housing industry in Norway, C24 (Øvrum 2013). As a consequent to the increased costs, the increase in income of the finished product must be able to compensate.

It is a contradiction that the requirements for structural timber become stricter, while the economic incentive for producing quality timber is reduced. Forest owners are only rewarded by the volume the timber contains, thus forest owners focus less on silviculture increasing quality. For forest owners to be interested in producing timber in higher strength classes, the potential increase in income at the end of the value chain must be traced all the way back to the forest owners.

For presorting to be feasible, the indicators that influence grade yield must be easily obtainable through existing forest inventories or be simple measurements performed by either harvesters or by quick pre-logging inventories like Øvrum (2013) proposed. In addition, presorting will acquire training of harvester operators to be able to detect the indicators with influence on strength properties and systems for separating the timber in the forest and at the loading site.

Today, it is difficult for sawmills to differentiate between logs from given stands and also between types of trees and logs (Høibø et al. 2014). In addition, the settings on grading machines cover to large areas to grade accurately. If a system of tracing individual logs through the conversation chain was invented, this should open up for using valuable information also for the running production in the sawmill (Høibø et al. 2014).

5 Conclusion

For density, H_{rel} was the most important fixed effect, and density increased with increasing H_{rel}. For MOE, H/D, DBH and the interaction between H_{rel} and DBH were important fixed effects. MOE increased with increasing H/D and interaction between H_{rel} and DBH, while it decreased with increasing DBH. For MOR, DBH was the most important fixed effect, and MOR decreased with increasing DBH.

Variance due to site accounted for a smaller proportion of the total variance in MOE and MOR than in density, while the within-tree variance accounted for a larger proportion of the variance in MOE and MOR than in density. Density was better explained than MOE and MOR at stand level, while this difference was much smaller, and partly opposite when also tree and log variables were included. This is probably because the density varies quite a lot at stand level, while MOE and MOR were also influenced by knots and other defects which may vary between trees and within trees. Since the density, MOE and MOR are explained differently on stand, tree and log level, this means that the potential for sorting at different levels are not equal for density, MOE and MOR.

For density, variables at stand, tree and log level reduced the site and tree variance to a greater extent than IP-value from Dynagrade. For MOE and MOR, variables at stand, tree and log level alone did not reduce the site and tree variance to a greater extent than IP-value, but the contribution from these variables improved the grading with Dynagrade.

Presorting using forest inventory data has the potential of improving the grading yield, but an implementation will require great effort and a desire from the entire value chain to be feasible.

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Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no