Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Ecology
and Natural Resource Management

Philosophiae Doctor (PhD)
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Density and bending properties of Norway spruce (*Picea abies* (L.) Karst.) structural timber – Inherent variability, site effects in machine strength grading and possibilities for presorting

Densitet og bøyeegenskaper til konstruksjonslast av gran (*Picea abies* (L.) Karst.) – Iboende variasjon, bestandseffekter ved styrkesortering og muligheter for forsortering

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Every end is a beginning towards new adventures!

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Table of contents

Summary

Density, modulus of elasticity (MOE) and bending strength (MOR) are the most important properties for structural timber. These properties vary significantly within European species, both between and within countries. The great variations found between sites, between trees within sites, and within single trees make individual strength grading of each single board crucial. Structural timber is graded into strength classes with specific requirements to timber properties. Since most of the strength-grading machines in use account for only a part of the large variation, it is important that the choice of strength classes fit with the wood properties of the raw material used. Therefore, it is necessary to have profound knowledge about the variability of timber properties and to use this information to determine which raw materials are suitable for particular applications. The aim of the study was to investigate the variability in density and bending properties of Norway spruce structural timber to determine site effects on machine strength grading and to determine the possibility of improving machine strength grading by presorting.

The models were based on 1551 boards from 17 sites from Southern Norway, Eastern Norway and Trøndelag. The timber was sawn and graded in local sawmills. The MOE and MOR were obtained by a four-point bending machine and density by a small specimen test. The geographical and forest inventory data, as well as measurements on the tree, were collected and used for modelling timber properties.

The variability of density and bending properties was first investigated based on the material from three sites in a local study and it showed that substantial parts of the variability of density, MOE, and MOR were explained by differences between sites, relative tree size, and longitudinal position within the stem. This was further investigated on the whole dataset and important variables describing variation in density, MOE and MOR between sites were site index and altitude. For density, latitude also gave additional information. At the tree level, age, diameter in breast height and longitudinal position within the tree were the most important variables. Large parts of the site variances in density, MOE, and MOR and a substantial part of the tree variance in MOR were explained by the models.

Secondly, a study of site effects on machine strength grading showed that both grading based on resonance frequency and grading based on dynamic MOE show significant effects of site

related to altitude, latitude and site index. The site effects were smaller for grading based on dynamic MOE than for grading based on resonance frequency, and for both grading methods, the site effects were smaller for bending strength than for modulus of elasticity and density. It was shown that mass density can explain major parts of the variances due to site of all the properties, including MOE and MOR, and it can be used as a second indicating property together with frequency. Simulations showed that it is possible to fulfill the requirements of the strength classes with a higher yield when sorting is based on a combination of exclusions based on the mass density and the frequency-based indicating property.

Lastly, the possibility of doing presorting based on acoustic measurements and forest inventory data to increase the grade yield was investigated on strength grading with Dynagrade machines. The tested tools were based on either measuring sound velocity in standing trees or on measuring resonance frequency in logs. Both the acoustic measurement in trees and the acoustic measurement in logs explained parts of the variability of the indicating property measured by Dynagrade strength grading machine, but the accuracy was better for the log measurement than for the tree measurement. A model using acoustic velocity from standing trees was substantially improved by introducing forest data, i.e., height to diameter ratio, age, and relative longitudinal position in the tree. The improvement by combining sound velocity in logs with log data, i.e., log tapering, was minor. Simulations showed that it is possible to increase the C30 yield with presorting based on the developed models of approximately 16 percent units for the model using tree velocity and 22 percent units for the model using log velocity.

Symbols and abbreviations

Abbreviations and symbols used in text and formulas

Abbreviation	Explanation
SI	Site index, dominant height at age 40
Alt	Altitude
Lat	Latitude
BA	Basal area
Age	Age
DBH	Diameter at breast height
DBH_{rel}	Ratio of DBH of the sample trees to the mean DBH of the site
H	Tree height
H/DBH	Tree slenderness
DBH/AGE	Ratio of DBH to the age of the trees
KH_{180}	Height to the whorl where live branches covered half of the circumference
KH_{360}	Height to the whorl where the live branches covered the whole circumference
LP_{rel}	Relative longitudinal position of the board in the tree
ST_{300}	Acoustic velocity measured with Hitman ST300
LT	Log taper
LD	Log diameter in top end
LV	Log volume
HM_{200}	Acoustic velocity measured with Hitman HM200
IP	Indicating property
DYN-IP	Indicating property from Dynagrade
E_{dyn}	estimate indicating property of Precigrader, calculated from Dyn-IP and ρ
KD	Knot diameter
KCD	Knot cluster diameter
MOE	Modulus of elasticity
MOR	Bending strength
MC	Moisture content
$MOE_{loc,12}$	Local modulus of elasticity adjusted to 12% moisture content
$MOE_{glob,12}$	Global modulus of elasticity adjusted to 12% moisture content
MOR_{12}	Bending strength adjusted to 12% moisture content
MOR_{150}	Bending strength adjusted for board size
ρ_{12}	Density adjusted to 12% moisture content

Symbol	Explanation
Y	Modelled property
μ	Mean in variance component analysis or intercept in covariate model
f(A, B,…)	Fixed effects
S_i	Random site effect
$T_j(S_i)$	Random tree effect
e	Residuals
σ_S^2	Variance component describing the variance for S_i
σ_T^2	Variance component describing the variance for $T_j(S_i)$
σ_e^2	Variance component describing the variance for *e*

List of Papers

This thesis consists of the following papers that are referred to by the roman numerals (I-V)

Paper I	Høibø, O., Vestøl, G.I., Fischer, C., Fjeld, L., Øvrum, A. (2014) Bending properties and strength grading of Norway spruce: variation within and between stands. *Canadian Journal of Forest Research* 44(2): 128-135.
Paper II	Fischer, C., Vestøl, G.I., Øvrum, A., Høibø, O. (2015) Pre-sorting of Norway spruce structural timber using acoustic measurements combined with site-, tree-, and log characteristics. *European Journal of Wood and Wood Products* 73(6): 819-828.
Paper III	Vestøl, G.I., Fischer, C., Høibø, A., Øvrum, A. Between- and within-site variation of density and bending properties of *Picea abies* structural timber from Norway. *Scandinavian Journal of Forest Research*, accepted for publication.
Paper IV	Fischer, C., Vestøl, G.I., Høibø, A. Modelling the variability of density and bending properties of Norway spruce structural timber. *Canadian Journal of Forest Research*, in review.
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1 Introduction

Norway spruce (*Picea abies*) is the most important species for commercial timber production in Norway, and strength-graded structural timber is one of the main products for most saw- and planning mills. Of the 10.2 million cubic meters of industrial roundwood cut for sale in 2015, 74.3% was spruce, 24.0% was pine and 1.6% was broadleaves (Statistics Norway 2015). According to the Norwegian Stress Grading Inspection Scheme, about 1/3 of the annual production of sawn timber is strength graded (Øvrum, personal communication), making the grade yield from strength grading important to the profitability of the sawmill industry.

1.1 Properties of structural timber

Structural timber is classified into strength classes according to EN338 (Standard Norge 2009a), and even though the strength class reflects the obtained strength of the board, strength classes are defined by requirements regarding strength, MOE, and density. Currently, most structural timber is graded to C24, and the highest strength class produced in Norway at the moment is C30. There is reason to believe that the strength properties of Norwegian timber are less than fully utilized, since most studies on properties of structural timber from Norway have reported an average MOR larger than 40 N/mm^2 (Table 1) (Foslie and Moen 1968; Lackner and Foslie 1989; Eikenes et al. 1996; Haartveit and Flæte 2002; Vestøl et al. 2012), with some exceptions for spruce from Northern Norway (Nagoda 1985), Western Norway (Eikenes 1991; Lackner and Foslie 1989) and at very high site indices and low plant density (Høibø 1991). Other European studies also report an average MOR of 40 N/mm^2 for conifers (Ranta-Maunus 2009; Stapel and Denzler 2010).

Table 1. Comparison of previous studies from the study area.

Study	N	MC (%)	Density (kg cm^{-3})	MOE (kN mm^{-2})	MOR (N mm^{-2})
Foslie and Moen 1968	1351	15	470	12.7	49.6
Eikenes 1991	630	12	330	10.0	33.2
Høibø 1991	141	12	395	10.1	31.4
Eikenes et al. 1996	105	12	-	11.4	42.0
Haartveit and Flæte 2002	144	12	434	12.4	45.3
Vestøl et al. 2012	333	12	442	12.9	50.9

1.2 Variability of density, modulus of elasticity (MOE), and bending strength (MOR)

Knowledge about important timber properties and how they vary is necessary for efficient utilization of the timber resources. Density, MOE and MOR vary considerably between countries (Ranta-Maunus 2009), but also within countries (Hautamäki et al. 2013, Moore et al. 2013, Gardiner et al 2011, Lackner and Foslie 1988, Nagoda 1985, Foslie 1985, Foslie and Moen 1968). Furthermore, there are large variations between sites, trees within sites and within single trees (Zobel and van Buijtenen 1989, Høibø 1991, Vestøl et al. 2012).

Density is an important physical wood property, both in itself but also since it is correlated with most mechanical properties. For Norway spruce (*Picea abies* L. Karst), density is negatively correlated with growth rate (Persson 1975), leading to lower density for more dominant trees (Pape 1999) and for trees from areas with wider spacing (Johansson 2003). On the other hand, density has been found to be positively correlated with temperature sum (Wilhelmsson 2001), which fits well with Høibø (1991) and Nagoda (1985). Høibø (1991) found a higher density at the same annual ring width in a material from the region around Oslo (latitude: 59 °N) than Nagoda (1985) found for a material from further north (latitude: 65.5–69.5 °N).

The vertical variation in density within Norway spruce trees shows divergent patterns. While Kuçera (1994) found an increase in density with increasing distance from the ground, Atmer and Thörnqvist (1982) found a slight decrease from the ground up to 75% of the stem height. Hakkila (1996) and Repola (2006) found a slight decrease in density up to 50% of the stem height, followed by an increase in the upper half. In radial direction density is found to decrease over the first three to five annual rings but slightly increase further throughout the mature wood (Kuçera 1994, Kliger et al. 1998).

Bending properties are correlated with density, but they are also influenced by other clear wood properties and by defects, of which knots are the most important. The effect of knots on MOR is due mainly to the fibre deviation that occurs around the knots (Hanhijärvi et al. 2005). Knot diameter depends to a large extent on branch longevity. Branch longevity is dependent on light conditions for the individual tree, and thus on silviculture. In general, knot diameter increases with distance from the ground to the lower part of the living crown, followed by a subsequent decrease towards the top of the tree (Colin and Houllier 1991; Vestøl and Høibø 2001). Colin and Houllier (1992) modelled vertical variation of branch diameter with variables related to tree size, crown size and social status of the tree. Mäkinen and Hein (2006) found branch diameter to increase with decreasing stand density. Furthermore, dominant trees have larger knots compared to co-dominant and suppressed trees (Colin and Houllier 1991, Høibø 1991, Colin and Houllier 1992, Vestøl and Høibø 2001).

Hanhijärvi et al. (2005) found that the effect of knot area ratio (KAR) was stronger on MOR than on MOE, while the situation was the opposite for density. For both bending properties, the correlations with density were higher than the correlations with KAR. The additional effect of knots on the bending properties results in different variance structures, since density and knots vary in different ways in Norway spruce (Vestøl et al 2012). One difference is the longitudinal variation within trees. The increasing knot diameter with increasing height in the lower part of the stem can be counteracted by increasing density, and the net effect may even be different for MOE and MOR (Vestøl et al. 2012). Another difference is due to the effect of climate on density. In the Nordic countries, the average temperature decreases with latitude and altitude, and a corresponding decrease in density has been found (Wilhelmsson et al. 2002). This leads to an additional effect of site on density, and it is probably stronger on MOE than on MOR since MOE is more strongly correlated with density. Because MOR is influenced by knots to a larger extent, there is a larger effect of silviculture on this property, and the relative importance of climate is smaller. Some studies (Høibø 1991, Vestøl et al. 2012) have shown that MOR varies more between trees within a site than between sites. Since density decreases and knot diameter increases with diameter growth of stems in a stand, one will get the combined effect of both factors, resulting in lower density, MOE and MOR for timber from more dominant trees.

1.3 Strength grading

1.3.1 Visual grading

Standards for visual grading are developed for different species and different areas. In Europe visual grading is regulated in EN14081-1 (Standard Norge 2011), and timber grades are assigned to strength classes as defined in EN1912 (Standard Norge 2012a). Visual grading is the traditional grading method, and is performed by certified personnel who determine the grade according to visual criteria, of which knots are the most important. The accuracy of visual grading is limited since there is a relatively low correlation between knot size and bending properties. For instance, Hanhijärvi et al. (2005) found an R^2 between knot size and MOR of approximately 0.2, while Ranta-Maunus et al. (2011) found an R^2 of 0.31. Structural timber of pine and spruce from the Nordic countries is visually graded to T1, T2 or T3 according to INSTA-142 (Standard Norge 2009c), and the grades are assigned to strength classes C18, C24, and C30, respectively, in EN1912 (Standard Norge 2012a). European grading standards (NS-EN1912, DIN 4074-1, NS-INSTA 142, NF B 52-001) allow visual classification up to strength class C30 for spruce. Stapel (2014) showed that spruce timber from Central, Eastern, and Northern Europe graded according to INSTA-142 rules did not meet the requirements for C30. The graded timber in the study, however, was mainly from Central and Eastern Europe. When taking into account only the results for timber from Northern Europe, where the INSTA-142 grading rule is originated, the requirements for C30 might be met to a larger extent. Eikenes (1996) found that timber from Western Norway did not meet the requirements unless an additional limitation on annual ring width was used.

1.3.2 Machine strength grading

In Europe, machine strength grading is regulated by EN14081, parts 1–4 (Table 2). Machine strength grading is performed by measuring a nondestructive indicating property for the timber, and setting values defining the limit for certain grades. Machine strength grading can be performed either as machine-controlled or as output-controlled strength grading. If the strength grading is machine-controlled, the machine has been approved for use on timber from a specific growth area by experts in the European standardization committee CEN TC124/WG2/TG1. The settings are fixed, and all grading machines of the same type operate the same way within defined limits. For output-controlled machine strength grading the grading process is continuously checked, and grading machines of the same type are verified independently and can perform differently depending on their settings (Bacher 2008). In Europe, machine-controlled strength grading is most common since it is economically more feasible when using different species and low production volumes (McKenzie and Zhang 2007). However, the definition of 'growth area' in the machine-controlled system has been widely debated for the last 20 years. Large variations in wood properties are found when different tree species are compared. The European standard for strength grading of structural timber, EN 14081-1 (Standard Norge 2011), describes some factors that can influence grading results: type of species, geographic origin, dimensional requirements, varying requirements for different uses, quality of material available, and historic influences or traditions. Recent studies on the effect of origin on structural timber properties only consider differences between countries or regions within countries (Chrestin 2000; Ranta-Maunus 2009; Ranta-Maunus and Denzler 2009; Hautamaki et al. 2013; Stapel et al. 2015). However, the wood properties also vary considerable both between and within sites, and also within trees. Determining well-defined growth areas has therefore been difficult, since local variations are often larger than variations between regions. These local differences are difficult to detect with the current machines (Ranta-Maunus 2010; Stapel and Denzler 2010).

Table 2. Normative references for structural timber.

Standard	Title
EN384	Determination of characteristic values of mechanical properties and density
EN338	Structural timber – Strength classes
EN408	Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties.
EN 14081-1	Timber structures – Strength graded structural timber with rectangular cross section Part1: General requirements
EN 14081-2	Timber structures – Strength graded structural timber with rectangular cross section Part 2: Machine grading, additional requirements for initial type testing.
EN 14081-3	Timber structures – Strength graded structural timber with rectangular cross section. Part 3: Machine grading; additional requirements for factory production control
EN 14081-4	Timber structures – Strength graded structural timber with rectangular cross section. Part 4: Machine grading – Grading machine settings for machine controlled systems
ISO 3131	Wood – Determination of density for physical and mechanical tests
INSTA 142	Nordic visual strength grading rules for timber
EN 1912	Structural timber - Strength classes - Assignment of visual grades and species

The actual statistical method in use for defining the limits for the indicating property for the different strength classes is based on a proposal by Rouger (1997). However, the proposal has been shown to have several weaknesses: it is only based on a limited data set and has a problem regarding the machine output. Several studies presented other strength-grading suggestions (Sandomeer et al. 2008, Ziethen and Bengtsson 2009, Ranta-Maunus and Turk 2010). Ranta-Maunus and Turk (2010) suggested adaptive settings, where setting values can be adjusted according to detected quality, specifically by using average values from the running production to detect ‘quality shifts’. Ziethen and Bengtsson (2009, 2011) suggested using the ‘prediction limit method’. However, neither the adaptive settings method nor the prediction limit method has been implemented thus far, since both methods have failed to reliably grade low-quality subsamples.

1.3.3 Machine grading methods

Earlier grading machines were based on MOE calculations from flatwise bending of the timber. Productionwise, this is inefficient since the boards have to move through the machine in longitudinal direction. Most current machines are based on the dynamic MOE of the boards, measured from the axial vibration of the boards which is much faster and easily included, and today over 90% of structural timber produced in Norwegian sawmills is machine strength graded, by mainly using Dynagrade strength-grading machines. Dynagrade measures the resonance frequencies originating from a strike by a metal hammer to the end of the board (Boström 1997). Together with length, which is measured by laser, the machine calculates a so-called indicating property (IP-value) as defined in EN 14081-2 (Standard Norge 2012c). This IP-value is correlated with the strength of the boards, with an R^2-value of about 0.5 for Norway spruce (Hanhijärvi and Ranta-Maunus 2008; Hanhijärvi et al. 2005; Hoffmeyer 1995; Larsson et al. 1998; Olsson et al. 2012; Ranta-Maunus 2012). Using resonance frequency to calculate an IP-value is a quite efficient way of predicting both the MOE and the strength of the boards. However, such grading machines are inaccurate when it comes to predicting density. Ranta-Maunus et al. (2011) found an R^2 value between IP-value from a frequency-based machine and density of only 0.12.

There are different options to increase the reliability of strength grading. Using more advanced strength-grading machines is one. Nowadays, several machines include a density measurement in addition to frequency measurements. This improves the correlation by approximately 40% (Ranta-Maunus et al. 2011). Precigrader is a common machine that uses such a combination. The Precigrader IP-value is calculated from the resonance frequency and timber length measurements, similar to Dynagrade, and a density measurement, which is derived from the dimensions and the weight of the board. Including density makes the grading much less vulnerable to variations between sites, compared to using IP-value only based on resonance frequency (Ranta-Maunus 2012). The European research project ‘Gradewood’, which tested the grading accuracy of six different grading machines, showed that multi-sensor machines measuring density, resonance frequency, and knots were the most accurate (Ranta-Maunus et al. 2011).

Recent studies (Ranta-Maunus 2012, Hautamäki et al. 2013, Lukacevic et al. 2015) suggest using combined IP-values, and it is already used by more accurate strength-grading machines. Golden Eye-706 and Combiscan, examples for more accurate grading machines using combined IP-values, reached R^2 values of 0.63 at and 0.54, respectively, between MOR and IP-value (Ranta-Maunus et al. 2011). For the two machines, they found R^2 values of 0.82 and 0.79, respectively between MOE and IP-value and 0.51 and 0.50 between IP-value and density, respectively. Lukacevic et al. (2015) showed that strength grading done on the basis of one single factor, such as MOE, density or knottiness, gives no reliable prediction of MOR, while strength grading based on a combination of IP-values reaches better correlations. Ranta-Maunus (2012) suggested using two IP-values, one IP-value for MOE and another for density, due to the low correlation of a frequency-based IP-value with density. Ranta-Maunus (2012) showed that the accuracy of strength-grading of Norway spruce could be improved by combining MOE frequency-based IP-value and density-based IP-value instead of only using dynamic MOE. He also showed that the growth area, where same settings can be used, could be wider when using two IP-values.

1.4 Presorting

Strength grading is performed after sawing, when there are limited opportunities to adjust the processing of the timber. Precise presorting of logs allows for better utilization of the raw material, since timber products and dimensions can be adjusted to the respective timber properties. As consequence, the production can be adjusted to meet the demands of the market. Sorting and classification even earlier in the conversion chain, before cross-cutting the stems, provide the means to more optimal production and information about strength and stiffness before harvesting can therefore be of great value.

Timber properties such as density, MOE, and MOR can be modelled by means of geographical and forest inventory data. Høibø and Vestøl (2010) developed models predicting strength and MOE of Scots pine round logs using tree and stand characteristics. Lei et al. (2005) and Liu et al. (2007) have developed such models for black spruce timber. Liu et al. (2007) showed that the best tree and stand characteristics for predicting bending stiffness of naturally grown black spruce are DBH, crown length, stem taper and stand density. Lei et al. (2005) showed that stem taper, DBH and crown length are important variables when modelling MOE and MOR with stand and tree characteristics only. For Norway spruce, Haartveit and Flæte (2002) found that MOE and MOR negatively correlated with stem taper and crown length. Øvrum (2013) found that the average ratio of tree height to DBH was a good site indicator for the grade yield of Norway spruce structural timber. Høibø (1991) found a negative correlation between MOR and planting distance for Norway spruce, which fits well with the effect of taper (Lei et al. 2005) since increased planting distance yields trees with larger taper. Hautamäki et al. (2013) have developed models for Norway spruce from Finland and Russia.

Models describing variation between and within trees also allows for optimized cross-cutting. Further, predictions of properties based on forest inventory data might be used together with data from strength-grading machines to make timber grading more accurate (Stapel and van de Kuilen 2013, Lukacevic et al. 2015) and grade yield higher.

Studies have been performed to introduce systems that will predict timber strength based on measurements on logs. Examples are approaches based on external log shape (Grace 1993; Jäppinen and Beauregard 2000) and X-ray scanning of logs (Oja et al. 2001; Oja et al. 2005; Brännström et al. 2007). One approach that is easy to implement is measuring acoustic velocity in standing trees or in logs. Acoustic measurement tools for standing trees are e.g. Hitman ST300 from Fibregen (Figure 1*a*) and for logs e.g. Hitman HM200 from Fibregen (Figure 1*b*). Auty and Achim (2008) and Lindström et al. (2009) showed that acoustic velocity measured on standing Scots pine trees is a reliable indicator of static bending properties. For Radiata pine, a significant positive correlation between acoustic velocity of trees and logs (Tsehaye et al. 2000a; Tsehaye et al. 2000b), and between acoustic velocity in logs and the timber stiffness (Dickson et al. 2004; Carter et al. 2006, Walsh et al. 2014), was found. Moore et al. (2013) found a positive correlation between acoustic measurement and MOE for Sitka spruce, and Rais et al. (2014) found the same for Douglas fir. For Norway spruce, Perstorper (1999) showed that it was possible to reduce up to 50% of the variation in MOR of the sawn timber by using the dynamic MOE of the logs as independent variable. Edlund et al. (2006) expanded upon this study using a resonance-based acoustic measurement to pre-grade logs of Norway spruce, and found a substantially higher grade yield in logs with high velocity.

Figure 1. Acoustic measurement tools a) Hitman ST300 for standing trees and b) Hitman HM200 for logs.

1.5 Research motivation and objectives

- **Variability of timber properties (Paper I, III, IV)**

Information about the variation of wood properties prior to sawing is a prerequisite for efficient utilization of the timber. For structural timber such information is important due to the limitations in applications of boards rejected by strength grading. Most recent studies about the effect of origin on structural timber only consider differences between countries or regions within countries (Chrestin 2000; Ranta-Maunus 2009; Ranta-Maunus and Denzler 2009; Hautamäki et al. 2013; Stapel et al. 2015). For most species, wood properties vary between and within sites, as well as within trees, since growing conditions and parameters describing tree growth are related to the relevant wood properties. Recent studies on structural timber from Norway spruce from Norway mostly only consider materials from limited areas (Table 1). Foslie and Moen (1968) showed a negative effect of altitude on MOR, and Vestøl et al. (2012) found a negative effect of site index on both density and bending properties, but apart from these studies information about the variability of the timber properties is limited.

The first aim of this thesis is to investigate the variability of density, MOE and MOR in structural timber, and to develop models that can be used to estimate distributions of timber properties from an area, or to presort logs to structural timber. Models describing timber properties based on forest inventory data can also be used for predicting effects of silviculture on timber properties.

- **Site effects on strength grading (Papers I and V)**

Unexplained variances due to site after grading are critical since it may lead to systematical deviance for subsamples of timber. If large site effects remain after grading, grading has to be conservative in order to meet the requirements, and the properties of the timber resource are not efficiently utilized. The literature survey presented earlier in the introduction describes a different variability of density and bending properties, and the grading system must be able to describe the variability of all properties with sufficient accuracy. Most of the structural timber produced at Norwegian sawmills is machine-graded based on axial vibration of the boards, and graded based on an IP-value calculated from resonance frequency and length of the boards or these features in combination with mass density.

The aim of this part of the study is to estimate site effects in machine grading of Norwegian spruce timber and to test whether the site effects are related to the origin of the timber, and further whether the site effects can be explained by using mass density as a second indicating property.

- **Presorting (Papers I, II, III and IV)**

Information about timber properties early in the conversion chain is an advantage since it allows for allocation of logs and adaption of sawing pattern for particular products. Models describing the variability of timber properties can be used for presorting, either on a large scale by describing which sawmill has a timber procurement that may achieve a higher grade, or on a smaller scale by sorting trees or logs.

The aim is to study whether acoustic measurements on trees and logs can be used alone or in combination with forest inventory data to increase the grade yield of timber graded with Dynagrade (Paper II). Furthermore, it will be evaluated how the models describing variability of timber properties (Paper I, III and IV) can be used for presorting.

2 Material and Methods

2.1 Material

The study is based on timber from 17 sites in Southern Norway, Eastern Norway and Trøndelag (Figure 2). The material from three sites in Østfold county (Table 3; sites 15, 16, and 17) was collected in a small pre-study. The material was chosen to ensure a broad material representing different growing conditions in the procurement area of spruce to Norwegian sawmills. The sites included a latitudinal gradient from 58.3 °N to 63.7 °N and an altitudinal gradient from 150 m to 845 m above sea level at about 60 °N to 61 °N.

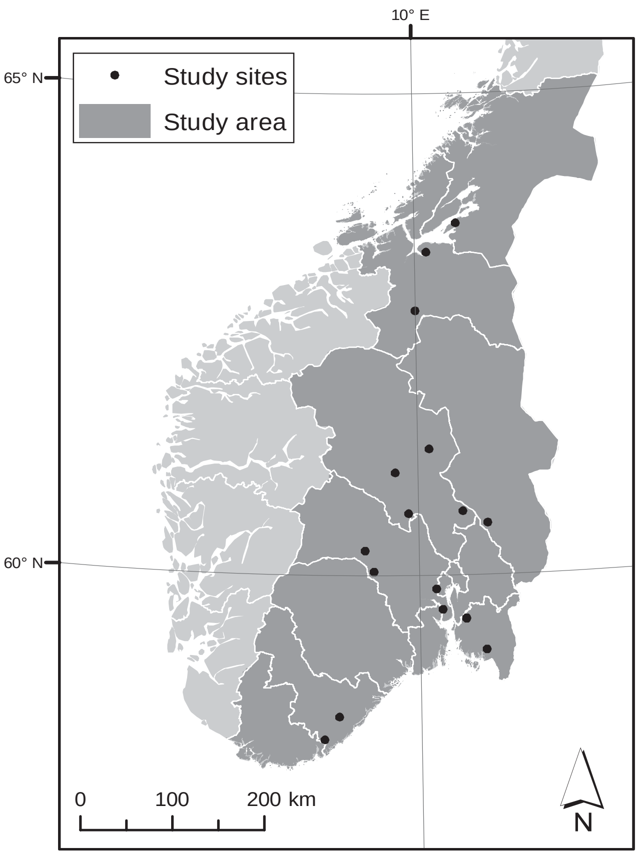

Figure 2. Sampling areas in Southern Norway, Eastern Norway and Trøndelag.

2.2 Methods

2.2.1 Forest variables

On each site the diameter at breast height was recorded for all trees within a selected area, and trees with a breast height diameter larger than 20 cm were considered. According to the DBH distribution, five diameter classes were created with an equal number of trees in each class. Three trees were subsequently randomly selected from each diameter class.

Site level data were altitude (Alt in m.a.s.), latitude (Lat), longitude (Lon) basal area (BA in m^2 ha^{-1}) and site index (SI in m). Site index, defined as dominant height at age 40 (Tveite 1977), was calculated from age at breast height and the height of the three largest trees sampled from each site. For sites 15, 16 and 17 (Table 3) site index was taken from forest inventory plans and controlled with height and age at stump height for the three largest trees, taking estimated number of years from stump height to breast height into account. Geographical and forest inventory data, mean Age, and mean DBH for each site are presented in Table 3.

Table 3. Geographical data and site index, and sample tree measurements.

Site	Geographical data and site index				Sample trees		
	Lat (°N)	Lon (°E)	Alt (m.a.s.)	SI (m)	N trees	mean Age (years)	mean DBH (mm)
1	58.2889	8.1957	170	14	13	138	330
2	58.5288	8.4627	210	20	15	66	299
3	59.6401	10.4487	150	26	15	49	269
4	59.8567	10.3284	380	17	15	76	279
5	60.0383	9.1125	700	11	14	153	332
6	60.2555	8.9446	800	11	14	124	266
7	60.5320	11.3701	370	20	15	58	240
8	60.6371	9.7993	544	11	15	108	263
9	60.6618	10.8852	220	20	15	104	290
10	61.0632	9.5403	845	14	14	91	292
11	61.3102	10.2391	630	14	15	120	294
12	62.7471	9.9898	470	14	15	128	276
13	63.3521	10.2455	150	17	15	119	316
14	63.6511	10.9141	100	14	15	125	282
15	59.2185	11.2637	80	24	15	80	246
16	59.5469	10.8980	102	11	15	161	212
17	59.5411	10.8937	115	17	15	157	283

Variables measured on tree level were diameter at breast height (DBH in mm), age at stump height (Age in years), tree height (H in dm), height to the whorl where live branches covered half of the circumference (KH_{180} in dm), height to the whorl where live branches covered the whole circumference (KH_{360} in dm), and acoustic velocity (ST300 in km/s). Other variables on tree level that were calculated from these are DBH/AGE-ratio (mm), H/DBH-ratio (dm/mm) and relative DBH (DBH_{rel}), defined as the ratio of the DBH of the tree to the mean DBH in each stand. Small end diameter (LD in mm), and acoustic velocity (HM200 in km/s) were measured on each log, and log taper was calculated (LT in mm/m). Relative board height (LP_{rel}), defined as the ratio of the longitudinal position of the board within the tree to the height of the tree, was calculated for each board.

2.2.2 Sawing and grading

The trees were cut into logs of 3.6 m, 4.2 m and 4.6 m, depending on top diameter. Minimum top diameter was 15 cm. The logs were sawn into boards of 38 × 100 mm, 50 × 100 mm, 50 × 150 mm, 50 × 200 mm or 50 × 225 mm, depending on the top diameter . The timber was dried at each sawmill and the mean moisture contents were 14%, 16%, 17% and 19%, respectively.

After sawing and drying, the boards were graded with a Dynagrade strength-grading machine at each sawmill processing the logs in question. Precigrader IP-value was simulated from Dynagrade IP-value and mass density, which was calculated by cross section of the timber and the recorded weight. Because of the difference in moisture content the IP-values were adjusted to 12% moisture content according to EN14081-4 (Standard Norge 2009b) for Dynagrade and ITT/78/12/04 (CEN 2012) for Precigrader.

2.2.3 Measurements at laboratory

Local and global MOE and MOR were tested with four-point bending in a universal static testing machine (Instron 5800) (Standard Norge 2012b) (Figure 3). The boards were shortened to 20 times the nominal height (nominal cross-sectional board height) before testing. The critical section, i.e. the position where failure is expected, was located in the middle two-thirds of the board. If the quality was homogeneous along the board and in order to maximize the longitudinal range in each tree, the upper part of the logs within a board was chosen, unless for boards from butt logs, where boards were taken closest to the stump. The boards from the three Østfold sites, numbered 15, 16 and 17 in Table 3, were always shortened accordingly, without locating the critical section.
The biggest knot (KD in mm) and knot cluster (KCD in mm) in the middle 75% of the board length were measured according to INSTA-142 (Standard Norge 2009c). Density and moisture content were determined from small, clear samples taken close to the failure point.

Prior to testing, the boards where conditioned in a climate with 65 % RH and 20 °C, resulting in a moisture content ranging from 8.9% to 17.4%, with an average of 13.6%. Density was adjusted by 0.5% for each percentage point deviation from 12% moisture content. MOE was adjusted with 1% for each percent deviation from 12%. The adjustments were done according to EN384 (Standard Norge 2010), except that the corrections were made on individual boards. For modelling purposes (Paper I, III, IV), local MOE was used and MOR was adjusted for moisture content, while for studies on machine grading (Paper V) global MOE was used and MOR was adjusted for board size as described in EN384 (Standard Norge 2010).

Figure 3. Four-point bending machine from Instron 5800 used for MOE and MOR testing.

2.2.4 Statistical analysis

The procedures for the statistical modelling are described in detail in each paper. Thus, only a brief summary of the method is presented in this thesis.

Linear mixed models were chosen to model variations in grade yield (Paper II), density, bending strength (MOR) and modulus of elasticity (MOE) (Paper I, III, IV, V). With linear mixed models it is possible to split the variance into different levels. Levels that were used in this study were variance between sites, between trees within sites, within trees, and for grade yield also within logs.

$$Y = \mu + f(A, B, \ldots) + S_i + T_j(S_i) + e \qquad \text{(Equation 1)}$$

Y represents Dynagrade IP-value, density (ρ_{12}), $MOE_{loc,12}$/$MOE_{glob,12}$, or MOR_{12}/MOR_{150}, μ represents the mean in variance component analyses or intercept in covariate models, $f(A, B, \ldots)$ represents the different fixed effects in the different models. S_i represents the random site effect, $T_j(S_i)$ represents the random tree effect, and e represents the residuals. The random effects were assumed to be normally distributed, and are given by the variance components σ_S^2, σ_T^2 and σ_e^2.

3 Results and Discussion

3.1 Variability of timber properties (Papers I, III and IV)

The variability of density and bending properties was analysed on timber from three sites in Østfold county (Table 1, sites 15, 16, and 17) in **Paper I**. The analysis showed that density, $MOE_{loc,12}$ and MOR_{12} were negatively correlated with DBH_{rel}, defined as the ratio of diameter at breast height for the actual tree to the mean diameter at breast height for all trees in the stand. The longitudinal variation in density was different between the three stands. The density increased upwards in trees from site 15, while it decreased in trees from site 16 and site17. The longitudinal reduction in density with height above ground was more pronounced in trees from site16 compared to those from site 17 (Table 4). Together with longitudinal variation in knot diameter, density affected the longitudinal variation in bending properties. In trees from site 16 and site 17, the longitudinal variations in density and knot size exhibited a cumulative effect, resulting in a vertical decrease in both $MOE_{loc,12}$ and MOR_{12}. For trees from site 15, the longitudinal variations in density and knot size counteracted each other, resulting in almost no vertical decrease for both $MOE_{loc,12}$ and MOR_{12}. Density and MOR_{12} were significantly different between the three sites, with decreasing values with increasing site index. $MOE_{loc,12}$ was higher for site 16 and site 17 compared to site 15.

Table 4. Statistics for density, MOE, and MOR models in Paper I.

Y	Site	SI	Model	R^2	RMSE	Variance components	
						σ_T^2	σ_e^2
ρ_{12}	16	11	$743 - 114DBH_{rel} - 293LP_{rel} + 140DBH_{rel}*LP_{rel}$	0.78	32	570	594
	17	17	$763 - 197DBH_{rel} - 247LP_{rel} + 169DBH_{rel}*LP_{rel}$				
	15	24	$464 - 41.2DBH_{rel} + 95.4LP_{rel} - 22.8DBH_{rel}*LP_{rel}$				
$MOE_{loc,12}$	16	11	$27.3 - 6.04DBH_{rel} - 6.51LP_{rel}$	0.61	2.2	2.72	3.22
	17	17	$25.5 - 6.04DBH_{rel} - 5.69LP_{rel}$				
	15	24	$20.7 - 6.04DBH_{rel} - 1.44LP_{rel}$				
MOR_{12}	16	11	$114 - 31.5DBH_{rel} - 27.2LP_{rel}$	0.65	8.5	23.7	53.8
	17	17	$106 - 31.5DBH_{rel} - 25.7LP_{rel}$				
	15	24	$88.4 - 31.5DBH_{rel} - 5.20LP_{rel}$				

The mean values seemed to be related to site index, but due to the low number of sites no such conclusion could be drawn. Moreover, the number and geographical range of sites were too narrow to include any climatic effects on wood density and bending properties. A larger study material was therefore included to study the variability of density and bending properties in structural timber from Southern Norway, Eastern Norway, and Trøndelag.

Paper III presents models that can be used to describe distributions of timber properties for different Norwegian regions based on data on the forest resources (Norwegian National Forest Inventory). The material showed larger variability in MOR_{12} and $MOE_{loc,12}$ than in density, and variance due to site constituted 41.4% for density, 25.9% for $MOE_{loc,12}$, and 13.2% for MOR_{12}. Major parts of the variances due to site were explained by altitude and site index, and for density also by latitude. All effects were negative, but since site index is reduced with altitude, they counteract each other. However, for all properties the effect of altitude was stronger than the effect of site index, resulting in a net reduction with increasing altitude. Density explained major parts of the variance due to site in both $MOE_{loc,12}$ and MOR_{12}, and the geographical variations are in accordance with Wilhelmsson et al. (2002), who found an additional effect of temperature sum on the effect of annual ring width on density. The models were combined with data from the Norwegian National Forest Inventory to estimate distributions of timber properties in timber from Southern Norway, Eastern Norway and Trøndelag. As compared to the tabulated values of EN338 (Standard Norge 2009a) without correcting for timber size, sampling size or grading principle, the simulations showed that without sorting, the requirements for C24 were met in 90% of the sites, the requirements for C30 were met in 50% of the stands, while only 10% of the stands met the requirements for C40 (Figure 4).

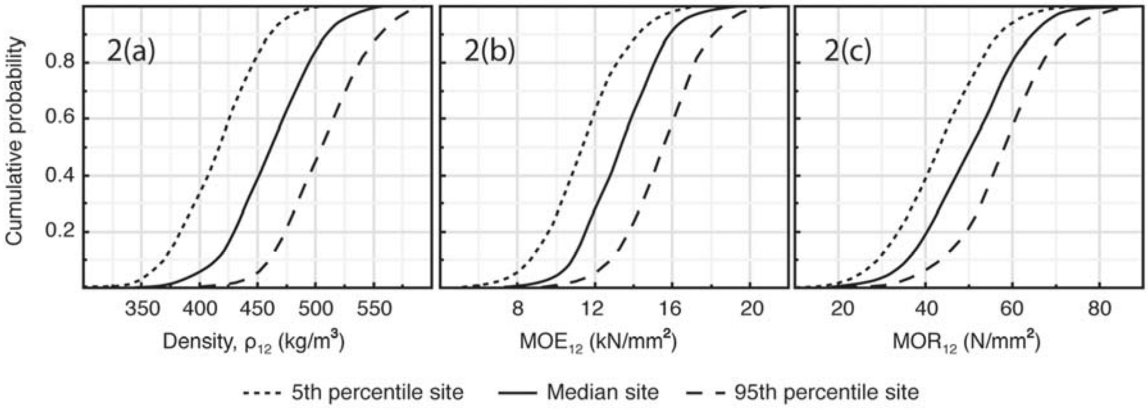

Figure 4. Simulated distributions of timber properties of Norway spruce from Southern Norway, Eastern Norway and Trøndelag. 2(a): density, 2(b): MOE, 2(c): MOR.

In **Paper IV**, models describing variations between stands, between trees within a stand, and within trees are presented (Table 5). The study was based on timber from all 17 sites (Table 1), and the material was randomly divided into a modelling part and a validation part. The models presented showed that the variability of the density and bending properties of Norway spruce structural timber could, to some extend, be explained by geographical data and forest inventory data, including external tree measurements. There was a negative effect of site index and a combined effect of age and DBH on density, representing the negative effect of annual ring width, as stated in several earlier studies (e.g. Kollmann and Coté 1968, Pape 1999 and Wilhelmsson et al. 2002). Density decreases with increasing annual ring width and increases with temperature sum. The latter correponds to the negative effects of altitude and latitude. The between-site variation in bending properties co-varied with density. Due to a larger residual variance of bending properties caused by occurrence of knots, the effect of latitude was not significant on bending properties. The models explained major parts of the site variances for all the properties modelled, whereas the within-tree variances were explained to a lesser extent. A substantial part of the MOR_{12}-variance due to trees was explained, while the variance due to trees was explained to a lesser extent for density and $MOE_{loc,12}$. This can be explained by the large variation in knot diameter between and within trees within a stand, and the fact that the effect of knot size is greater for MOR than it is for density and MOE.

Table 5. Models for density, MOE, and MOR from Paper IV.

	ρ_{12} (kg m^{-3})	MOE$_{loc,12}$ (kN mm^{-2})	MOR$_{12}$ (N mm^{-2})
Variance component model			
σ_S^2	1575.97 (51.5%)	2.91 (35.5%)	32.13 (20.6%)
σ_T^2	829.51 (27.1%)	2.86 (34.8%)	63.54 (40.7%)
σ_e^2	654.65 (21.4%)	2.44 (29.7%)	60.63 (38.8%)
Variance components from model step			
σ_S^2	104.88 (7.9%)	0.31 (6.5%)	1.50 (1.6%)
σ_T^2	702.49 (52.7%)	2.12 (44.5%)	31.30 (34.0%)
σ_e^2	526.34 (39.5%)	2.34 (49.0%)	59.41 (64.4%)
Covariate Models			
ρ_{12} =	$1241.96-8.12SI-0.17Alt-9.04Lat+0.40Age-0.39DBH-294.06LP_{rel}+0.11KH_{180}$ $+11.23SI*LP_{rel}+0.15Alt*LP_{rel}+0.56DBH*LP_{rel}-0.60KH_{180}*LP_{rel}$		
MOE$_{loc,12}$=	$20.55-0.15SI-0.01Alt+0.02Age-0.02DBH-6.47LP_{rel}+0.20SI*LP_{rel}+0.01ALT*LP_{rel}$		
MOR$_{12}$ =	$73.59-0.02Alt+0.12Age-0.10DBH-6.39LP_{rel}$		

The materials for this study was sampled for several purposes. In order to develop models, having timber from sites representing a wide range of altitudes, latitudes and site indices was prioritized over having a representative sample for the study area, since the latter would require timber from a larger number of sites. The sample (Sites 1–14) was compared with statistics from the Norwegian National Forest Inventory (**Paper III**), and showed an underrepresentation of timber from low site indices, a slight overrepresentation of timber from sites at lower altitudes and an underrepresentation of timber from sites at intermediate altitude. The representation of latitude was close to the distribution shown in the statistics from the Norwegian National Forest Inventory. When combining the models developed in **Paper III** with statistics from the Norwegian National Forest Inventory to estimate timber properties in the study area, the estimated mean values were slightly higher than those obtained from empirical data. The difference was mainly due to an underrepresentation of sites with a low site index. However, for modelling purposes it might have been better to have even more sites with higher site indices where the timber properties depend more on silviculture. Moreover, all the sites at higher altitudes were located at intermediate latitudes, and this may explain why the models in **Paper III** and **IV** did not show any interaction effect between altitude and latitude on density, which might have been expected. The models in **Paper IV** showed small effects of the included site and tree variables that depend on silviculture, but a much larger effect of site variables that depend on climate. This might be due to small differences in silviculture between sites. Besides site index and geographical data, timber properties also depend on silviculture, cross-cutting, and sorting, and these factors were not taken into account when choosing sites for data sampling.

3.2 Site effects on strength grading (Papers I and V)

Accuracy in grading is important for the reliability of timber, and a higher yield is possible if there is a better correlation between the indicating property and the grade-determining properties (Hoffmeyer 1995). Geographical variations that are not accounted for by the grading machine are particularly critical since they may lead to systematical differences between sawmills with different timber procurement areas. The setting values are defined for areas as large as several countries, but studies have shown that the differences within countries can be even larger than the differences between countries (Ranta-Maunus 2012).

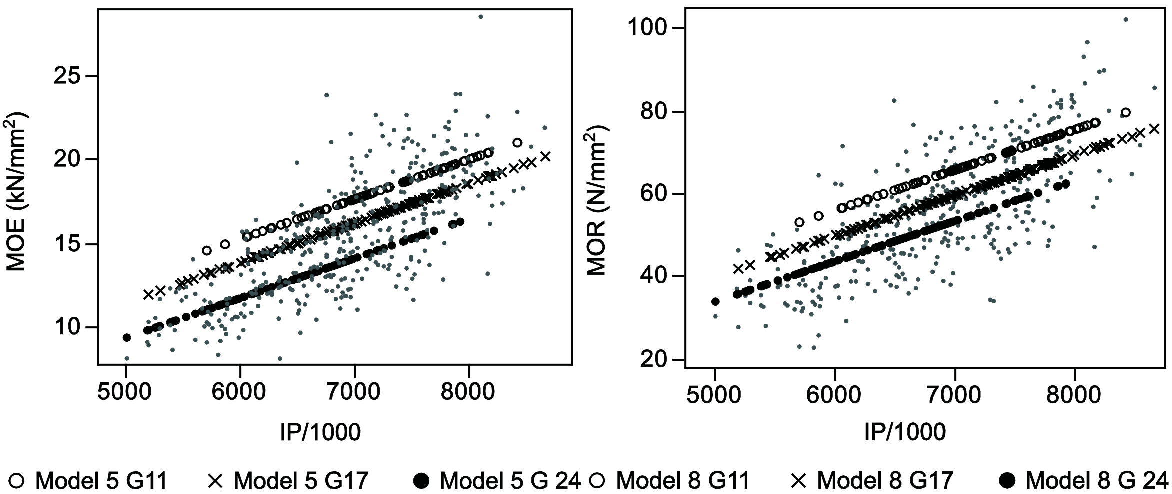

Figure 5. Site effects on relationship between IP-value from machine strength grading and MOE (left) and MOR (right) as described by model 1 and 5, respectively, for site 15 (G24), site 16 (G11), and site 17 (G17).

In **Paper I** it was shown that the relationship between indicating property from Dynagrade and MOR was different for timber from each of the three sites in Østfold (Table 3, sites 15, 16 and 17). For a given value of indicating property, the models predicted the highest values of MOR_{12} for timber from the site 16, somewhat lower for timber from site 17, and the lowest values for site 15. The same differences were also found for $MOE_{loc,12}$ (Figure 5). The differences corresponded with differences in site index, but due to the limited number of sites and the limited geographical variation it could not be concluded that the differences were due to site index only. The difference could be explained by density, and the random effect of site became non-significant when density was added to the models. Adding the effect of knot diameter to the models with indicating property and density only had minor effects on the model, and it only explained the variances within trees and within sites. This indicated that grading systems that include density measurements are able to be more consistent across sites, and the improvement was larger for $MOE_{loc,12}$ than for MOR_{12}.

In order to estimate site effects by means of variances due to site, a similar study (**Paper V**) was done on timber from sites with a larger geographical variation (Table 1, sites 1–14). In addition to IP-value from Dynagrade, this study also used dynamic MOE (E_{dyn}), estimated from mass density and indicating property from the Dynagrade machine, as an estimate of indicating property from Precigrader strength grading machine. The study showed that strength-grading based on Dyn-IP and on E_{dyn} both leave significant effects of site. For both grading principles the effect of site could be described by negative additional effects of altitude, latitude and site index. The site effects were larger for grading based on Dyn-IP than on E_{dyn}, and they were also larger for density and $MOE_{glob,12}$ than for MOR_{150}.

Table 6. Models based on Dyn-IP, E_{dyn}, and combined Dyn-IP and Den-IP to reduce site effects in predicting density, $MOE_{glob,12}$ and MOR_{150} in Paper V.

Y	Model	Fixed effects	R^2	RMSE	Variance components		
					σ_S^2	σ_T^2	σ_e^2
ρ_{12}	1a	424.571 + 3.853Dyn-IP	0.05	42	475 (26.8%)	723 (40.7%)	576 (32.5%)
	2	34.755 + 5.649Dyn-IP + 0.829Den-IP	0.74	22	23 (4.7%)	32 (6.7%)	422 (88.6%)
	3a	313.075 + 11.945E_{dyn}	0.45	32	181 (17.5%)	322 (31.2%)	529 (51.3%)
$MOE_{glob,12}$	5a	0.938 + 1.721Dyn-IP	0.49	1.9	0.81 (22.5%)	1.23 (34.3%)	1.55 (43.2%)
	6	-12.952 + 1.783Dyn-IP +0.030Den-IP	0.76	1.3	0.04 (2.6%)	0.32 (18.9%)	1.34 (78.5%)
	7a	-0.071 + 1.104E_{dyn}	0.69	1.4	0.38 (17.5%)	0.37 (17.1%)	1.43 (65.4%)
MOR_{150}	9a	-4.969+7.516 Dyn	0.39	8.6	3.3 (4.4%)	16.9 (22.7%)	54.2 (72.9%)
	10	-37.834 + 7.168Dyn-IP + 0.077Den-IP	0.47	7.9	0.3 (0.4%)	10.5 (16.6%)	52.8 (83.0%)
	11a	0.385 + 3.979E_{dyn}	0.45	8.1	1.8 (2.7%)	9.8 (14.8%)	54.7 (82.5%)

Models including mass density as a second covariate explained substantial parts of the variance due to site of density, $MOE_{glob,12}$ and MOR_{150} that was not explained by using Dyn-IP or E_{dyn} only (**Paper V**) (Table 6). This corresponds to the results of Ranta-Maunus (2012), who suggested using a second indicating property for density in addition to one based on a frequency measurement. Simulating characteristic properties showed that Dyn-IP and mass density explained different parts of the variability, and the requirements for the strength classes can be met with a higher yield if the exclusion is based on a combination of Dyn-IP and mass density. Mass density can be used to reduce the site effects on the bending properties in strength grading, and to facilitate the production of timber with more accurately specified properties for special purposes. When models based on E_{dyn} as the only covariate were compared to the corresponding models based on Dyn-IP and mass density together, the latter left a smaller $MOE_{glob,12}$-variance due to site, while the MOR_{150}-variances due to site were similar for the two models.

3.3 Presorting (Papers II)

Presorting can be used both to increase the grade yield and to improve the grading accuracy. In **Paper II** the possibility of using acoustic measurements to increase the grade yield from Dynagrade was analysed. The results showed that acoustic measurement on trees can explain a substantial part of the site variance, and such measurements could be considered during forest inventory or as a pre-harvesting tool. Another option is to have a tool like this installed in a harvester head, which would make it possible to get one record for each log, and not only one per tree, and thereby to improve the ability to predict variability within stems. This way, variability within stems would be easier to predict. The longitudinal variation of knot size is more consistent than the longitudinal variation of density in Norway spruce, and the improvement achieved by using acoustic measurements on individual logs is probably most pronounced for MOR since MOR is the feature that is most dependent on knot size. It was also shown that an acoustic measurement tool based on resonance frequency measurements in each log (HM200) is better correlated with machine strength grading than the measurement carried out on the standing tree using the ST300 tool, in part because it is able to describe differences due to logs and not only differences due to trees. Including forestry data and tree measurements could increase the accuracy of both ST300 models and HM200 models. While relative longitudinal position within the stem, height-to-diameter ratio, age and the interaction between ST300 and H/D-ratio were significant covariates for the ST300 model, log taper was the only significant covariate for the HM200 model. However, the effect of log taper was so small that the grade yield simulations were based on the simpler model with only HM200 measurement. For the ST300, simulations showed that models including forestry data gave increased grade yield but only slightly higher proportion of rejected boards for an exclusion rate of 50%. For the HM200 model the effects were even more pronounced (Table 7).

Table 7. Grade yield and mean IP-value Dynagrade for single C24, C30, and C35 and the combined grade C24/C30 and C30 for pre-sorted timber based on Model 3 and 4 of Paper II.

	Grade	Yield (%)	Mean IP-value
C24	C24	99.9	6.84
	Reject	0.1	4.18
C30	C30	67.9	7.26
	Reject	32.1	5.95
C35	C35	11.4	8.09
	Reject	88.6	6.67
C30/C24	C30	31.2	7.71
	C24	63.2	6.55
	Reject	5.6	5.17
C30 Model 3	C30	42.3	7.35
50% exclusion	Reject	7.7	6.13
	excluded	50.0	6.51
C30 Model 4	C30	44.1	7.39
50% exclusion	Reject	5.3	6.14
	excluded	50.0	6.42

4 Conclusions and final remarks

The results show that the bending properties have larger variability than density does, and that density is the property that has the largest variance due to site. Major parts of the variances due to site are explained by altitude and site index, and for density also by latitude. A local study showed that considerable parts of the within-site variation of density, MOE and MOR could be explained by relative tree size and longitudinal position within the stem, but these effects were comparably small in timber sampled from a wider geographical range. Models describing the variability of density and bending properties have been developed, and they explain major parts of the site variances for all properties and a substantial part of the MOR-variance due to trees.

Strength grading of Norway spruce timber from Norway based on indicating property from Dynagrade or dynamic MOE (E_{dyn}) leaves significant effects of site related to altitude, latitude and site index. The site effects are larger when the grading is based on indicating property of Dynagrade than when it is based on E_{dyn}, and they are also larger for density and MOE than for MOR. Density explains large parts of the variances due to site of both MOE and MOR, and by using mass density as a second indicating property together with the indicating property of Dynagrade it is possible to meet the requirements of the strength classes with a smaller exclusion rate than is possible when only one indicating property is used.

Presorting by acoustic measurements is shown to make it possible to increase the grade yield of higher strength classes. While acoustic measurements on logs can be considered a reliable tool on its own, and could be used in the log yard, acoustic measurements on trees must be combined with information about stand and tree in order to make it efficient enough to be used in practice. Nevertheless, forest inventory could be a field where tree measurements may be applied.

The models describing the variability of timber properties are most efficient for describing the variation of timber properties between stands. They can be used for estimating the distribution of timber properties in the procurement area of a sawmill or to select stands with timber that is suited for higher strength classes. The models also describe some of the variation within sites, with diameter at breast height and age as the most important variables, and can to some extent be used to estimate effects of silviculture on timber properties. Some of the models describing variability in timber properties (Paper I, III and IV) can be used for presorting structural timber.

The models presented in Paper III describe variations in timber properties by means of altitude, latitude and site index, and can be used to determine which grades are achievable for a sawmill based on the respective timber procurement. Sawmills that use timber with a large variation in timber properties can also use the models to sort timber from different origins, and use different grade combinations for timber depending on its origin. This last option is most useful for sawmills that use timber from lower altitudes, since the models predict the highest mean values of density, MOE and MOR for timber from a lower site index at low altitude. Also the models presented in Paper I and in Paper IV use effects of tree measurements and longitudinal position within stem to predict timber properties. By combining forest inventory data and data measured by the harvester, it is possible to estimate the properties of timber from single logs, and to define requirements for logs that are to be used as raw material for structural timber.

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PAPER I

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ARTICLE

Bending properties and strength grading of Norway spruce: variation within and between stands[1]

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Abstract: Current strength grading of Norway spruce (*Picea abies* (L.) Karst.) structural timber is only able to describe parts of the great variability in density and bending properties. This study assesses whether information about the origin of the timber can be used to predict its strength and stiffness, alone or in combination with machine strength grading. Three hundred and seventy-three boards from 45 trees sampled from three stands in eastern Norway were studied. Substantial parts of the variability of density, modulus of elasticity (MOE), and bending strength or modulus of rupture (MOR) of the boards studied were explained by origin (differences between sites, relative tree size (diameter at breast height), and longitudinal position in stem). Origin also gave a reduction in residual variance in addition to what was obtained by machine grading based on resonance frequencies. For MOR, the improvement was larger than what was obtained by adding density, whereas for MOE, the density was more important than information about origin.

Résumé : Le classement actuel du bois de charpente d'épicéa commun (*Picea abies* (L.) Karst.) en fonction de la résistance peut décrire seulement une partie de la grande variabilité de la densité et des propriétés de flexion. Cette étude évalue si l'information concernant l'origine du bois peut être utilisée, seule ou combinée au classement mécanique, pour prédire la résistance et la rigidité. Nous avons étudié 373 planches provenant de 45 arbres échantillonnés dans trois peuplements situés dans l'est de la Norvège. Une partie importante de la densité, du module d'élasticité (MOE) et du module de rupture (MOR) des planches qui ont été étudiées était expliquée par l'origine (différences entre les stations, taille relative des arbres (diamètre à hauteur de poitrine) et position le long de la tige). L'origine réduisait aussi la variance résiduelle en plus de ce qui était obtenu avec le classement mécanique utilisant les fréquences de résonance. Dans le cas du MOR, l'amélioration était plus importante que celle qui était obtenue par l'ajout de la densité, tandis que dans le cas du MOE, la densité était plus importante que l'information au sujet de l'origine. [Traduit par la Rédaction]

Introduction

Density, modulus of elasticity (MOE), and bending strength or modulus of rupture (MOR) are the most important properties for structural timber. Visual grading was earlier the most common strength grading method. Such grading was based on characteristics such as grain deviation and knot structure, reaction wood, and other visual characteristics considered important for measuring strength. Visual strength grading is relatively inaccurate, but accuracy has been improved by using grading machines. The accuracy is nevertheless still relatively poor, and great efforts are being made to improve the accuracy and thereby the grade yield.

Kollmann and Krech (1960) showed the importance of using MOE because of its relatively good statistical correlation with MOR. Fewell (1982) found that the dynamic MOE was a good single predictor for MOR. Many grading machines today make use of this relationship. Despite a relatively good correlation between MOR and dynamic MOE, it is still challenging to use wood efficiently compared with other building materials that are more precisely described. Improved precision and accuracy when sorting and grading may improve the efficiency. However, within-board variation may still be a problem related to solid wood, which from nature is a variable material.

Dynagrade is by far the most commonly used machine for strength grading in Norway. It measures the resonance frequencies originating from a strike by a metal hammer on the end of the board (Boström 1997). In combination with length, which is measured by a laser, the machine calculates a so-called indicating property (IP) as defined in EN 14081-2 (Standard Norge 2010*b*). This IP value is correlated with the strength of the boards, with an R^2 value of about 0.5 for Norway spruce (*Picea abies* (L.) Karst.) (Hanhijärvi and Ranta-Maunus 2008; Hanhijärvi et al. 2005; Hoffmeyer 1995; Larsson et al. 1998; Olsson et al. 2012; Ranta-Maunus 2012). The dynamic MOE also depends on density; therefore, grading machines measuring density in addition to resonance frequencies have been found to grade more accurately (Hanhijärvi and Ranta-Maunus 2008; Hanhijärvi et al. 2005; Johansson et al. 1998; Ranta-Maunus 2009; Ranta-Maunus et al. 2011).

Earlier investigations have shown that the strength properties of Norway spruce vary greatly within Norway (Foslie 1985; Foslie and Moen 1968; Lackner and Foslie 1988; Nagoda 1985), and visual strength grading is not able to account for all of this variation. This makes visual strength grading unreliable for use on Norway spruce boards from trees grown in western Norway (Eikenes 1991; Foslie 1985; Lackner and Foslie 1988) and northern Norway (Nagoda 1985) and for boards from fertile sites (Høibø 1991). Better ability to grade timber reliably has been shown for Norway spruce grown in western Norway when using a Computermatic grading machine and grown in northern Norway when using a Cook–Bolinder machine (Eikenes 1991; Nagoda 1985). Høibø (1991), however, found characteristic values below the requirements when

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boards originating from high-altitude, fertile plantations were graded with a Computermatic machine. All of these studies were conducted using the national setting values valid at that time. Chrestin (2000) found that the characteristic values for strength classes graded with the same setting values were lower for Norway spruce from mountainous regions in northern Sweden than for boards from central Sweden and some parts of southern Sweden. He suggests that the regions in Sweden should probably have different setting values when Cook–Bolinder machines are used.

Machine strength grading became part of European standardization during the 1990s, and setting values for different machines valid for particular species and growth areas have been established. The background for this approach is the inconsistencies in the relationship between machine-measured properties and strength due to growth differences. This system is called a "machine-controlled system", and the foundation for the system is laid out in EN 14081 parts 1 to 4 (Standard Norge 2011). This standard also allows for "output-controlled systems", which use dynamic setting values based on input from tests on timber from the running production in the particular mill. This system is used in North America, Australia, South Africa, and New Zealand, but in Europe, very few mills have embraced this system thus far.

The machine-controlled system has been subject to great debate over the last 20 years, especially with respect to the definition of "growth area". Making well-defined determinations of growth areas is found to be difficult as local variations are often larger than variations between regions. These local differences are difficult to detect with the current machines (Ranta-Maunus 2010; Stapel 2008; Stapel and Denzler 2010). A study of more than 6000 pieces of spruce and pine showed that increasing size in growth regions gives lower yield due to the inconsistent correlation between strength properties and measurable nondestructive variables (Ranta-Maunus 2009, 2010; Ranta-Maunus et al. 2011; Stapel and Denzler 2010). The variability within one strength class is also large (Deublein et al. 2010; Ranta-Maunus 2010; Ranta-Maunus and Denzler 2009), and new ways of determining the setting values have been suggested. One approach uses adaptive settings (Ranta-Maunus and Turk 2010) with average values from the running production to detect "quality shifts", which requires changed setting values. Another method, called "the prediction limit method" (Ziethén and Bengtsson 2009, 2011), is assessed by Ranta-Maunus (2012). Both methods fail to reliably grade low-quality subsamples. By introducing measured density in addition to IP value, all subsamples achieve sufficiently high characteristic values for all grade-determining properties (MOR, MOE, and density). An approach such as this is recommended to make setting values more consistent for larger growth areas. The additional effect of density might be due to the different effects that density and knots – fibre deviation have on MOR and MOE, respectively. Both MOR and MOE depend on density, but the relationship between MOR and MOE varies because knot size has a greater effect on MOR than on MOE (Vestøl et al. 2012).

Another option may be to use forest inventory data that provide information about tree and stand characteristics in addition to data from a grading machine. Forest data are also inventoried early in the conversion chain, facilitating a more optimal utilisation of the wood raw material. Tree and site data indirectly provide information about both knot structure (Colin and Houllier 1991) and density (Høibø and Vestøl 2010), and to some extent, such data might differentiate between the effect of density and grain angle on bending properties. Such factors may constitute part of the reason for why different setting values in grading machines should be used for different regions and stands. Vestøl et al. (2012) showed that the relationship between MOR and MOE varies depending on both relative tree size and longitudinal position in the stem. Both density and knot size vary with relative tree size, but the effect is greater for knot size (Høibø 1991). Longitudinally, knot diameter increases with distance from the ground, with a subsequent decrease close to the top of the tree (Colin and Houllier 1991; Mäkinen and Colin 1998), whereas the longitudinal variation in density is not consistent for Norway spruce. Kucera (1994) found an increase in density with distance from the ground, whereas Atmer and Thörnqvist (1982) found a slight decrease from stump height to 75% of stem height. Hakkila (1966) and Repola (2006) found a slight decrease in density in the lower half, followed by an increase in the upper half. The radial density profile also varies. The relationship between density and knot diameter will therefore vary between and within trees, as well as between stands, due to factors such as site index (SI), temperature sum during the growing season, and silvicultural regime. Machine grading systems that are not able to differentiate between density and fibre deviations might therefore benefit from information about stands and trees.

The aim of the study was to analyse site and tree effects on density, MOE, and MOR of structural Norway spruce timber and to assess whether information about the origin of the timber can be used to predict the strength and stiffness, alone or in combination with machine strength grading.

Material and methods

The methodology of this study follows Vestøl et al. (2012), with some exceptions. Site, tree, and board variables are defined in Table 1. Forty-five trees were sampled from three sites in Østfold County in southeastern Norway. The site indices, defined as dominant height at age 40 years, were 11, 17, and 24 m (Tveite 1977). These sites are hereafter referred to as G11, G17, and G24, respectively. Forest inventory and geographical data for the three sites are presented in Table 2. All stands were in the oldest maturity class, but the stand with the highest SI was much younger than the other two sites. The sites were chosen to obtain large variation in age and SI and cannot be considered as random or representative for the area.

Diameter at breast height (DBH) was recorded for all trees within a selected area of each site, and trees with a DBH larger than 20 cm were classified into five diameter classes with an equal number of trees in each. Three trees were sampled from each class. The sampling was random, but trees with rot, ramicorn branches, or other excessive damage were avoided. The data measured on each sampled tree were the average of maximum and minimum DBH both over the bark (DBH) and under the bark (DBH_{ub}), total tree height (H_{total}), height to the whorl at which the living crown covered half of the circumference (H_{180}), and height to the whorl at which the crown covered the whole circumference (H_{360}). Mean values of the sampled trees from each site are presented in Table 3. Because the sample trees were required to have DBH ≥ 20 cm, the sample represented different parts of the diameter distribution within the stand. Relative diameter (DBH_{rel}), defined as the ratio of DBH of the sample trees to the mean DBH of the stand, was on average 1.23 for the G11 site, 1.16 for the G17 site, and 1.17 for the G24 site.

Most logs were cross-cut to 42 dm in length, but some were cut to 35 dm. The aim was to maximise the longitudinal range from each stem, and the shorter logs were made if it was possible to make one extra log with the required dimension. The shorter logs were mostly from the G11 site, but there were also some from the G17 site. Minimum small-end diameter was 14 cm under the bark.

Logs with small-end diameter larger than 30 cm were sawn into four boards of 50 × 200 mm; logs with small-end diameter between 19 and 30 cm were sawn into two or four boards of 50 × 150 mm; and logs with small-end diameter between 14 and 19 cm were sawn into two boards of 50 × 100 mm. The numbers of logs and boards from each site are presented in Table 4. The boards were dried in an industrial kiln and conditioned in 65% relative humidity (RH) and 20 °C before testing. All boards were graded in

Table 1. Variable definitions.

Variable	Abbreviation	Unit
Site variables		
Site index, dominant height at age 40 years, Tveite (1977)	SI	m
Site number	Site	
Tree variables		
Diameter at breast height over bark	DBH	mm
Diameter at breast height under bark	DBH_{ub}	mm
Ratio of DBH of the sample trees to the mean DBH of the stand	DBH_{rel}	mm
Total tree height	H_{total}	m
Height to the whorl at which the living crown covered half of the circumference	H_{180}	m
Height to the whorl at which the crown covered the whole circumference	H_{360}	m
Total age of the tree	Age	years
Board variables		
Relative longitudinal position, calculated as the proportion of longitudinal board position to tree height	LP_{rel}	m
Density at 12% moisture content	ρ_{12}	kg·m^{-3}
Knot diameter of the largest knot within the 2/3 centre part of the board length (minimum measure, which is similar to if it was measured on the tree)	KD	mm
Modulus of elasticity at 12% moisture content	MOE_{12}	kN·mm^{-2}
Modulus of rupture at 12% moisture content	MOR_{12}	N·mm^{-2}
Indicating property, calculated from resonance frequencies and board length	IP	

Table 2. Site data.

Site	Latitude (°N)	Longitude (°E)	Altitude (m)	Site index (m)	Mean DBH (cm)
G11	59.5469	10.8980	102	11	21.2
G17	59.5411	10.8937	115	17	28.3
G24	59.2185	11.2637	80	24	24.6

Note: DBH, diameter at breast height.

Table 3. Tree data.

Site	No.	DBH_{ub} (cm)	H_{total} (m)	H_{360} (m)	H_{180} (m)	Age (years)
G11	15	24.4	20.6	13.3	10.3	161
G17	15	30.9	29.0	22.6	19.9	157
G24	15	26.9	28.0	19.5	17.9	80

Note: Refer to Table 1 for definition of variables.

Table 4. Sample tested.

		No. of boards of each dimension		
Site	No. of logs	50 × 100 mm	50 × 150 mm	50 × 200 mm
G11	41	33	44	5
G17	68	39	83	42
G24	57	46	63	18
All	166	118	190	65

a Dynagrade at the sawmill, and an IP value as defined in EN 14081-2 (Standard Norge 2010*b*) was recorded for each board.

All boards were shortened to 20 times nominal height (nominal cross-sectional board height) before testing. Boards from butt logs were taken from the end closest to the stump, whereas boards from the other logs were taken from the end closest to the top. MOR and local MOE were tested in four-point bending according to EN 408 (Standard Norge 2012), using the cross section at the midspan between the loading points for calculations. These measurements were used as true reference values in the model development and analyses. Diameter of the thickest knot in the central longitudinal section (KD) was measured prior to the bending test. Density and moisture content were measured from samples close to the failure point. The moisture content ranged from 10.2% to 17.4%, with an average of 13.8%. The average was 12.7% for 50 × 100 mm, 14.4% for 50 × 150 mm, and 13.9% for 50 × 200 mm. According to EN 384 (Standard Norge 2010*a*), density was adjusted by 0.5% for each percentage point deviation from 12% moisture content. Both MOE and MOR were adjusted by 2% for each percentage point deviation from 12% moisture content. The correction for moisture content on MOE is as prescribed by EN 384, except that corrections were made on individual values instead of characteristic values. EN 384 does not prescribe any corrections for moisture content on MOR.

Statistical analysis

Variations of density (ρ_{12}), MOE_{12}, and MOR_{12} were analysed in linear mixed models in which the random variance was divided into tree effect and residual variance:

$$Y = \mu + f(A, B, \ldots) + T_i + e \tag{1}$$

where Y represents density (ρ_{12}), MOE_{12}, or MOR_{12}, $f(A, B, \ldots)$ represents the different fixed effects to be tested, T_i (i = 1, …, 45) represents the random tree effect, and e represents the residuals. T_i and e were assumed to be normally distributed and given by the variance components $\sigma_T{}^2$ and $\sigma_e{}^2$.

Site differences were tested by covariance analysis, with DBH_{rel} and relative longitudinal position (LP_{rel}) as covariates. LP_{rel} was calculated as the proportion of longitudinal board position to tree height. Longitudinal board position was calculated from the position of the board at the midspan between the loading points in the bending test. The covariates adjusted for differences in the sample from each site.

Site effects on strength grading were tested by means of covariance analyses of MOE_{12} and MOR_{12} with IP value as covariate, and the models were compared with the results of using information about origin alone or in combination with IP value and density (ρ_{12}). The models were evaluated by means of R^2 and root mean square error (RMSE) of the fixed-effects part.

The linear mixed models were calculated using the restricted maximum likelihood method (REML) in JMP software (version 9.0.3; SAS Institute Inc., Cary, North Carolina) following Littell (2006). SAS 9.2 (SAS Institute Inc.) was used to test the random tree effect in the models and to calculate percentiles. Comparisons were made by centre polynomials, and hypotheses were rejected if the probability of type I error was smaller than 0.05.

Results

Mean values, standard deviations, and fifth percentiles of density and bending properties are presented for each dimension in Table 5. The fifth percentiles were calculated by ranking the observations. MOR_{12} was positively correlated with density (r = 0.71) and negatively correlated with knot diameter (r = –0.54). MOE_{12}

Table 5. Density and bending properties by board dimension.

		Density, ρ_{12} (kg·m^{-3})			MOE$_{12}$ (kN·mm^{-2})			MOR$_{12}$ (N·mm^{-2})		
Dimension (mm)	No.	Mean	s	ρ_{05}	Mean	s	E_{05}	Mean	s	f_{05}
50 × 100	118	511	66	417	15.3	4.2	8.8	58.5	16.8	33.1
50 × 150	190	494	68	394	15.6	3.4	10.2	56.2	14.0	33.5
50 × 200	65	456	51	380	13.9	2.7	9.5	50.2	8.7	32.8
All	373	493	67	399	15.2	3.6	9.9	55.9	14.4	33.4

Note: Refer to Table 1 for definition of variables; s, standard deviation; $\rho_{05,}$ E_{05}, and $f_{05,}$ fifth percentiles for density, MOE, and MOR, respectively.

was also positively correlated with density (r = 0.79) and negatively correlated with knot diameter (r = –0.44). There was a positive correlation between MOR$_{12}$ and MOE$_{12}$ (r = 0.82), and a negative correlation between density (ρ_{12}) and knot diameter (r = –0.27).

Density variations

Analysis of covariance (ANCOVA) showed significantly different density (ρ_{12}) between sites (F = 83.73, p < 0.0001). Estimated least square means are presented in Table 6, and the model is presented as model 1 in Table 7. Tukey–Kramer HSD comparison showed significantly different density between all sites, with the highest value in boards from site G11, lower in boards from site G17, and even lower in boards from site G24 (Table 6). The covariates included in model 1 were DBH$_{rel}$ (F = 34.36, p < 0.0001), LP$_{rel}$ (F = 11.88, p = 0.0006), interaction between LP$_{rel}$ and site (F = 43.61, p < 0.0001), interaction between DBH$_{rel}$ and LP$_{rel}$ (F = 13.02, p = 0.0004), interaction between DBH$_{rel}$ and site (F = 4.14, p = 0.0242), and interaction between DBH$_{rel}$, LP$_{rel}$, and site (F = 5.17, p = 0.0062). The interaction effects estimated a more pronounced longitudinal decrease in density in trees from the G11 site than in trees from the G17 site. A longitudinal increase in density was found for the G24 site. The interaction effects also estimated a more pronounced longitudinal variation in the smaller trees, particularly from the G11 and G17 sites. The fixed-effects part of the model reduced the residual variance with 78% (R^2 = 0.78), and RMSE was 32 kg·m^{-3}. The random tree effect was significant (p = 0.0001) and constituted 49.0% of the variance not explained by the fixed effects in the model.

Model 1 was further adjusted for the effect of board number, i.e., whether it was an inner board or an outer board. This reduced the RMSE to 31 kg·m^{-3}. When comparing the F values, a somewhat larger effect of DBH$_{rel}$ and a smaller effect of LP$_{rel}$ were found after introducing board number to model 1.

MOE variations

ANCOVA showed significantly different MOE$_{12}$ between sites (F = 29.92, p < 0.0001). Estimated least square means are presented in Table 6, and the model is presented as model 2 in Table 7. Tukey–Kramer HSD comparison showed significantly higher MOE$_{12}$ in boards from sites G11 and G17 than in boards from site G24, while the difference between sites G11 and G17 was not significant (Table 6). The covariates included in model 2 were DBH$_{rel}$ (F = 35.54, p < 0.0001), LP$_{rel}$ (F = 76.06, p < 0.0001), and interaction between LP$_{rel}$ and site (F = 9.94, p < 0.0001). The covariate function showed decreasing MOE$_{12}$ with increasing DBH$_{rel}$ and decreasing MOE$_{12}$ with increasing LP$_{rel}$. The interaction effect estimated a more pronounced longitudinal decrease in trees from the G11 site, somewhat less in trees from the G17 site, and almost no longitudinal variation in trees from the G24 site. The largest effect of site on MOE$_{12}$ was found in boards from the lower part of the stems, while the difference was minor in the upper part. The fixed-effects part of the model reduced the residual variance with 61% (R^2 = 0.61), and RMSE was 2.2 kN·mm^{-2}. The random tree effect was significant (p = 0.0002) and constituted 45.8% of the variance not explained by the fixed effects in the model (model 2; Table 7).

Model 2 was also adjusted for the effect of board number, i.e., whether it was an inner board or an outer board. This only reduced the RMSE slightly. When comparing the F values, a somewhat larger effect of DBH$_{rel}$ and a smaller effect of LP$_{rel}$ were found after introducing board number to model 2.

Table 6. Estimated least square means of density, MOE, and MOR of boards from each site.

	Least square means		
Site	Density, ρ_{12} (kg·m^{-3})	MOE$_{12}$ (kN·mm^{-2})	MOR$_{12}$ (N·mm^{-2})
G11	562a	17.5a	65.4a
G17	502b	16.0a	57.9b
G24	431c	12.5b	46.4c

Note: Refer to Table 1 for definition of variables. Identical letters following values indicate no statistical difference (Tukey–Kramer test, p > 0.05).

MOR variations

ANCOVA showed significantly different MOR$_{12}$ between sites (F = 41.08, p < 0.0001). Estimated least square means are presented in Table 6, and the model is presented as model 3 in Table 7. Tukey–Kramer HSD comparison showed significantly different MOR$_{12}$ between all sites, with the highest value in boards from site G11, lower in boards from site G17, and even lower in boards from site G24 (Table 6). The covariates included in model 3 were DBH$_{rel}$ (F = 99.20, p < 0.0001), LP$_{rel}$ (F = 83.09, p < 0.0001), and interaction between LP$_{rel}$ and site (F = 12.83, p < 0.0001). The covariate function showed decreasing MOR$_{12}$ with increasing DBH$_{rel}$ and decreasing MOR$_{12}$ with increasing LP$_{rel}$. The interaction effect estimated a more pronounced longitudinal decrease in trees from the G11 site, somewhat less in trees from the G17 site, and almost no longitudinal variation in trees from the G24 site. The largest effect of site was found in boards from the lower part of the stems, while the difference was minor in the upper part. The fixed-effects part of the model reduced the residual variance with 65% (R^2 = 0.65), and RMSE was 8.5 N·mm^{-2}. The random tree effect was significant (p = 0.0007) and constituted 30.6% of the variance not explained by the fixed effects in the model.

Model 3 was adjusted for the effect of board number, i.e., whether it was an inner board or an outer board. This reduced the RMSE to 8.4 N·mm^{-2}. When comparing the F values, a somewhat larger effect of DBH$_{rel}$ and a smaller effect of LP$_{rel}$ were found after introducing board number to model 3. However, introducing the board height to model 3 gave no significant reduction of the residual variance (p = 0.98).

Machine strength grading

ANCOVA showed that the relation between MOE$_{12}$ and IP value was significantly different between sites (F = 17.49, p < 0.0001). For a given IP value, model 5 (Table 8) estimated highest MOE$_{12}$ in boards from site G11, lower in boards from site G17, and even lower in boards from site G24 (Fig. 1). The fixed-effects part of the model reduced the residual variance with 60% (R^2 = 0.60), and RMSE was 2.3 kN·mm^{-2}. The random tree effect was significant (p < 0.0001) and constituted 42.1% of the variance not explained by the fixed effects in the model (Table 8). By introducing ρ_{12} to model 5, the effect of site was not significant (p = 0.51). A model with IP value and ρ_{12} as fixed effects (model 5b) reduced the residual variance with 78% (R^2 = 0.78), and

Table 7. Statistics for density, MOR, and MOE models.

		Parameter estimates						Variance components	
Y	Site	β_0	β_1	β_2	β_3	R^2	RMSE*	σ_T^2	σ_e^2
ρ_{12} model 1	G11	743	–114	–293	140	0.78	32	570	594
	G17	763	–197	–247	169				
	G24	464	–41.2	95.4	–22.8				
MOE_{12} model 2	G11	27.3	–6.04	–6.51	—	0.61	2.2	2.72	3.22
	G17	25.5	–6.04	–5.69	—				
	G24	20.7	–6.04	–1.44	—				
MOR_{12} model 3	G11	114	–31.5	–27.2	—	0.65	8.5	23.7	53.8
	G17	106	–31.5	–25.7	—				
	G24	88.4	–31.5	–5.20	—				

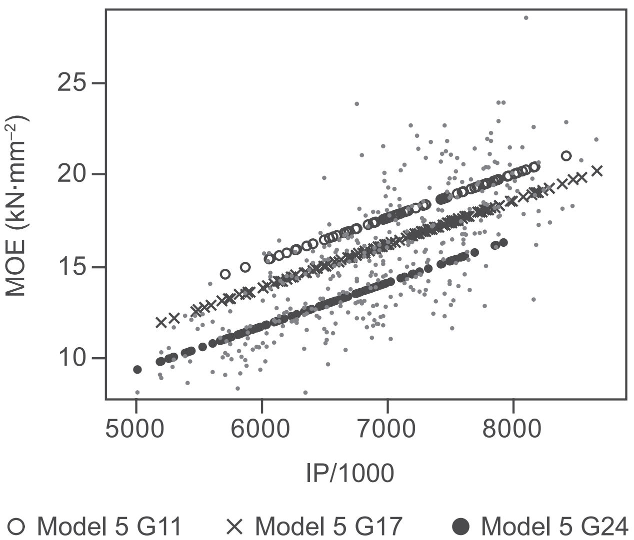
Note: $Y = \beta_0 + \beta_1 DBH_{rel} + \beta_2 LP_{rel} + \beta_3 DBH_{rel} \times LP_{rel}$. Refer to Table 1 for definition of variables.
*RMSE is expressed in kg·m^{-3}, kN·mm^{-2}, and N·mm^{-2} for ρ_{12}, MOE_{12}, and MOR_{12}, respectively.

Table 8. Statistics for models including IP value from machine grading by resonance vibration.

					Variance components	
Y	Model	Fixed effects	R^2	RMSE	σ_T^2	σ_e^2
MOE_{12} (kN·mm^{-2})	4	IP	0.47	2.6	4.08	2.95
	5	IP, Site	0.60	2.3	2.14	2.94
	5*b*	IP, ρ_{12}	0.78	1.7	0.31	2.54
	5*c*	IP, $\rho_{12,}$ KD	0.78	1.7	0.33	2.52
	6	IP, Site, DBH_{rel}, LP_{rel}	0.71	2.0	1.31	2.84
	6*b*	IP, ρ_{12}, DBH_{rel}, LP_{rel}	0.80	1.6	0.23	2.48
	6*c*	IP, DBH_{rel}, LP_{rel}	0.53	2.5	4.04	2.82
MOR_{12} (N·mm^{-2})	7	IP	0,47	10.5	63.5	51.4
	8	IP, site	0.55	9.7	42.2	51.2
	8*b*	IP, ρ_{12}	0.70	7.9	15.1	47.5
	8*c*	IP, $\rho_{12,}$ KD	0.71	7.7	14.6	45.4
	9	IP, site, DBH_{rel}, LP_{rel}	0.73	7.5	9.99	48.5
	9*b*	IP, ρ_{12}, DBH_{rel}, LP_{rel}	0.76	7.1	5.83	44.8
	9*c*	IP, DBH_{rel}, LP_{rel}	0.61	9.1	43.8	48.8

Note: Refer to Table 1 for definition of variables.

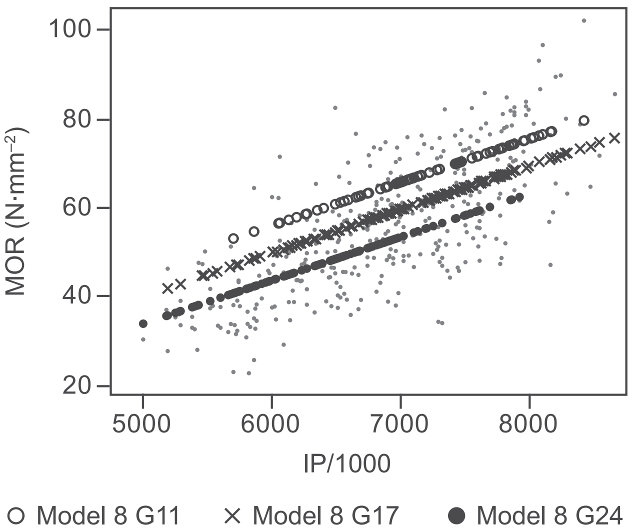
Fig. 1. Site effect on relationship between indicating property (IP) value from machine stress grading and modulus of elasticity (MOE) as described by model 5 for sites G11, G17, and G24.



RMSE was 1.7 kN·mm^{-2}. Adding KD to model 5*b* (model 5*c*; Table 8) did not reduce the residual variance significantly. A simplified model (model 4) with only IP value reduced the residual variance with 47% ($R^2 = 0.47$), and RMSE was 2.6 kN·mm^{-2}. The random tree effect was significant ($p < 0.0001$), and compared with the model with site effect, it constituted a higher proportion of the variance not explained by the fixed effects in the model (models 4 and 5, respectively; Table 8). A model combining IP value with site, DBH_{rel}, and LP_{rel} (model 6; Table 8) reduced the residual variance with 71% ($R^2 = 0.71$), and RMSE was 2.0 kN·mm^{-2}. Also for this model, the random tree effect was significant ($p < 0.0001$) but constituted a smaller proportion of the variance not explained by the fixed effects in the model (Table 8). A comparative model without site as a fixed effect (model 6*c*) reduced the residual variance with 53% ($R^2 = 0.53$), and RMSE was 2.5 kN·mm^{-2}. This model had a higher variance due to trees, while the residual variance was similar to that of model 6 (Table 8). By introducing ρ_{12} to model 6, the effect of site was not significant ($p = 0.89$). A model with IP value, ρ_{12}, DBH_{rel}, and LP_{rel} as fixed effects (model 6*b*) reduced the residual variance with 80% ($R^2 = 0.80$), and RMSE was 1.6 kN·mm^{-2}.

Also for MOR_{12}, an ANCOVA (model 8) showed that the effect of IP value differed significantly between sites ($F = 10.90$, $p = 0.0002$). For a given IP value, the model predicted lowest MOR_{12} in boards from site G24, higher in boards from site G17, and even higher in boards from site G11 (Fig. 2). The fixed-effects part of the model reduced the residual variance with 55% ($R^2 = 0.55$), and RMSE was 9.7 N·mm^{-2}. The random tree effect was significant ($p < 0.0001$) and constituted 45.2% of the variance not explained by the fixed effects in the model (Table 8). By introducing ρ_{12} to model 8, the effect of site was not significant ($p = 0.63$). A model with IP value and ρ_{12} as fixed effects (model 8*b*) reduced the residual variance with 70%, and RMSE was 7.9 N·mm^{-2}. Adding KD to model 8*b* (model 8*c*; Table 8) reduced the residual variance significantly. A simplified model with IP value only (model 7) reduced the residual variance with 47% ($R^2 = 0.47$), and RMSE was 10.5 N·mm^{-2}. The

Fig. 2. Site effect on relationship between indicating property (IP) value from machine stress grading and modulus of rupture (MOR) as described by model 8 for sites G11, G17, and G24.



random tree effect was significant ($p < 0.0001$), and compared with the model with site effect (model 8), it constituted a higher proportion of the variance not explained by the fixed effects in the model (Table 8). Model 9, which combined IP value with site, DBH_{rel}, and LP_{rel}, reduced the residual variance with 73% (R^2 = 0.73), and RMSE was 7.5 $N·mm^{-2}$. Also for this model, the random tree effect was significant (p = 0.0036) but constituted a smaller proportion of the variance not explained by the fixed effects in the model (Table 8). A comparative model without site as a fixed effect (model 9*c*) reduced the residual with 61% (R^2 = 0.61), and RMSE was 9.1 $N·mm^{-2}$. This model had a higher variance due to trees, while the residual variance was similar to that of model 9 (Table 8). By introducing ρ_{12} to model 9, the effect of site was not significant (p = 0.10). A model with IP value, ρ_{12}, DBH_{rel}, and LP_{rel} as fixed effects (model 9*b*) reduced the residual variance with 76% (R^2 = 0.76), and RMSE was 7.1 $kN·mm^{-2}$.

Discussion

The values of ρ_{12}, MOE_{12}, and MOR_{12} were higher, particularly for the G11 and G17 sites, than the values obtained in previous studies of Norway spruce grown in Norway (Foslie and Moen 1968; Høibø 1991; Vestøl et al. 2012). This is probably due to the high age and slow diameter growth for trees from these two sites. From the *F* values, it appears that density is more dependent on site, whereas MOR_{12} and MOE_{12} are more dependent on DBH_{rel} and LP_{rel}. Because the sites are from almost the same altitude and located in the same region, the climate is similar; hence, site differences in density and annual ring width are probably due to different age, silviculture, and site fertility. With a larger geographical range, climatic effects will add to the site variation of density, and the relationship between annual ring width and density will vary more between sites (Wilhelmsson et al. 2002). Together with knot size, this will increase the site differences in MOE and MOR and most probably reduce the accuracy of dynamic MOE machine strength grading without density recording.

DBH_{rel} was the single covariate that most reduced the MOR_{12} residual variance in models including the effect of site. The effects of DBH_{rel} on MOE_{12} and MOR_{12} are comparable with previous studies done on several softwood species. The large effect of DBH_{rel} is in accordance with Høibø (1991), who found a negative significant effect of DBH on grade yield of machine stress graded boards of Norway spruce. Liu et al. (2007) found a 58% reduction in the residual variance only using DBH in a model predicting MOR on boards of black spruce (*Picea mariana* (Mill.) B.S.P.). Høibø and Vestøl (2010) also found a large negative effect of DBH when they modelled MOE and MOR for round logs of Scots pine (*Pinus sylvestris* L.) with tree and stand characteristics.

The reduction in MOE_{12} and MOR_{12} with LP_{rel} corresponds to the longitudinal variation in density found in this study (models 1, 2, and 3 in Table 7) and the longitudinal knot diameter profiles found in numerous studies (Colin and Houllier 1991; Moberg 2000; Mäkinen and Colin 1998). The lower effect of longitudinal position in trees on MOE_{12} and MOR_{12} for boards from the G24 site can be explained by the longitudinal increase in density with LP_{rel}, which is opposite to the effect of knot size, which increases with LP_{rel} up to the central part of the crown (Colin and Houllier 1991; Moberg 2000). For the poorest site, a negative contribution from both density and knot size on MOE_{12} and MOR_{12} with increasing LP_{rel} may explain the more pronounced longitudinal decrease in MOE_{12} and MOR_{12} for this site. For the G17 site, the longitudinal variation in density (ρ_{12}) is changing from a negative effect to a positive effect when going from trees with small DBH_{rel} to trees with large DBH_{rel}. The increase in density with LP_{rel} for the most fertile stand corresponds to Kucera (1994), who studied longitudinal and radial density profiles of Norway spruce growing on sites with a high SI.

Models using information about the origin of the boards (site, DBH_{rel}, and LP_{rel}) reduced the MOE_{12} residual variance more than the IP value (model 2 (Table 7) and model 4 (Table 8), respectively). Adding site to IP value (model 5; Table 8) yielded approximately the same R^2 value as origin alone (model 2), while the additional effects of DBH_{rel} and LP_{rel} contributed more than IP and site (model 6 (Table 8) and model 5 (Table 8), respectively). This shows that information about origin of the boards provides significant additional information compared with what can be measured with machine stress grading not taking density into consideration. The site effect in model 6 is not explained, but it can be assumed to be an effect of density as site is not significant when ρ_{12} is taken into account (model 6*b*). Also, for the simpler model 5 with IP, the effect of site was significant, but it became insignificant when ρ_{12} was introduced to the model (model 5*b*). The effect of density is considerable (model 4 versus model 5*b*). This is natural, as the resonance frequency depends on both MOE and density. The additional effect of DBH_{rel} and LP_{rel} on MOE_{12} is limited when a correction for density (ρ_{12}) has been made (model 5*b* versus model 6*b*). The considerable effect of density (ρ_{12}) on MOE_{12} is in accordance with other studies (Kliger et al. 1995; Vestøl et al. 2012).

When it comes to MOR, the effect of DBH_{rel} and LP_{rel} are more important, both alone and in addition to IP and density (ρ_{12}) (models 3, 6, and 6*b*, respectively). The model including IP, site, DBH_{rel}, and LP_{rel} gave a larger reduction of the residual variance than the model with IP and density (ρ_{12}) (models 9 and 8*b*, respectively). This is contrary to what was found for MOE_{12} and is probably due to a larger effect of knot diameter on MOR (additional effect of KD on MOE and MOR (models 5*c* and 8*c*, respectively)) and that knot diameter to a greater extent than density depends on diameter growth (Høibø 1991) and longitudinal position in the stem. Colin and Houllier (1991) and Mäkinen and Colin (1998) found a considerable effect of longitudinal position in stem on knot diameter on Norway spruce and Scots pine, respectively. On the other hand, studies done on density and longitudinal position in the stem are not consistent (Atmer and Thörnqvist 1982; Hakkila 1966; Kucera 1994; Repola 2006). When removing the effect of site from model 9 (model 9*c*), the reduction of R^2 was smaller than it was for the comparative MOE model (model 6*c* versus model 6). The difference can be explained by a smaller effect of density and a larger effect of knot size on MOR, assuming that the effect of site is mainly due to differences in density.

Even though the material comes from a relatively limited area, there are significant site differences that IP cannot account for.

This shows that the effect of using smaller growth areas in general may be limited, as the local variation is often more important (Ranta-Maunus 2010; Stapel 2008; Stapel and Denzler 2010). This probably will also be the case for other areas and tree species due to differences in the relationship between density and knot size with origin (differences between sites, relative tree size, and longitudinal position in stem) and tree species. Output-controlled systems that use dynamic setting values based on input from tests of timber from the running production in a particular mill might not be a better solution either because of the large variation both between and within trees in a stand. Today it is difficult for sawmills to differentiate between logs from given stands and also between types of trees and logs. However, tracing individual logs through the conversion chain should make data from forest inventories and the harvester accessible and valuable for the running production in the sawmill.

To obtain a more complete picture of the different site effects, a larger study has to be carried out based on materials from different climatic zones and stands with different silvicultural regimes. Nevertheless, the results from this study show that large parts of the variations in density, MOE, and MOR of structural Norway spruce timber can be explained by its origin as described by differences between sites, relative tree size, and longitudinal position in stem. The effect of origin adds to the variation described by IP value in machine grading based on resonance frequencies and can be used to improve the accuracy of such strength grading. For MOR, the improvement is larger than we can get by adding density, whereas for MOE, density is more important. This probably is due to the larger effect of knot diameter on MOR than on MOE (Vestøl et al. 2012) and that knot diameter varies more than density within sites and trees. Still, the significance will vary between stands due to differences in climatic conditions, site fertility, and silvicultural regime. Some of the effects discussed are species-specific, whereas several are not. However, when models are developed, parameter estimates have to be estimated for different species.

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PAPER II

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ORIGINAL

Pre-sorting of Norway spruce structural timber using acoustic measurements combined with site-, tree- and log characteristics

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Abstract This study assesses whether acoustic velocity alone or in combination with information about the timber obtained in the forest or on the log-yard can be used for pre-sorting of Norway spruce (*Picea abies* [L.] Karst) structural timber. The study is based on 1235 boards from 205 trees sampled from 14 sites in Norway. In addition to various site-, tree- and log variables, acoustic velocity was obtained by Fibre-gen tools, the ST300 on standing trees and the HM200 on logs. Both ST300 and HM200 explained parts of the variability of the indicating property measured by Dynagrade strength grading machine, but the accuracy was better for HM200 than for ST300. The model with ST300 was substantially improved by introducing forest data, i.e., height to diameter ratio, age and relative longitudinal position in the tree while the improvement by combining HM200 with log data, i.e., log tapering, was minor. Grade yield after pre-sorting based on the developed models was simulated, and the results showed a possibility of increasing the C30 yield. The results show that acoustic velocity could be used either as an inventory tool, to give information about the available material from a site, or as a pre-sorting tool before sawing the logs to certain products.

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1 Introduction

Norway spruce is the most important species for the Norwegian sawmilling industry, and the main product from this species is structural timber, constituting about one-third of the annual output of sawn timber in Norway. Due to the large variation in strength properties and the limited accuracy of grading, strength grading has to be conservative in order to secure the safety of timber constructions. At the moment the highest strength class applied to structural timber from Norwegian sawmills is C30 according to EN338 (Standard Norge 2009a). However, since the average bending strength of spruce timber from Norway is more than 40 N/mm^2 (Foslie and Moen 1968; Lackner and Foslie 1989; Eikenes et al.1996; Haartveit and Flæte 2002), it should be possible to produce timber in higher strength classes. This would require a more accurate strength grading.

Dynagrade is the most common strength grading machine in Norway at the moment. It is based on the measurement of resonance frequencies originating from a strike by a metal hammer on the end of the board (Boström 1997). Combined with the length, which is measured by laser, the machine calculates a so-called indicating property (IP) (Eq. 1), where F is the first resonance frequency in longitudinal vibration and L is the length of the timber (Dynalyse AB 2010).

$$IP = F^2 \cdot L^2 \tag{1}$$

The IP-value is used to sort the boards into strength classes according to the limits in EN 14081-4 (Standard Norge 2009b).

Studies have been performed to introduce systems to predict timber strength based on measurements on logs. Examples are approaches based on external log shape

(Grace 1993; Jäppinen and Beauregard 2000) and X-ray scanning of logs (Oja et al. 2001, 2005; Brännström et al. 2007). Measuring acoustic velocity on standing trees or in logs is an approach which is possible to implement relatively easily, and with relatively low costs. These techniques are based on the same principle, which many sawmills use to grade structural timber. Auty and Achim (2008) and Lindström et al. (2009) showed that acoustic velocity measured on standing Scots pine trees is a reliable indicator of static bending properties. For Radiata pine, there has been found a significant positive relationship between acoustic velocity of trees and logs (Tsehaye et al. 2000a, b), and between acoustic velocity in logs and the timber stiffness (Dickson et al. 2004; Carter et al. 2006, Walsh et al. 2014). For Norway spruce, Perstorper (1999) showed that it was possible to reduce up to 50 % of the variation in bending strength of the sawn timber by using the dynamic modulus of elasticity of the logs as independent variable. Edlund et al. (2006) expanded this study using a resonance-based acoustic measurement to pre-grade logs of Norway spruce, and showed substantially higher grade yield in the logs with high velocity.

The acoustic velocity depends on the ratio of the modulus of elasticity to density. According to the general positive relationship of the modulus of elasticity and sound velocity (Kollmann and Côté 1968) and the positive relationship between the modulus of elasticity and density, IP value is expected to increase with density, leading to a greater grade yield with increasing density. The density in Norway spruce varies considerably between stands and between trees within the stand. Decreasing density for the same annual ring width is expected with decreasing temperature sum during the growing season (Wilhelmsson 2001). Within a stand the density decreases with increasing diameter growth of the tree (Zobel and van Buijtenen 1989; Høibø 1991; Wilhelmsson et al. 2002). Earlier studies indicate a longitudinal variation within the stem too, but this variation seems not to be consistent. Atmer and Thörnqvist (1982) found a slight decrease in density from stump height to 75 % of stem height while Tamminen (1964) described an upward increase followed by a slight decrease towards the top of the trees in the outer sapwood. Kuçera (1994) found, for a given ring number on a high site index, an increasing density upwards in the stem. In a recent study, Høibø et al. (2014) found increasing density with distance from the ground on a fertile site, similar to what Kuçera (1994) found, but a decrease in density with distance from the ground on a poor site. They also found a more pronounced vertical variation for the small trees compared to the dominant ones. Even if there are some inconsistences in density variation, information about the systematic part of the variation in density might be of significant value for the grading process, leading to higher grade yields.

Knot size is the most frequent degrading factor in visual strength grading of structural timber in Norway (Høibø 1991). One of the main effects of knot size on modulus of elasticity and IP-value is the fiber disturbance. Knot diameter increases for most of the trees with distance from the ground up to the lower part of the living crown, with a subsequent decrease towards the top of the tree (Mäkinen and Colin 1998). Therefore, a reduction in IP-values due to knot diameter can be expected with distance from the ground. There is also a positive relationship between diameter growth and knot diameter, leading to lower stiffness with increasing diameter growth (Høibø 1991).

Vestøl et al. (2012) found that the variation in bending properties between trees was more important than the effect of log position within the tree. Variation in IP-values for boards from different trees is therefore expected to be larger than for boards from the same tree. Knowledge of the systematic variation in acoustic properties within and between trees might enable pre-sorting of both trees and logs prior to sawing, and an improvement of grade yield later on in the conversion chain.

Combining acoustic measurements with other measurable variables has been attempted for other species, like black spruce, using diameter at breast height (Paradis et al. 2013); Radiata pine, using a branch index (Ridoutt et al. 1999); Sitka spruce, using ring width and log position (Moore et al. 2013); and Douglas fir, using DBH and log position within the stem (Wang et al. 2013). For Norway spruce, Øvrum (2013) showed that H/D-ratio is an effective early assessment in a stand to predict timber stiffness, obtained by Dynagrade. Brüchert et al. (2011) showed several models for early assessment of board stiffness for Norway spruce based on various measuring techniques at the different stages of processing along the value chain.

Walsh et al. (2014) classified logs according to acoustic velocity measured in a harvester head, and found significantly different MOE between the velocity classes. They also showed that this additional measurement did not significantly lower the productivity of the harvester.

Since structural timber is one of the main products from Norway spruce, information about strength and stiffness properties is highly relevant from a forest inventory point of view. Structural timber has different requirements when it comes to dimension and quality compared to other sawn wood products. Information about strength and stiffness before harvest might therefore be of great value, when the trees and tree parts are allocated to the different processing chains. Information about the acoustic velocity in trees and its relationship to grade yield might improve strength grading in the sawmill.

The aim of this study is to investigate the possibility of using acoustic measurements together with either forest inventory data or log measurements, to improve the grade yield of Norway spruce structural timber.

2 Materials and methods

2.1 Material

The study was based on timber sampled from 14 sites in southern Norway, from south-west of Oslo to north of Trondheim. This covers the main area of Norway spruce timber production in Norway. The recorded geographical and forest-inventory variables were: latitudinal (LAT) and longitudinal (LON) location of the site, altitude (ALT), basal area (BA), and site index (SI), defined as the dominant height at 40 years of age presented in the classification according to Tveite (1977); number of sample trees, mean DBH, and age of the sample trees are presented in Table 1.

2.2 Methods

Diameter at breast height (DBH) was recorded for all trees within a selected area at each site, and trees with DBH larger than 20 cm were divided into five strata with an equal number of trees in each. Three trees were randomly sampled from each stratum, but trees with obvious defects like rot or ramicorn branches were avoided. The selection ensured that the material represents the diameter distribution of trees suitable for timber production from each site. The variables recorded for each selected tree were average diameter at breast height (DBH), tree height (H), tree age at stump height (AGE), height to the whorl where the living crown covered half of the circumference (H_{180}), height to the whorl where the crown covered the whole circumference (H_{360}), and acoustic velocity (ST300) (Table 2). The slenderness ratio (H/D) was defined as the ratio of H to DBH of each selected tree. Relative diameter (DBH_{rel}) was calculated as ratio of DBH of a tree to the stand mean of DBH.

The trees were cut into logs of 3.6, 4.2, or 4.6 m. The relative longitudinal position within the tree (LP_{rel}), small end diameter (LD), and acoustic velocity (HM200) were measured, and log taper was calculated (LT). All variables used in the study are defined in Table 2.

The acoustic velocity in standing trees was measured with the ST300 tool from Fibre-gen. This tool is based on a time of flight measurement, using two probes inserted a few centimeters into the stem wood with a distance of about 1.2 m in the lower part of the tree. The sound velocity in logs was determined by the HM200 tool from Fibre-gen, which is a resonance-based measurement. Lately, various publications (Gao et al. 2012, 2013, 2014; Searles 2012; Unterwieser and Schickhofer 2012) have focused on the temperature dependency of sound velocity in wood. According to these studies, the velocity varies a lot, especially around and below the freezing point. The temperature during the velocity measurement varied between −3 and 24 °C; thus the acoustic velocities, both measured with ST300 and HM200, were adjusted to 20 °C according to the calibration equations by Gao et al. (2013).

The logs were sawn to either two or four boards with dimensions depending on the small-end diameter of the logs. The board dimensions were 38 by 100 mm, 50 by 100 mm, 50 by 150 mm, 50 by 200 mm, and 50 by

Table 1 Geographical data, forest inventory data, and sample tree measurements

Site	Geographical and forest inventory data					Sample trees		
	LAT (N)	LON (E)	ALT (m)	BA (m^2/ha)	SI (m)	N trees	Mean DBH (cm)	Mean Age
01	58.2889	8.1957	170	44	14	13	33.0	138
02	58.5288	8.4627	210	45	23	15	29.9	66
03	59.6401	10.4487	150	60	26	15	26.9	49
04	59.8567	10.3284	380	35	17	15	27.9	76
05	60.0383	9.1125	700	21	11	14	33.2	153
06	60.2555	8.9446	800	32	11	14	26.6	124
07	60.5320	11.3701	370	47	20	15	24.0	58
08	60.6371	9.7993	544	39	11	15	26.3	108
09	60.6618	10.8852	220	44	20	15	29.0	104
10	61.0632	9.5403	845	42	11	14	29.2	91
11	61.3102	10.2391	630	45	17	15	29.4	120
12	62.7471	9.9898	470	45	14	15	27.6	128
13	63.3521	10.2455	150	41	17	15	31.6	119
14	63.6511	10.9141	100	34	14	15	28.2	125

Table 2 Tested variables

Variables	Abbreviations	Unit
Site variables		
Site index, dominant height at age 40 years, Tveite (1977)	SI	m
Altitude	ALT	m.a.s.
Latitude	LAT	
Longitude	LON	
Basal area	BA	m^2/ha
Tree variables		
Age	AGE	years
Diameter at breast height, over bark	DBH	cm
Ratio of DBH of the sample trees to the mean DBH of the site	DBH_{rel}	
Tree height	H	m
Tree slenderness	H/D	m/cm
Height to the whorl where the living crown covered half of the circumference	H_{180}	m
Height to the whorl where the crown covered the whole circumference	H_{360}	m
ST300 velocity	ST300	km/s
Log variables		
Relative longitudinal position	LP_{rel}	%
Log taper	LT	mm/m
Log diameter in top end	LD	mm
HM200 velocity	HM200	km/s
Board variable		
Indicating property from Dynagrade 10^{-6}	IP	

225 mm. The boards were dried in industrial kilns and graded with Dynagrade grading machines at three different sawmills. The moisture content during grading differed between sawmills with mean moisture contents of 14, 16, and 19 %. Therefore the IP-values were corrected to a moisture content of 12 % according to EN 14081-4 (Standard Norge 2009b). Grade yield was estimated by using single grades C24, C30 and C35, and the corresponding lower limits of IP-value were 4.30 for C24, 6.48 for C30 and 7.78 for C35. The combined grade yield of C30 and C24 was also estimated, and then the corresponding limits for IP-value were 7.25 for C30 and 5.55 for C24 (Standard Norge 2009b).

2.3 Statistical analysis

In order to account for the different board sizes, each observation was weighted according to the board's proportion of the total board volume multiplied with the total number of observations. IP-values from Dynagrade (Table 2) were analysed in a variance component model where the random variance was divided into site-effect, tree-effect, log-effect, and residual variance (Eq. 2).

$$IP = \mu + S_i + T_j(S_i) + L_k(S_i, T_j) + e \quad (2)$$

S_i (i = 1–14) represents the random site effect, T_j (j = 1–205) represents the random tree effect, and L_k (k = 1–443) represents the random log effect, and *e* represents the residual variance. The residual variance describes the variance within logs. The random effects, given by the variance components σ^2_S, σ^2_T, σ^2_L and σ^2_e, were assumed to be normally distributed. Models for different applications were made by adding fixed effects to the variance component model:

- Tree-level models designed for estimating IP-value from trees based on ST300 alone and combined with site and tree variables;
- Log-level models designed for estimating IP-value from logs using HM200 technology alone and combined with log variables.

For both technologies, models with acoustic measurement as the only covariate were estimated. Additional effect of relative log height was tested. Then the models were expanded with either site and tree variables for the tree-level model, or log variables for the log-level model. Since ST300 was only applied to the lower part of the stems, additional models based only on data from butt logs were developed in order to compare the accuracy of HM200 with ST300. Covariates were added to the models if the probability of type I error was smaller than 0.05. However, since developing simple models was an aim, variables were not included in the model if the improvement of the model was negligible.

The linear mixed models were calculated using the restricted maximum likelihood (REML) method in the fit model platform in the JMP version 10.0 from SAS Institute Inc. (Cary, North Carolina) following Littell (2006). The presented R^2 and RMSE values were calculated from the residual values and did not include the contribution from the random effects.

3 Results

The distribution of IP-values from Dynagrade is presented in Fig. 1, and the grade yield of single grade C24, single grade C30, single grade C35 and combined C24 and C30, based on the setting values from EN 14081-4 (Standard Norge 2009b), are presented in Table 3.

Variance component analysis showed that the variance was distributed with 27.0 % due to site, 34.3 % due to tree, 11.5 % due to logs, and 27.3 % due to residual variance. A comparison made on a subsample of boards from the logs

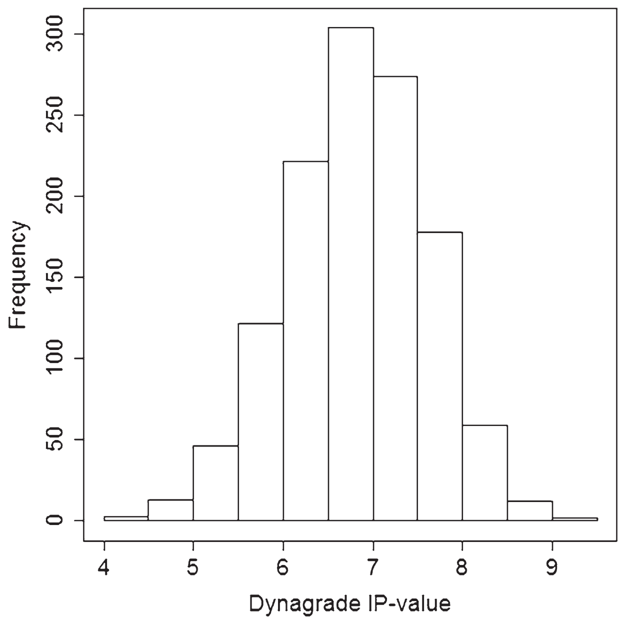

Fig. 1 Distribution of Dynagrade IP-value

Table 3 Grade yield and mean IP-value from Dynagrade for single C24, C30 and C35 and the combined grade C24/C30

Grade	Yield (%)	Mean IP
C24	99.9	6.84
Reject	0.1	4.18
C30	67.9	7.26
Reject	32.1	5.95
C35	11.4	8.09
Reject	88.6	6.67
C30	31.2	7.71
C24	63.2	6.55
Reject	5.6	5.17

All yields are shown as percentages of the total volume of boards

that yielded four boards showed significantly higher IP-values ($F = 9.6$, $p = 0.0022$) for the outer boards than for the inner boards. This difference is part of the residual variance in the following models.

3.1 Tree-level models with ST300

In the first step of modeling (Table 4, Model 1), acoustic velocity from ST300 ($F = 40.2$, $p < 0.0001$) was the only fixed effect in the model. The model reduced the random variance by 12.7 % (Table 4), and RMSE was 0.731. The reduction was mainly in the variance due to site, but also to some degree in the variance due to trees. There was an additional effect of relative log height ($F = 5.2$, $p = 0.0226$), but this was minor compared to the effect of acoustic velocity ($F = 39.0$, $p < 0.0001$). A model with both acoustic velocity and relative log height (Model 2) reduced the random variance by 12.8 %, and the RMSE was 0.730. There was a slight reduction of random variance from Model 1 to Model 2 in the variance due to logs, while the other variance components remained unchanged. The covariates included in the model combining ST300 with stand- and tree data were ST300 ($F = 19.4$, $p < 0.0001$), relative log height ($F = 4.1$, $p = 0.0426$), H/D ($F = 34.7$, $p < 0.0001$), AGE ($F = 9.6$, $p = 0.0028$) and the interaction between ST300 and H/D ($F = 5.5$, $p = 0.0197$) (Table 4). The fixed effects part of the model reduced the random variance by 25.0 %, and RMSE was 0.678. As compared with the variance component model, Model 3 mainly reduced the variance due to site, but also some of the variance due to tree (Table 4). Still, the variance due to site constituted 15.0 %, and the variance due to tree constituted 32.0 % of the random variance not explained by the fixed effects in the model.

3.2 Log-level models with HM200

IP-value from Dynagrade was positively correlated with acoustic velocity measured by HM200 in logs (Model 4; $F = 277.3$, $p < 0.0001$). The model reduced the random variance by 42.2 %, and RMSE was 0.595 (Table 4). The reduction consisted in all three types of variance, due to sites, trees, and logs. The additional effect of relative log height was not significant ($F = 1.6$, $p = 0.2076$).

Model 5 (Table 4) combines acoustic velocity from HM200 with log data that can be obtained in the log-yard. Log-taper ($F = 9.6$; $p = 0.0021$) was a significant additional effect to acoustic velocity, but compared to HM200 ($F = 232.6$, $p < 0.0001$) it had only a minor importance. The interaction between HM200 velocity and taper also was significant ($F = 8.1$, $p = 0.0048$), but it was not included in the model, since the improvement was small. The fixed effects part of the model reduced the random variance by 43.0 %, and RMSE was 0.591. The model reduced the variance due to trees and logs (Table 4). Still, the variance due to site constituted 12.6 %; the variance due to trees constituted 30.2 %, and the variance due to logs constituted 9.8 % of the random variance not explained by the fixed effects in the model.

3.3 Comparison of ST300 and HM200 on butt logs

Acoustic velocity measured on standing trees (ST300) was positively correlated with acoustic velocity measured on logs (HM200). When all logs were included, the R^2 was 0.31, while it was 0.43 when analysing only butt logs.

Table 4 Models

Fixed effects	R^2	RMSE	Variance components			
			σ^2_S	σ^2_T	σ^2_L	σ^2_e
Variance component model						
			0.167 (27.0 %)	0.214 (34.3 %)	0.071 (11.5 %)	0.170 (27.3 %)
Tree-level models (n = 1235)						
1. 4.04 + 0.64ST300	0.127	0.731	0.108 (20.6 %)	0.175 (33.3 %)	0.071 (13.6 %)	0.169 (32.4 %)
2. 4.14 + 0.63ST300 − 0.24LH_{rel}	0.128	0.730	0.108 (20.7 %)	0.175 (33.5 %)	0.070 (13.4 %)	0.169 (32.4 %)
3. 2.71 + 0.46ST300 − 0.21LH_{rel} + 2.05H/D + 0.01AGE − 1.61ST300 × H/D	0.250	0.678	0.068 (15.0 %)	0.145 (32.0 %)	0.070 (15.5 %)	0.169 (37.5 %)
Log-level models (n = 1235)						
4. 1.48 + 1.47HM200	0.422	0.595	0.045 (12.5 %)	0.111 (30.9 %)	0.036 (10.0 %)	0.168 (46.6 %)
5. 1.91 + 1.39HM200 − 0.15LT	0.430	0.591	0.045 (12.6 %)	0.107 (30.2 %)	0.035 (9.8 %)	0.168 (47.4 %)
Butt-log models to compare acoustic velocity (n = 443)						
6. 3.85 + 0.67ST300	0.158	0.772	0.185 (28.4 %)	0.220 (33.8 %)		0.245 (37.8 %)
7. 2.72 + 0.48ST300 + 1.60H/D + 0.01AGE	0.251	0.728	0.139 (23.8 %)	0.200 (34.2 %)		0.246 (42.0 %)
8. 0.82 + 1.63HM200	0.395	0.654	0.090 (18.6 %)	0.147 (30.5 %)		0.246 (51.0 %)
9. 1.15 + 1.60HM200 − 0.19LT	0.403	0.650	0.089 (18.7 %)	0.140 (29.5 %)		0.246 (51.8 %)

Model 6 describes the positive correlation between IP-value and ST300 ($F = 30.0$, $p < 0.0001$). The model reduced the random variance by 15.8 %. A corresponding model based on acoustic velocity measured by HM200 ($F = 98.4$, $p < 0.0001$) reduced the random variance by 39.5 % (Model 8). A model combining ST300 ($F = 14.2$, $p = 0.0002$) with H/D ($F = 14.2$, $p = 0.0002$), and AGE ($F = 7.4$, $p = 0.0080$) reduced the random variance by 25.1 % (Table 4, Model 7), while a combined model of HM200 and taper (Model 9) reduced the residual variance by 40.3 %. Taper ($F = 6.0$, $p = 0.0154$) had a significant effect, but it was of minor importance compared to the HM200 ($F = 96.6$, $p < 0.0001$).

3.4 Pre-sorting and grade yield improvement

The effect of pre-sorting on grade yield was simulated for single grade C30 by excluding an increasing portion of boards according to the predicted IP-values from the models defined in Table 4 (Fig. 2). The simulations based on models with acoustic velocity from ST300 are presented in Fig. 2a. The C30 yield increased more for the models combining ST300 with geographical and forestry data (Models 3 and 7) than for the corresponding models with only ST300 (Models 1 and 6). For instance, exclusion of about 50 % of the boards according to Model 3 increased the grade yield by approximately 16 % units, while the increase was around 12 % if the exclusion was based on Model 1.

The simulations based on models with acoustic velocity from HM200 are presented in Fig. 2b. Since the additional effect of log taper in Model 5 was small, the increase in C30 yield by increasing exclusion rate was similar to that of Model 4, where the exclusion was based on only acoustic velocity measured by HM200 (Fig. 2b). The increase in C30 yield was from the beginning on better for the HM200 models compared to that of Model 3 based on ST300. The C30 yield increased by approximately 22 % units if 50 % was excluded according to Models 4 and 5. The butt-log models showed a slightly better grade yield increase for the models including ST300 (Models 6 and 7). For the butt-logs models including HM200 velocity (Models 8 and 9) the increase was similar.

The gain of pre-sorting also depends on the possible applications of the excluded timber. Figure 3a, b show the relationship between the IP-value from Dynagrade and the predicted values from Model 3 and Model 4, respectively with examples of pre-sorting for C30 single grade with 50 % exclusion based on each model. The chosen ST300-model was the best model including site and tree variables, while the chosen HM200-model did not include other log variables, since these had only a minor effect on the model. The yields and mean IP-values for C30 timber, rejected timber and excluded timber are presented in Table 5.

4 Discussion

Since ST300 was applied on the tree-level, the models are only able to describe site- and tree variance, and not the variance between logs and between boards from the same log. According to the variance component analysis, the variance due to site and tree constituted 61.3 % of the

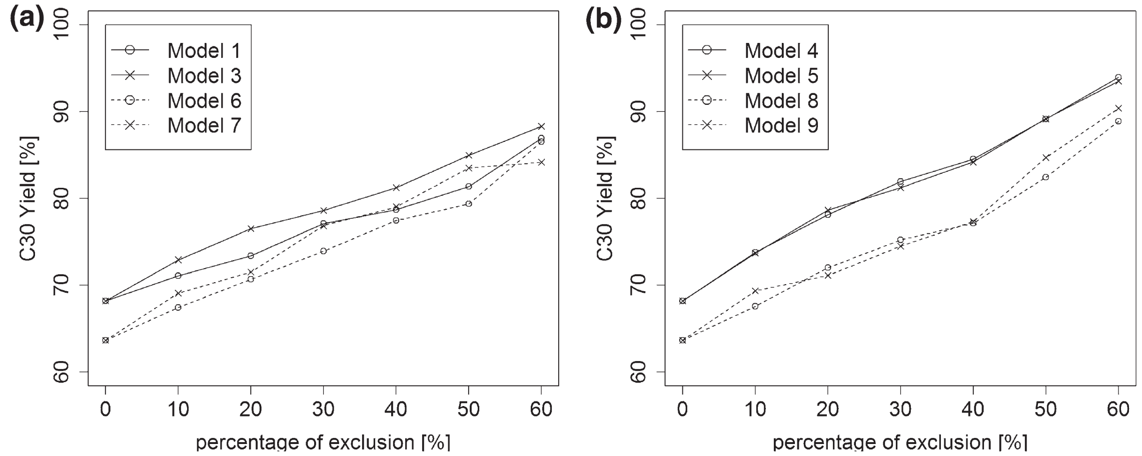

Fig. 2 Improvement in grade yield of C30 for the different models based on either **a** ST300 velocity or **b** HM200 velocity

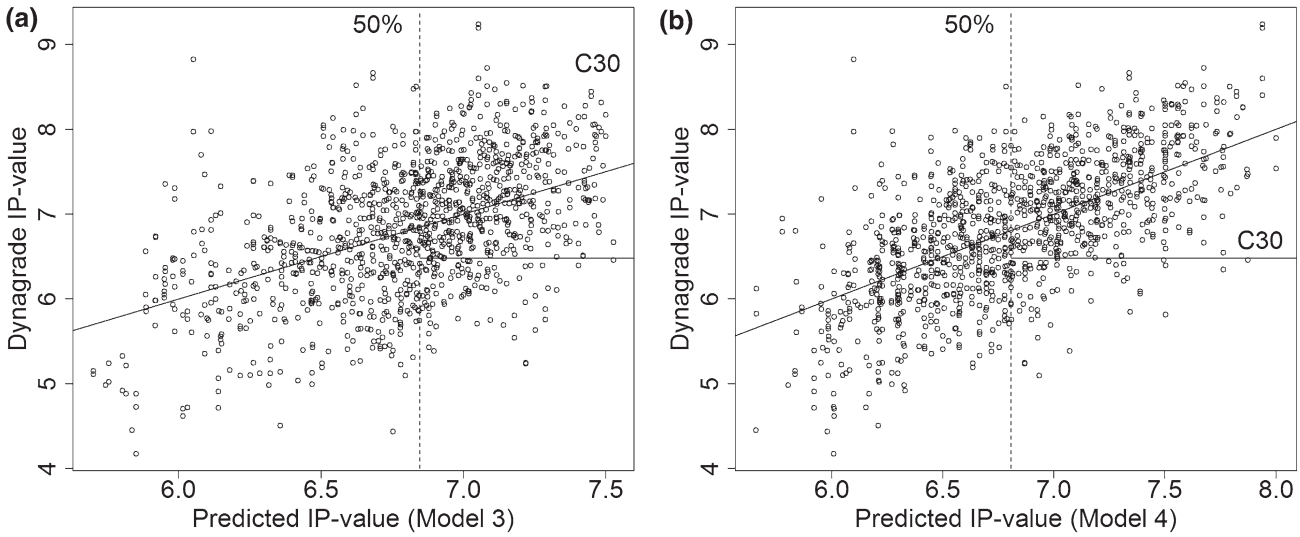

Fig. 3 Relationship between IP-value and predicted value of the model **a** combining ST300 with forest information (Model 3) and **b** for HM200 and C30 single grade for the better 50 %

variance in IP-value. Model 1 reduced the variance by about one-third and it reduced more of the variance due to site than the variance due to tree. This variance component was reduced by 35.3 %, meaning that ST300 explained a substantial part of the variance between sites. This shows the potential of measuring acoustic velocity as part of the forest inventory. Paradis et al. (2013) suggested using ST300 velocity as part of conventional forest surveys to obtain low-cost assessments of wood properties at the regional scale. It could either be used during regular field inventory, or as a product-based pre-harvest measurement. The latter would be a simple and low-cost alternative to fixed tools on the log-yard or in the harvester and could give a reasonable evaluation on site-level about the expected timber quality. Adding the effect of relative log height (Model 2) also enabled the model to explain some of the variance between logs. Carter et al. (2013) improved the relationship between the velocity measured on standing

Table 5 Grade yield and mean IP-values of presorted timber based on Model 3 and Model 4

Pre-sorting	Grade	Yield (%)	Mean IP
Model 3	C30	42.3	7.35
50 % exclusion	Excluded	50.0	6.51
	Reject	7.7	6.13
Model 4	C30	44.1	7.39
50 % exclusion	Excluded	50.0	6.42
	Reject	5.3	6.14

All yields are shown as percentages of the total volume of boards trees and the velocity measured on logs by using a regression including log position in addition to tree velocity. Wang et al. (2013) found the combination of log acoustic velocity and log position to be better predictors of average lumber MOE than log acoustic velocity alone. However, this could not be shown for the log models based on HM200 velocity in this study.

The lower IP-values from logs higher up in the tree may in part be due to a low proportion of outer boards, since the outer boards had significantly higher IP-values than the inner boards. The introduction of forest data improved the model by reducing both the variance due to site and the variance due to trees (Model 3). Other investigations have shown that including more variables in addition to acoustic properties improves the prediction of IP-value. Grabianowski et al. (2006) and Auty and Achim (2008) pointed out that age explains parts of the variance which velocity is not able to predict for Radiata pine and Scots pine respectively. This was shown in the present study as well. Moore et al. (2013) reported significant additional effects of altitude, breast height age and DBH for models predicting the IP-value of boards of Sitka spruce grown in Scotland. Altitude had no significant effect in the present study, but the influence of DBH was significant. However the H/D ratio was even more significant and was therefore included instead of the DBH in the model. The H/D ratio describes the slenderness of a tree, and it was found to be an indicator for strength and stiffness in several studies. For Norway spruce, Øvrum (2013) and Haartveit and Flæte (2002) found that more slender stems yield timber with higher MOE. Since increasing planting distance gives trees with larger taper, the effect of H/DBH also corresponds well with the findings of Høibø (1991), who found a negative correlation between bending strength and planting distance for Norway spruce.

Several studies have pointed out the dependency of acoustic velocity on temperature. For example, Searles (2012) found a poor relation between acoustic velocity of standing trees in summer and winter. Gao et al. (2013) showed that the adjustment for temperature, especially around the freezing point, is very difficult and uncertain. This could constitute challenges in implementing the equipment on the log-yard or in the harvester-head used in areas where the temperature is below or near the freezing point for longer periods. However, using acoustic velocity as a pre-harvesting tool gives the opportunity to perform in seasons when the temperatures are well above freezing point and the effect of temperature is less important.

HM200 is applied on the log-level, and therefore it has the possibility of predicting site-, tree-, and log variance. According to the variance component analysis, these variance components constituted 72.8 % of the variance of IP-values. The model with HM200 (Model 4) could only reduce the variance more than half of what was possible when the pre-sorting was performed on the log-level. The model reduced all variance components except for the residual variance, and the reduction in percentage was biggest for site variance, followed by log and tree variance. The model was only slightly improved by adding other log-variables, and they mainly reduced the variance due to tree (Model 5). The effect of taper in Model 5 corresponds to the effect of H/D in Model 3, since more slender trees yield logs with smaller taper. There is also longitudinal variation in tapering within trees (Kantola et al. 2007), but most effects of longitudinal position is accounted for by HM200, since relative log height was not significant together with HM200.

The models with HM200 (Models 4 and 5) are more accurate than those with ST300 (Models 1–3). This is in part due to the ability of HM200 to predict differences between logs from the same tree, while ST300 is only applied to a small part of the tree, with one value representing all the boards from the tree. Models based on data from only butt logs also show poorer prediction ability for ST300 (Models 6 and 7) than for HM200 (Models 8 and 9). However, the differences in R^2 were smaller than for the whole material. This difference can be seen as a lower variance due to logs in the model with HM200 (Model 4) than in the model with ST300 (Model 1). Carter et al. (2013) suggested that compression wood near the base of the stem in trees from relatively steep slopes influences the sound velocity measured in trees more than the sound velocity measurement on logs. In a review, Wang (2013) showed that many studies have found significant differences between tree velocity and log velocity. He pointed out that a major reason for this deviation is the different measurement techniques. While both HM200 and Dynagrade measure resonance frequency, ST300 measures sound velocity in the form of time of flight. As such, the HM200 is more closely related to the principle behind the IP-values of Dynagrade.

Since pre-sorting is most efficient with a machine grade yield of approximately 50 %, C30 was chosen as a trial in this study (Table 3). Edlund et al. (2006) compared MOE classes based on acoustic measurements on Norway spruce logs with the grade yield of machine grading, and found a significant increase for the C30 grade yield for the higher MOE classes. The results are not directly comparable, since he used the bending type machine Cook-Bolinder with threshold values for combined grading C30/C24/C18 and also grouped the logs in many “velocity groups”. Excluding the lower 50 % in the pre-sorting based on Model 3 resulted in both a higher yield of C30 and a slightly higher proportion of reject (Table 5). This corresponds to Rais et al. (2014), who showed that a threshold value based on acoustic velocity is a good option of increasing the grade yield of Douglas fir. The grade yield increased from 7 to 25 % when sawing only the best 25 % of the material (Rais et al. 2014). In this study, the mean IP-value of the excluded timber was only slightly lower than for C24 from combined C30 and C24 grading without pre-sorting. Pre-sorting based on Model 4 resulted in an even higher yield of C30 and a lower proportion of reject than pre-sorting based on Model 3. The mean IP-value of the excluded timber from this pre-sorting (Table 5) was somewhat lower than for C24 from combined C30 and C24 grading without pre-sorting (Table 3). The 50 % level was chosen as an example in this study and in practice different factors would influence the level of exclusion and the level could be adjusted according to the demands.

EN14081-1 (Standard Norge 2011) restricts the possibility of pre-sorting by not allowing re-grading of timber. However, using only the better part of the material for continued grading has been proven safe and even increases the characteristic values of the graded material (Brännström 2009). The most obvious solution is to use the excluded part for non-structural timber products. However, it should also be possible to use the excluded trees or logs for structural timber in a lower strength class if the requirements are fulfilled. The results of this study have shown that for this material with almost 100 % single grade C24, the proportion of C30 can be increased by pre-sorting based on acoustic measurements. With 50 % exclusion, the mean IP-value of the excluded timber (Table 4) was only slightly smaller than for C24 when the whole sample was graded in combination with C30 (Table 3). The difference increases with exclusion rate. However, using the excluded trees or logs for the production of structural timber in practice, would require revised setting values calculated according to EN 14081-2 (Standard Norge 2010) based on timber from excluded trees and logs only.

5 Conclusion

This study shows that acoustic measurements on standing trees and logs can be considered as a practical indication for strength grading and could be used as pre-sorting tools depending on the strength classes one is aiming for. When velocity is measured on trees with a time of flight tool, a combination of velocity and information about stand and tree has to be considered in order to make it efficient enough to be used in practice. Nevertheless, forest inventory could be a possible field of application for the ST300 tool. The HM200 tool can be considered as reliable enough to be used on the log-yard. This study is based on IP-values from strength grading with Dynagrade. As such, testing of density, stiffness and strength is required to assess secure levels of pre-sorting of material from different origins.

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PAPER III

Between- and within-site variation of density and bending properties of *Picea abies* structural timber from Norway

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ABSTRACT

This study provides an analysis on the variability of structural timber of Norway spruce (*Picea abies*) grown in Norway. Density, modulus of elasticity and bending strength were measured on 1188 boards from 205 trees, sampled from 14 sites throughout Southern Norway, Eastern Norway and Trøndelag. The area represents the procurement area for the majority of Norwegian sawmills. The variability of the timber properties was analysed in a linear mixed model where the random variance was divided into variance due to site, variance due to trees and within-tree variance. Models describing variance due to site based on site index, altitude and latitude were developed, and combined with data from the Norwegian National Forest Inventory to estimate mean values and variability of the timber properties. The results showed that major parts of the variance due to site are explained by altitude and site index, and for density also by latitude. Major parts of the variance due to site and the variance due to trees in bending strength and modulus of elasticity were explained by density.

Keywords

Bending strength, density, modulus of elasticity, Norway spruce, Picea abies, structural timber

INTRODUCTION

Information about wood variation prior to sawing is a prerequisite for efficient utilization of the timber. This is particularly important for structural timber since the strength grading is performed after sawing and drying, and there are limitations to the use of the rejected boards. The grade yield of strength-graded timber depends on the inherent quality of the timber, cross-cutting and grading of logs, dimensions of logs and sawn timber, accuracy of strength grading and the combination of grades. To obtain a high grade yield it is important to adapt the combination of grades to the available timber. Since most sawmills buy logs from forests nearby, the quality is to some extent given, but for regions with significant variations in growth conditions, there might be a large variation in wood properties. Also regional differences may determine which strength classes it is possible to obtain.

Density, modulus of elasticity and bending strength are important properties of structural timber, and the requirements for different strength classes are given in EN 338 (CEN 2009a). C30 is the highest strength class produced by Norwegian sawmills today, and most sawmills produce structural timber only in strength class C24. Some recent studies of structural timber have indicated that there is a potential for exploiting higher strength classes (Vestøl et al. 2012; Høibø et al. 2014), but these studies are local, and more knowledge about geographical variation is required to determine which regions or sites are most suitable for this. The last extensive study of structural timber properties in Norway spruce from Southern Norway, Eastern Norway and Trøndelag was published in 1968 (Foslie & Moen 1968). The forestry practice has changed since then, and also new areas are used for timber production. The Norwegian National Forest Inventory provides data on the Norwegian forest resources, and the data give information about volumes of different species at different site indices, in different age classes and at different altitudes and latitudes (Landsskogtakseringen 2014). Knowing how timber properties vary with these variables would make it possible to estimate distributions of timber properties for a region or for the procurement area of a sawmill.

Wood density is negatively correlated with annual ring width (Nylinder & Hägglund 1954), and it varies both spatially within trees (Kuçera 1994; Gjerdrum & Eikenes

2014), between trees in a stand (Høibø 1991; Vestøl et al. 2012; Høibø et al. 2014) and between stands (Vestøl et al. 2012; Høibø et al. 2014). Braaten (1996) did a literature survey on the effects of site index, altitude and latitude on density of spruce grown in Norway, and concluded that the correlations were low. This is probably due to a large variation within sites. Klem (1965) studied Norway spruce from southern and western Norway and found dry density to be correlated with altitude and site index, but not with latitude. When correcting for annual ring width, Høibø (1991) found a higher density in Norway spruce grown in south-eastern Norway than Nagoda (1985) found in samples collected from northern Norway. Both Ericson (1960) and Wilhelmsson et al. (2002) found a positive additional effect of temperature sum on the relationship between annual ring width and density for Norway spruce grown in Sweden. Under Nordic conditions temperature sum decreases with increasing altitude and latitude (Morén and Pertuu 1994), and the additional effect of temperature on density leads to a lower density for a given annual ring width if the timber is grown at a more northern latitude or at a higher altitude.

The mechanical properties are correlated with density, but they also depend on other clear wood properties and on defects, of which knots and fibre deviations are the most important. Some local studies of Norway spruce from different parts of Norway have shown large variability in the mechanical properties (Foslie 1985; Nagoda 1985; Lackner & Foslie 1988), but Foslie and Moen (1968) did not find any significant difference in bending strength when comparing timber from different regions in southern Norway. They found lower bending strength in 3”x8” timber from higher altitudes, but not for 2”x4”. Chrestin (2000) found lower mechanical properties in timber from mountainous regions in northern Sweden than in central and southern Sweden. Hautamäki et al. (2013) found higher bending strength in timber from Finland than from north-western Russia, and also regional differences within Finland. The regional differences in MOE were not so clear, but timber from more fertile sites was found to have lower MOE.

The additional effect of knots on bending properties also results in different variance structure since density and knots vary differently in Norway spruce (Vestøl et al. 2012; Høibø et al. 2014). Knot diameter depends to a great extent on branch longevity. Branch longevity is related to light conditions for the single tree, and consequently to the silviculture. Density is more dependent on climate. The negative effects of altitude and site index found by Klem (1965) correspond to the combined effect of annual ring width and temperature sum that was found by Ericson (1960) and Wilhelmsson et al. (2002). Vestøl et al. (2012) found that density was somewhat more dependent on site than the bending properties were in a local study in Norway. More dominant trees in a forest stand have both larger knots (Colin & Houllier 1991; Høibø 1991; Vestøl & Høibø 2001) and lower wood density (Høibø 1991; Vestøl et al. 2012; Høibø et al. 2014). Both these effects lead to lower MOE and MOR in timber from more dominant trees. While knot size increases with increasing distance from the ground followed by a subsequent decrease towards the top (Colin & Houllier 1991; Vestøl & Høibø 2001), the longitudinal variation of wood density is not consistent in Norway spruce. Both a decrease with distance from the ground (Atmer & Thörnqvist 1982) and an increase with distance from ground (Kuçera 1994) have been reported. Hakkila (1966) and Repola (2006) found slightly decreasing density in the lower half of the stem followed by an increase in the upper half. The different longitudinal variation of knot size and density results in a different relation between density and the bending properties (Vestøl et al. 2012).

Many sawmills use grading machines based on calculating a dynamic MOE from axial vibration of the timber. The machines measure an indicating property that is used to sort the boards into strength classes according to limits in EN 14081-4 (CEN 2009b). The simplest and least accurate machines measure only the resonance frequency and the length of the boards, while the density must be estimated to calculate the dynamic MOE. Since density and knot diameter to some extent depend on different factors, a machine using only resonance frequency and length as predictor for strength will not be consistent between stands and regions. This is partly due to different effects of density on MOE and MOR depending on the sizes of knots in the timber (Vestøl et al. 2012). Høibø et al. (2014) found that density explained the site-effects on the relationship between indicating property and the bending properties in a local study in Norway. Grading machines, which also record wood density, have been found to be more accurate (Hanhijärvi et al. 2005; Hanhijärvi & Ranta-Maunus 2008), but it remains to be shown which part of the variation is explained.

Most previous studies about the effect of origin on structural timber only consider differences between countries or regions within countries (Chrestin 2000; Ranta-Maunus 2009; Ranta-Maunus & Denzler 2009; Hautamäki et al. 2013; Stapel et al. 2015). Some studies done on spruce from Norway have shown different variability of density and bending properties (Vestøl et al. 2012; Høibø et al. 2014). These studies are local, however, and a material with a larger geographical variation is required to estimate the variance due to site. The aim of this study is to investigate the variability of density, MOE and MOR in structural timber in order to estimate distributions of timber properties in materials from Southern Norway, Eastern Norway and Trøndelag based on data from the Norwegian National Forest Inventory.

MATERIALS AND METHODS

The methodology of this study follows Vestøl et al. (2012) and Høibø et al. (2014), with some exceptions. The study was based on Norway spruce timber from 205 trees, sampled from 14 sites in Southern Norway, Eastern Norway and Trøndelag (Figure 1). The selection of sites includes a latitudinal gradient from 58.3 °N to 63.7 °N and an altitudinal gradient from 150 m to 845 m above sea level at about 60 °N to 61 °N.

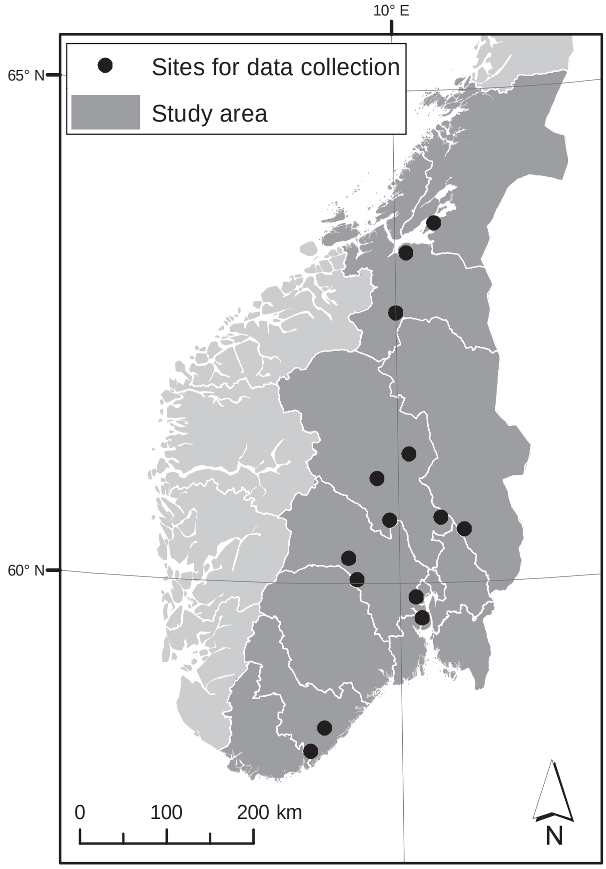

Figure 1. Study area and locations of the sites used for data collection.

Since all sites from higher altitude were from intermediate latitudes, the correlation between altitude and latitude was small and not significant (r = -0.04). A representative distribution of site index was aimed for within each region, and the sites represent different growing conditions in the procurement area of spruce to Norwegian sawmills. Site index was negatively correlated with altitude (r = -0.62), while the correlation between site index and latitude was not significant (r = -0.22). All sites were ordinary forests in age class 4 or 5, and most of them were about to be harvested. Geographical data and forest inventory data are presented in Table 1.

Table 1. Geographical data and site index.

Site	Latitude (°N)	Longitude (°E)	Altitude (m)	Site index, H_{40} (m)
1	58.2889	8.1957	170	14
2	58.5288	8.4627	210	20
3	59.6401	10.4487	150	26
4	59.8567	10.3284	380	17
5	60.0383	9.1125	700	11
6	60.2555	8.9446	800	11
7	60.5320	11.3701	370	20
8	60.6372	9.7993	544	11
9	60.6618	10.8852	220	20
10	61.0632	9.5403	845	14
11	61.3102	10.2391	630	14
12	62.7471	9.9898	470	14
13	63.3521	10.2455	150	17
14	63.6511	10.9141	100	14

An area was selected at each site, and the diameter distribution was obtained by recording diameter at breast height for all trees within the area. The trees with a breast height diameter larger than 20 cm were classified into five diameter classes with an equal number of trees in each. Three trees were sampled from each class. The sampling was random, but trees with rot, ramicorn branches or other excessive damages were avoided.

The trees were cut into logs with lengths of 3.6 m, 4.2 m or 4.6 m. In order to obtain two boards of at least a 38 by 100 mm dimension, a small end diameter of at least 15 cm was required. The logs were sawn to either two or four boards with dimensions depending on the small-end diameter of the logs. The board dimensions were 38 by 100 mm, 50 by 100 mm, 50 by 150 mm, 50 by 200 mm or 50 by 225 mm (Table 2). The boards were dried in industrial kilns and then strength-graded using a Dynagrade machine (Dynalyse 2010). All but one board were accepted in single C24 when using settings for Nordic countries (CEN 2009b). A more detailed analysis of the grade yield, including other grades and combination of grades, is given by Fischer et al. (2015).

Table 2. Sample and yield of tested pieces of sawn timber from each site by dimension.

Site	N.o. trees	N.o. logs	N.o. boards of each dimension				
			38x100 mm	50x100 mm	50x150 mm	50x200 mm	50x225 mm
1	13	39	-	27	47	18	-
2	15	43	-	30	57	14	-
3	15	52	-	40	61	2	-
4	15	43	-	41	39	7	-
5	14	41	-	26	47	20	-
6	14	26	-	27	21	4	-
7	15	25	4	27	10	4	-
8	15	32	5	29	27	2	-
9	15	56	1	29	58	31	-
10	14	24	2	28	-	19	-
11	15	52	-	29	58	24	-
12	15	40	14	22	32	4	4
13	15	54	7	29	39	18	19
14	15	43	7	30	34	6	8

The boards were conditioned in 65% relative humidity and 20 °C, and shortened to 20 times nominal height before testing. Following EN 408 (CEN 2010b), the worst part of each board was chosen in the testing section. Bending strength (MOR) and local modulus of elasticity (MOE) were tested in four-point bending according to EN 408 (CEN 2010b), using the cross-section at the mid-span between the loading points for calculations. Density and moisture content were measured from samples of clear wood taken close to the failure point. The moisture content ranged from 8.9% to 16.2%, with an average of 13.6%. The average was 13.5% for 38x100 mm, 13.3% for 50x100 mm, 13.7% for 50x150 mm, 13.6% for 50x200 mm and 14.3% for 50x225 mm. In accordance with EN 384 (CEN 2010a), density was adjusted by 0.5% for each percentage point deviation from 12% moisture content. Both MOE and MOR were adjusted by 1% for each percentage point deviation from 12% moisture content. The correction on MOE was as prescribed by EN 384, except that corrections were made on individual values instead of characteristic values. EN384 does not prescribe any corrections for moisture content on MOR. No corrections for size effect were made.

Statistical analysis

The variability of density, local modulus of elasticity and bending strength was analysed using linear mixed models, where the random variance was divided into site variance, tree variance and residual variance (Equation 1). The residual variance represented variance between boards from a tree.

$$Y=\mu+f(A, B, \ldots)+ S_i+T_j(S_i)+e \qquad \text{(Equation 1)}$$

Y represents density (ρ_{12}), MOE_{12} or MOR_{12}, μ represents the mean in variance component analyses or intercept in covariate models, f(A, B, …) represents fixed effects, S_i (i=1-14) represents the variance due to site, T_j (j=1-205) represents variance due to trees, and e represents the residuals. The random effects were assumed to be normally distributed and were given by the variance components σ_S^2, σ_T^2 and σ_e^2, respectively.

Variance component analysis was performed on all properties. Then covariate functions describing the effect of density on MOE_{12} and MOR_{12} were added. Covariate models describing effects of latitude, altitude and site index were estimated for all properties, and these models were combined with data from the Norwegian National Forest Inventory (Landsskogtakseringen 2014) to simulate distributions of properties in timber from Southern Norway, Eastern Norway and Trøndelag. The data from the Norwegian National Forest Inventory were recorded from 2010 to 2014. The estimates from the simulations were compared with the empirical data to evaluate how representative the data is for the study area.

The linear mixed models were calculated using the restricted maximum likelihood method (REML) in JMP software (version 10.0; SAS Institute Inc., Cary, North Carolina) following Littell et al. (2006). Hypotheses were rejected if the probability of type I error was smaller than 0.05.

RESULTS

Mean values, standard deviations and fifth percentiles (PCTL) of density and bending properties for each dimension are presented in Table 3. The fifth percentiles were calculated by ranking the observations. Coefficients of variation (CV) were 0.095 for density, 0.186 for MOE_{12} and 0.243 for MOR_{12}.

Table 3. Density and bending properties of sawn timber by dimension.

Dimension (mm)	N	MOR_{12} (Nmm^{-2})			MOE_{12} ($kNmm^{-2}$)			ρ_{12} (kgm^{-3})		
		Mean	Std. dev.	5^{th} PCTL	Mean	Std. dev.	5^{th} PCTL	Mean	Std. dev.	5^{th} PCTL
38x100	40	50.9	11.6	31.8	13.0	2.0	8.8	467	37	404
50x100	414	50.0	11.5	29.9	13.0	2.4	8.9	457	40	389
50x150	530	47.2	11.0	29.4	13.0	2.4	9.5	450	43	380
50x200	173	43.0	12.0	22.8	12.4	2.7	8.3	434	44	370
50x225	31	42.9	9.3	24.1	12.0	2.2	7.5	422	40	353
All	1188	47.6	11.6	28.4	12.9	2.4	9.0	450	43	379

Density variations

Variance component analysis of density showed that the variance due to trees was the largest, constituting 41.4%, while the variance due to site constituted 27.9% and the residual variance, representing the within-tree variance, constituted 30.7% (Table 4).

Neither latitude (p=0.61), nor altitude (p=0.17) nor site index (p=0.28) had any significant effect on density as covariates when used alone. A multiple covariate model with all three variables reduced the variance due to site with 94.0% (Model 1 in Table 4). Density was significantly reduced both by site index (F=25.7; p=0.0005), altitude (F=13.2; p=0.0045) and latitude (F=16.8; p=0.0024). There was a significant positive interaction between site index and altitude (F=6.6; p=0.029), describing a smaller effect of site index at higher altitudes. The other interactions were not significant and were therefore not included in the model. The variance not explained by the fixed effects part of the model was distributed with 2.3% due to site, 56.1% due to trees and 41.6% residual variance (Table 4).

MOE-variations

Variance components analysis of MOE_{12} showed that the residual variance and the variance due to trees were similar, constituting 35.7% and 38.3%, respectively, while the variance due to site constituted 25.9% (Table 4).

Neither latitude (p=0.94) nor site index (p=0.88) had a significant effect on MOE_{12} as covariates when used alone, while there was a significant negative effect of altitude (p=0.014). A covariate model with altitude and site index reduced the variance due to site with 75.2% (Model 2 in Table 4). MOE_{12} was significantly reduced both by site index (F=12.7; p=0.0044) and by altitude (F=28.5; p=0.0002). The additional effect of latitude showed a negative trend, but it was not significant (p=0.13) and therefore not included in the model. There were no significant interactions between the variables. The variance not explained by the fixed effects part of the model was distributed with 7.9% due to site, 47.6% due to trees and 44.4% residual variance (Table 4).

MOE_{12} was positively correlated with density (F=289.5; p<0.0001), and density reduced the random variance of MOE_{12} with 41.6% (Model 3 in Table 4). As compared with the variance component analysis, density explained 68.2% of the variance due to site, 56.9% of the variance due to trees, and 7.9% of the residual variance. The variance not explained by density was distributed with 14.4% due to site, 28.7% due to trees and 56.9% residual variance (Table 4).

MOR-variations

The variance component analysis of MOR_{12} showed that residual variance and the variance due to trees were similar, constituting 46.2% and 40.6%, respectively, while the variance due to site constituted only 13.2% (Table 4).

Neither latitude (p=0.46), nor altitude (p=0.090) nor site index (p=0.42) had significant effect on MOR_{12} as covariates when used alone. A covariate model with site index and altitude reduced the variance due to site with 75.3% (Model 4 in Table 4). MOR_{12} was significantly reduced both by site index (F=14.6; p=0.0028) and by altitude (F=19.4; p=0.0009). The additional effect of latitude was not significant (p=0.91) and was therefore not included in the model. None of the interactions were significant. The variance not explained by the fixed effects part of the model was distributed with 3.6% due to site, 45.0% due to trees and 51.4% residual variance (Table 4).

MOR_{12} was positively correlated with density (F=190.5; p<0.0001), and density reduced the random variance with 28.8% (Model 5 in Table 4). As compared with the variance component analysis, density explained 78.6% of the variance due to site, 42.8% of the variance due to trees, and 5.7% of the residual variance. The variance not explained by density was distributed with 4.1% due to site, 33.3% due to trees and 62.6% residual variance (Table 4).

Table 4. Variance component analyses and models for density, MOE and MOR.

Y	Model	Covariate model	R^2	RMSE	Variance components		
					σ_S^2	σ_T^2	σ_e^2
ρ_{12}		-	-	-	521	771	572
	1	ρ_{12} = 1074-8.84SI-0.246ALT-7.33LAT+0.0109SI*ALT	0.260	37	31	771	572
MOE_{12}		-	-	-	1.57	2.32	2.16
	2	MOE_{12} = 18.7-0.220SI-0.0056ALT	0.171	2.22	0.39	2.32	2.16
	3	MOE_{12} = 0.90+0.027 ρ_{12}	0.416	1.87	0.50	1.00	1.99
MOR_{12}		-	-	-	18.2	55.8	63.6
	4	MOR_{12} = 71.1-0.943SI-0.0186ALT	0.079	11.1	4.5	55.7	63.6
	5	MOR_{12} = -4.34+0.117 ρ_{12}	0.288	9.8	3.9	31.9	60.0

Simulated distributions of timber properties

Predicted mean values for each property ($\bar{Y}'$) were estimated from Models 1, 2 and 4 (Table 4) weighted with data on volumes of spruce in age-class 4 and 5 at different site indices, altitudes and latitudes, between 58 °N and 65 °N in counties in Southern Norway, Eastern Norway and Trøndelag. Volumes in protected areas were excluded. The variance due to site predicted by the models was added to the random variance due to site, while the variance due to trees and the residual variance were taken from the models. Estimated mean values and variance components are given in Table 5.

Table 5. Estimated variability of MOR, MOE and density of sawn timber from Southern Norway, Eastern Norway and Trøndelag.

	MOR_{12} (Nmm^{-2})		MOE_{12} ($kNmm^{-2}$)		ρ_{12} (kgm^{-3})	
Mean:	50.7		13.4		461	
Variance components	Var	%	Var	%	Var	%
Site, σ_S^2	21.1	15.0	1.60	26.3	692	34.0
Tree(site), σ_T^2	55.7	39.7	2.32	38.2	771	37.9
Residual, σ_e^2	63.6	45.3	2.16	35.5	572	28.1

Distributions of timber properties within sites were simulated for samples of 500 boards based on the assumption of normal distribution of the variance components (Equation 2). For each property, simulations were performed for average stands and for stands with mean values at the fifth percentile and 95th percentile, respectively.

$$Y = \bar{Y}' + k \cdot \sigma_S + N\left(0, \sqrt{\sigma_T^2 + \sigma_e^2}\right) \quad \text{(Equation 2)}$$

Sites with average timber properties were simulated with k=0, the fifth percentile with k= -1.645, and the 95th percentile with k=1.645. The simulations are presented in Figure 2. Simulations show that for an average site, the fifth percentile of density is 397 kg/m^3, median MOE_{12} is 13.3 kN/mm^2, and the fifth percentile of MOR_{12} is 32.0 N/mm^2. For 90 % of the stands, the fifth percentile of density ranged from 357 kg/m^3 to 451 kg/m^3, median MOE_{12} ranged from 11.4 kN/mm^2 to 15.6 kN/mm^2, and the fifth percentile of MOR_{12} ranged from 25.6 N/mm^2 to 38.2 N/mm^2.

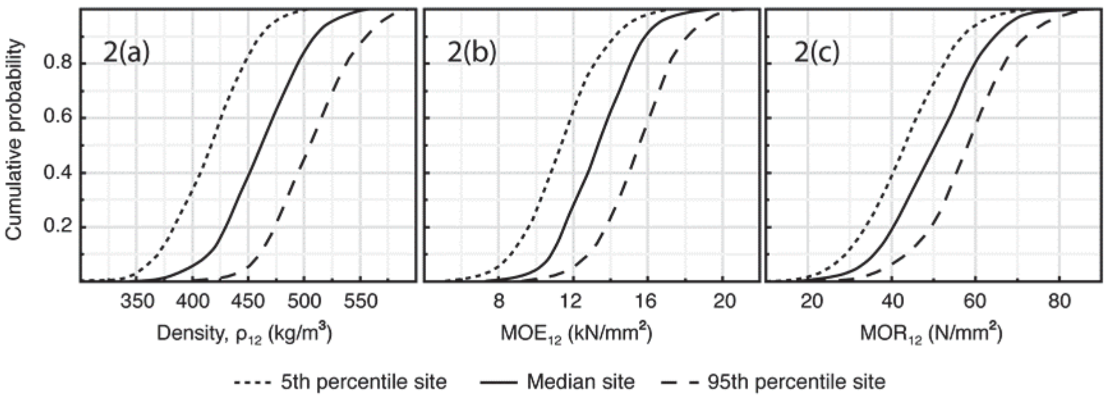

Figure 2. Simulated distributions of timber properties of Norway spruce from Southern Norway, Eastern Norway and Trøndelag. 2(a): density, 2(b): modulus of elasticity, 2(c): bending strength.

Discussion

The sampling for this study was designed to study effects of altitude, latitude and site index, and both mean values and variances due to site in the dataset (Table 4) were lower than those simulated with data from the Norwegian National Forest Inventory (Table 5). The difference is mainly due to an underrepresentation of timber from low site indices. There was also a slight overrepresentation of timber from sites at lower altitudes and an underrepresentation of timber from sites at intermediate altitude, but this would have had an opposite effect, if any, and it was not noticeable. The representation of latitude was close to the distribution shown in the statistics from the Norwegian National Forest Inventory.

A comparison of recorded and simulated mean values and coefficients of variation (CV) with previous studies of timber properties in the same area in Norway is presented in Table 6. The values given by Foslie and Moen (1968) were originally given for timber with 15% moisture content. Those values were corrected to 12% using the same corrections as in this study. The values of MOE and MOR given by Vestøl et al. (2012) and Høibø et al. (2014) were corrected back to original moisture contents (13% and 13.8%) before using the same correction factors as in this study. The most comparable study, with regard to number of specimens and range of sampling area, is the one done by Foslie and Moen (1968). The current study shows 2.8% lower mean density, almost equal mean MOE, and 0.5% lower mean MOR than Foslie and Moen (1968) obtained in their study. One important difference is that they tested visually graded timber, and 4.7% of the boards were excluded before testing. Also the coefficients of variation were similar to what Foslie and Moen (1968) found, while Vestøl et al. (2012) found slightly smaller variations and Høibø et al. (2014) found larger variations. Vestøl et al (2012) studied timber from a limited area, and the larger variability found in the present study was mainly due to a larger variance between sites. Using Models 1, 2 and 4 (Table 4) to estimate variances due to site in density, MOE and MOR, respectively, on data from Vestøl et al (2012) showed only minor differences from what was estimated in their study. Foslie and Moen (1968) and Høibø et al. (2014) did not present variance components that could be compared.

Table 6. Comparisons with previous studies from the study area.

Data	N	ρ_{12}		MOE_{12}		MOR_{12}	
		(kgm^{-3})	CV	($kNmm^{-2}$)	CV	(Nmm^{-2})	CV
This study	1188	450	0.095	12.9	0.186	47.6	0.243
Model predictions for the study area	-	461	0.097	13.4	0.184	50.7	0.232
Foslie & Moen 1968	1351	463	0.10	12.8	0.20	50.1	0.23
Vestøl et al. 2012	333	442	0.086	12.9	0.177	50.9	0.214
Høibø et al. 2014	373	493	0.136	14.9	0.237	54.9	0.257

The simulated mean density was close to what Foslie and Moen (1968) found, while the simulated mean MOE and mean MOR were slightly higher than in both this study and the study of Foslie and Moen (1968). The simulated coefficients of variation (Table 6) were similar to those obtained from the empirical data. Simulations show that timber from average stands meets the requirements on all properties in C30 without sorting when comparing directly to the tabulated values of EN338 without using any correction factors for timber size, sampling size or grading principle. Considering the simulations of extreme stands, the requirements for C24 are met in 90% of the stands, while some sorting is required to meet the requirements for bending strength in C40 in 10% of the stands. This applies to all the tested properties, even though there are some deviations from EN384 in how bending strength is adjusted for moisture content and dimension.

The data showed some geographical trends in density variations, but it was not possible to find any significant effect of a single geographical variable. This may be due to a negative correlation between site index and altitude, a limited number of sites and large variations in growth conditions within geographical areas. There were particularly large variations between the sites at low altitude, where also the variation in site index was largest. When correcting for these variations, the data showed that density is reduced with both altitude and latitude, as well as with site index, when the other variables are constant. Also, the effect of expected reduction of site index with increasing altitude is smaller than the effect of altitude itself, resulting in a predicted net decrease of all the tested properties with increasing altitude. This indicates that some of the site effects can be due to climate, since both altitude and latitude are negatively correlated with temperature. This fits well with the findings of Wilhelmsson et al. (2002), who found that in the case of equal annual ring width, the density increases with increasing temperature sum during the growing season. The additional effect of site index may be explained by the effect of annual ring width on density. At same spacing, ring width gets larger in timber from sites with a higher site index, usually leading to lower density for Norway spruce.

The variances due to site in bending properties followed the density variations, but the site effects were smaller, and the variability within sites was larger (Table 4). This was also found by Moore et al. (2013) in a study of Sitka spruce from UK. Even though the level of the properties was different in their study, the proportions of the different variance components were similar. None of the site variables were significant alone, and only site index and altitude were significant in combination, while the effect of latitude was not. Nor did Foslie and Moen (1968) find any significant difference between regions in southern Norway. They found lower bending strength in 3”x8” timber from higher altitude, but not for 2”x4”. Chrestin (2000) found lower mechanical properties in timber from mountainous regions in northern Sweden than in central and southern Sweden. Hautamäki et al. (2013) found variations in strength between geographic regions in Finland and Russia to be consistent with variations in density and knottiness.

The presented models can be used to estimate distributions for a region, but not for single stands. Besides site index and geographical data, timber properties also depend on silviculture, cross-cutting and sorting, and these factors are not taken into account in these models. The variance component analysis and the models assume equal variance due to trees and residual variance across sites, but studies have shown that both the difference between trees and the longitudinal variation in knot size is larger on sites with higher site index (Moberg 2001; Vestøl & Høibø 2001). This means that there is a stronger effect of silviculture on stands with higher site index, and with appropriate silviculture it is possible to obtain better timber properties than predicted by the presented models. The sampled stands were chosen from ordinary forests without considering silviculture. It must be assumed that they are representative for the silviculture in the area, however, and the estimated variations within sites were also similar to those obtained by Vestøl et al (2012).

Density explained major parts of the variance due to site for both MOE and MOR, and the geographical variation followed the same trends for all properties. This corresponds to the results found by Hautamäki et al. (2013) in Finland and Russia. Wilhelmsson et al. (2002) showed that density of spruce in Sweden is reduced with altitude and latitude, and that the relationship between annual ring width and density varied according to temperature sum. This means that grading systems that include density recording should be less dependent on the origin of the timber, which was also found by Høibø et al. (2014). Ranta-Maunus (2012) suggested using two indicating properties, of which one would be for density, and showed that this resulted in more reliable estimation of timber quality. This study indicates that such grading may be more reliable across sites.

The variability of density, MOE and MOR of structural timer from Southern Norway, Eastern Norway and Trøndelag has been estimated. The results show that the bending properties have larger variability than density, and that density has the largest proportion of variance due to site. Major parts of the variances due to site are explained by altitude and site index, and for density also by latitude. However, since the effect of site index in part compensates for the effect of geographical location, no variable was significant without correcting for the other. Together with data on the Norwegian forest resources, the models developed make it possible to estimate distributions of timber properties in a region but not for single stands, since that would require some information about the effect of silviculture. Density explains major parts of the variation between sites in MOE and MOR. This indicates that grading systems that include density measurements are able to be more consistent across sites.

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PAPER IV

Modelling the variability of density and bending properties of Norway spruce structural timber

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Abstract

Density, modulus of elasticity (MOE) and bending strength (MOR) are important properties of structural timber, and knowledge about the variability is important for an efficient use of the timber. In order to utilize such information in the production of structural timber, the knowledge must be available before sawing. This study presents models describing the variability of density and bending properties of Norway spruce boards within individual trees and among trees and stands based on geographical data and forest inventory data including external tree measurements.

The models were based on 1551 boards from 17 sites from Southern Norway, Eastern Norway and Trøndelag. Important variables describing variation in density, MOE and MOR between sites were site index and altitude. For density, latitude gave additional information. At tree level, age, DBH and longitudinal position within the tree were the most important variables. The models explained major parts of the site variance of all properties and for MOR a substantial part of the variance due to trees. Besides being used for predicting the properties of structural timber from current forest resources, the models also provide information that can be used to predict the effects of silviculture on timber properties in future forest stands.

Keywords: MOE, MOR, density, geographical data, forest inventory data

Introduction

Within species in Europe, density, modulus of elasticity (MOE) and bending strength (MOR) vary significantly both between regions (Ranta-Maunus 2009) and within regions (Foslie 1985, Foslie and Moen 1968, Lackner and Foslie 1988, Nagoda 1985, Hautamäki et al. 2013, Moore et al. 2013, Gardiner et al. 2011). The large variation which is found between sites, trees within sites and within the single tree (Zobel and van Buijtenen 1989, Vestøl et al. 2012, Høibø et al. 2014) makes individual strength grading of each single board crucial for effective use of timber as structural material.

Today most sawmills use machine strength grading, which is more accurate than visual grading. This has led to higher yields of higher grades, giving better competitiveness for timber as a structural material (Ranta-Maunus 2009). However, most of the stress grading machines used account for only a relatively small part of the total variation. Methods to improve the sorting and grading are therefore needed. Predictions of properties based on forest inventory data might be used together with data from stress grading machines to make timber grading more accurate (Stapel and van de Kuilen 2013, Høibø et al. 2014, Lukacevic et al. 2015) and grade yield higher. Incorporating information on the variation between and within trees makes more optimal crosscutting possible (Høibø et al. 2014).

Wood density is an important timber property by itself (Standard Norge 2009), but also since it is widely used as an indicator of timber qualities due to its positive correlation with most mechanical properties. For Norway spruce (*Picea abies* L. Karst), density is negatively correlated with growth rate (Persson 1975), leading to lower density for more dominant trees (Pape 1999). On the other hand, density was found to be positively correlated with temperature sum (Wilhelmsson 2001), which fits well with Høibø (1991), who has found a higher density at the same annual ring width in material from the region around Oslo (latitude: 59°N) than Nagoda (1985) found for material further north (latitude: 65.5 – 69.5°N).

For planted Norway spruce trees, density was found to decrease across the first three to five annual rings, and slightly increase further throughout the mature wood (Kuçera 1994). Kliger et al. (1998) found the same pattern. The longitudinal variation in density shows divergent patterns. While

Kuçera (1994) found an increase in density with an increase in the height in the tree for a given ring number from the pith, Atmer and Thörnqvist (1982) found a slight decrease from the ground up to 75% of the stem height. Hakkila (1996) found a slight decrease in density up to 50%, followed by an increase in the upper half. Repola (2006) confirmed this. Høibø et al. (2014) found density to increase with height on rich sites, while it was opposite on poor sites.

Knot diameter is another very important stem characteristic greatly influencing the strength of timber (Kellogg and Kennedy 1986). Mäkinen and Colin (1998) found an increase in branch diameter with increasing diameter at breast height and crown length for Scots pine (*Pinus sylvestris* L.). Knot size has been shown to increase with diameter growth for Norway spruce (Vestøl and Høibø 2001), leading to a decrease in bending properties (MOE and MOR) (Høibø 1991). Colin and Houllier (1991) found knot diameter to increase with longitudinal distance from the ground, followed by a decrease closer to the top. This pattern was confirmed for several species, such as Scots pine (Mäkinen and Colin 1998), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Maguire et al. 1999), Sitka spruce (Auty et al. 2012) and Norway spruce (Mäkinen et al. 1998).

Since structural timber has to fulfill requirements on density, MOE and MOR (Standard Norge 2009) profound knowledge about the relationships between these properties is important for the design of economic and reliable timber structures (Steiger and Arnold 2009). Høibø et al. (2014) found that detailed site- and tree-level information can be used to improve the grading accuracy. The relationship between density and bending properties vary considerably between trees, stands and regions, but the importance of these properties also vary with use. Due to the negative effect of the temperature sum on density (Wilhelmsson et al. 2002), we expect to find a negative effect of latitude and altitude on density, leading to a negative effect on MOE. The corresponding effects on MOR may be smaller, as MOR was found to be less affected by density and more by knot diameter (Vestøl et al. 2012). As described earlier, the longitudinal variation in density shows divergent patterns in Norway spruce. According to Høibø et al. (2014), it adds to the effect of knot size on poor sites while it counteracts the effect of knot size on more fertile sites. Therefore, the total effect of longitudinal position can be expected to be different for MOE and MOR, and it may also depend on site index.

Models describing the properties of structural timber based on site and tree variables have been developed for some species. Lei et al. (2005) and Liu et al. (2007) have developed models predicting the strength and stiffness of black spruce timber on the basis of tree characteristics. Similar models have been developed for Scots pine logs from Norway (Høibø and Vestøl, 2010). The models show that tree and stand level characteristics predict strength and stiffness fairly well. Lei et al. (2005) showed that stem taper, DBH and crown length are important variables when modelling MOE and MOR based on only stand and tree characteristics. Liu et al. (2007) showed that the best tree and stand characteristics for predicting the bending stiffness of naturally grown black spruce are DBH, crown length, stem taper and stand density. Haartveit and Flæte (2002) found that MOE and MOR negatively correlate with stem taper and crown length. Øvrum (2013) found the average ratio of tree height to DBH to be a good site indicator for the grade yield of structural timber, probably due to its correlation with crown ratio. Hautamäki et al. (2013) developed models for Norway spruce from Finland and Russia. They found that MOE is the best predictor for MOR, followed by ring width, density and knot area ratio, while for MOE, density is the best single predictor, followed by ring width and the number of annual rings.

Models describing the properties of structural Norway spruce sawn timber from Norway so far are all limited to certain regions and do not represent the wide range of altitude and latitude over which this species occurs in Norway. This means that the models cannot be expected to account for differences in structural timber properties due to climate. As far as we know, studies considering such effects in models predicting structural wood properties are limited. The aim of this study was therefore to develop models that describe the variability of density and bending properties of Norway spruce structural timber from forests throughout the most important procurement area for sawmills in Norway. The models should also provide a better understanding of how silviculture affects the properties of structural timber from different regions.

Material and methods

The study is based on timber from 17 sites from Southern Norway, Eastern Norway, and Trøndelag (Figure 1). The sites numbered 15, 16 and 17 were used in an earlier study published by Høibø et al. (2014). The material was chosen from a wide range of latitude, altitude and site index, representing the growing conditions for spruce in Norway. The sites were randomly divided into 11 modelling sites and six validation sites. The site-level data were altitude (Alt in m.a.s.), latitude (Lat), basal area (BA in m^2 ha^{-1}) and site index (SI in m). Site index, defined as dominant height at age 40 (Tveite 1977), was calculated from age at breast height and the height of the three largest trees sampled from each site. For sites 15, 16 and 17, the site indices according to Tveite (1977), were obtained from forest inventory plans, and controlled from height and age at stump height for the three largest trees sampled, taking estimated number of years from but end to breast height into account. The site-level and forest inventory data for each site is presented in Table 1.

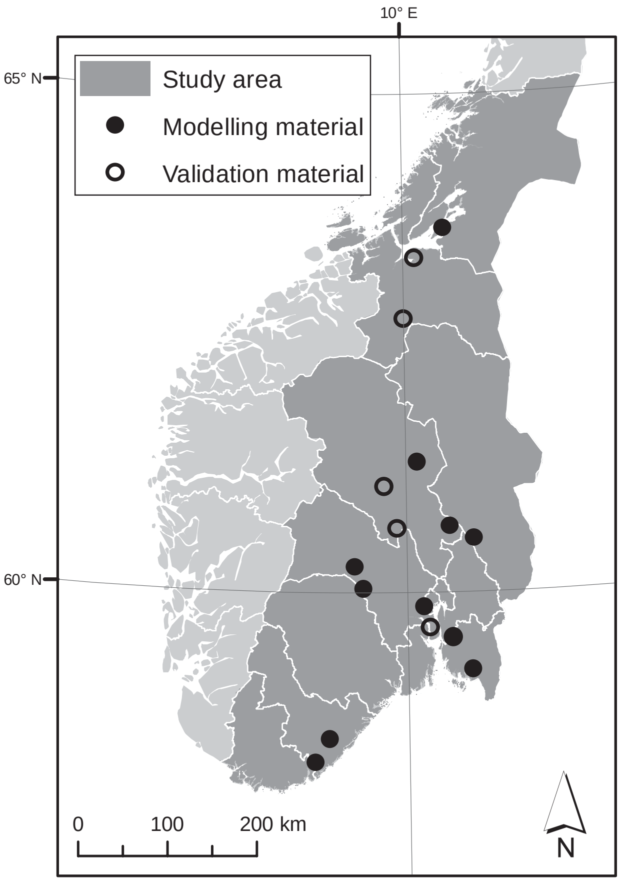

Figure 1. Sampling areas in southeastern Norway.

At each site, diameter at breast height (DBH in mm) was recorded for all trees within a selected area. Trees with a DBH larger than 20 cm were classified into five diameter classes with an equal number of trees in each class. Three trees were randomly selected from each diameter class in order to give a representative sample for the trees with a DBH greater than 20 cm.

Table 1. Geographical and forest inventory data.

Site No.	N trees	LAT (N)	LON (E)	ALT	SI	mean AGE	mean DBH
Modelling material							
01	13	58.2889	8.1957	170	14	138	33.0
02	15	58.5288	8.4627	210	20	66	29.9
04	15	59.8567	10.3284	380	17	76	27.9
05	14	60.0383	9.1125	700	11	153	33.2
06	14	60.2555	8.9446	800	11	124	26.6
07	15	60.5320	11.3701	370	20	58	24.0
09	15	60.6618	10.8852	220	20	104	29.0
11	15	61.3102	10.2391	630	14	120	29.4
14	15	63.6511	10.9141	100	14	125	28.2
15	15	59.2185	11.2637	80	24	80	24.6
16	15	59.5469	10.8980	102	11	161	21.2
Validation material							
03	15	59.6401	10.4487	150	26	49	26.9
08	15	60.6371	9.7993	544	11	108	26.3
10	14	61.0632	9.5403	845	14	91	29.2
12	15	62.7471	9.9898	470	14	128	27.6
13	15	63.3521	10.2455	150	17	119	31.6
17	15	59.5411	10.8937	115	17	157	28.3

The tree variables measured were DBH, age at stump height (Age in years), tree height (H in m), height to the whorl where live branches covered half of the circumference (KH_{180} in dm) and height to the whorl where live branches covered the whole circumference (KH_{360} in dm). Other tree-level variables that were calculated from these are DBH/Age (mm), H/DBH and relative DBH (DBH_{rel}). The latter was defined as the ratio of individual tree DBH to mean DBH of the stand. All variables are presented in Table 2 and correlations are presented in Table 3.

Table 2. Variables used for modelling.

Variables	Abb.	Unit
Site variables		
Site index, dominant height at age 40	SI	m
Altitude	Alt	m.a.s.
Latitude	Lat	
Basal area	BA	m^2 ha^{-1}
Tree variables		
Age	Age	years
Diameter at breast height, over bark	DBH	mm
Ratio of DBH of the sample trees to the mean DBH of the site	DBH_{rel}	
Tree height	H	dm
Tree slenderness	H/DBH	dm mm^{-1}
Ratio of DBH to the age of the trees	DBH/Age	mm
Height to the whorl where live branches covered half the circumference	KH_{180}	dm
Height to the whorl where live branches covered the whole circumference	KH_{360}	dm
Relative longitudinal position of the board in the tree	LP_{rel}	
Board variable		
Modulus of elasticity	MOE_{12}	kN mm^{-2}
Modulus of rupture/ bending strength	MOR_{12}	N mm^{-2}
Density	ρ_{12}	kg m^{-3}

The trees were cut into logs of 3.6 m, 4.2 m and 4.6 m, depending on the top diameter. The minimum top diameter was 15 cm, to make sure that it was possible to produce at least two boards with a cross-section of 38 × 100 mm. The logs were sawn, without shortening the length, into boards of 38 × 100 mm, 50 × 100 mm, 50 × 150 mm, 50 × 200 mm and 50 × 225 mm, depending on the top diameter.

The boards where conditioned in a climate with 65% RH and 20 °C before testing. MOE and MOR were calculated from the results of four-point bending. The test was done according to the requirements in EN 408 (Standard Norge 2010b). Accordingly, the critical section, i.e. the position at which failure is expected, was located. The boards were shortened to 20 times the nominal height (nominal board width defined as nominal cross-sectional board height according to EN 408 (Standard Norge 2010b)) with the critical section located in the middle two-thirds of the board. To ensure the best possible range in height in the tree, the upper part of boards from the upper log was chosen if the quality was homogenous along the board. The boards from sites numbered 15, 16 and 17 were located systematically within the log, depending on which log they had been taken from, boards from the butt log were taken from the end closest to the stump, whereas boards from the other logs were taken from the end closest to the top (Høibø et al. 2014). The relative longitudinal position (LP_{rel}) was defined as the ratio of the longitudinal within-tree position of the center of the board to the height of the tree.

Table 3. Correlation matrix for tested variables.

	SI	BA	ALT	LAT	DBH	H	AGE	DBH/Age	DBH_{rel}	H/DBH	KH_{180}	KH_{360}	LP_{rel}
SI	1	0.78	-0,53	-0,23	-0,01	0.47	-0,67	0.71	-0,05	0,49	0,46	0,40	0,06
BA		1	-0.36	-0.13	-0.12	0.29	-0.58	0.56	-0,07	0,43	0,41	0,31	0.03
ALT			1	0,14	-0,07	-0.54	0,04	-0.16	-0,13	-0,47	-0,53	-0,55	-0,06
LAT				1	-0,07	-0.11	0,13	-0.25	-0,13	-0,05	-0,12	-0,07	-0,02
DBH					1	0.60	0,29	0.27	0,87	-0,58	0,18	0,23	0,11
H						1	0,08	0.27	0,49	0,28	0,70	0,72	0.13
AGE							1	-0.78	0,31	-0,27	0,08	0,15	0,01
DBH/Age								1	0,22	-0,04	0,05	-0,01	0.05
DBH_{rel}									1	-0,55	0,12	0,13	0,10
H/DBH										1	0,51	0,45	-0.01
KH_{180}											1	0,89	0.11
KH_{360}												1	0.11
LP_{rel}													1

Density and moisture content were determined from cross-sectional specimens of clear wood taken as close to the failure point as possible. The moisture content of the material varied from 8.9% to 17.4%, with an average of 13.6%. According to EN 384 (Standard Norge 2010a), density was adjusted by 0.5% for each percentage point deviation from 12% moisture content and MOE was adjusted by 1% for each percentage point deviation from 12% moisture content. Even though EN 384 (Standard Norge 2010a) does not prescribe an adjustment of MOR for moisture content, MOR was adjusted as well using the same correction factor as for MOE. All adjustments were made on single observations.

The number of observations, the minimum, maximum and mean values, and the standard deviations of density and bending properties are presented in Table 4. The validation material had a wider range of values than the modelling material for all properties. The correlation matrix for the material as a whole shows a positive correlation between MOR and density (r = 0.55) and a negative correlation between MOR and knot size (r = -0.50). There was a positive correlation between MOE and density (r = 0.68) and a negative correlation between MOE and knot size (r = -0.35). MOE and MOR were positively correlated (r = 0.79) and density and knot size were negatively correlated (r = -0.17).

Table 4. Number of observations, minimum, maximum, mean values, and standard deviations of density and bending properties of the measured boards.

	N	5% percentile	95% percentile	mean	Std dev
Modelling material					
MOE_{12} (kN mm^{-2})	984	9.45	18.24	13.51	2.80
MOR_{12} (N mm^{-2})	984	30.26	70.32	49.61	12.16
Density, ρ_{12} (kg m^{-3})	984	388.77	561.21	463.62	52.41
Validation material					
MOE_{12} (kN mm^{-2})	567	8.74	18.96	13.12	2.96
MOR_{12} (N mm^{-2})	567	27.89	69.71	48.22	12.83
Density, ρ_{12} (kg m^{-3})	567	369.81	562.37	454.74	54.08
All					
MOE_{12} (kN mm^{-2})	1551	9.13	18.44	13.37	2.86
MOR_{12} (N mm^{-2})	1551	98.56	12.97	49.10	12.42
Density, ρ_{12} (kg m^{-3})	1551	381.52	561.51	460.32	53.12

Statistical analysis

Linear mixed models were used to analyse variations in density, MOR and MOE. Random variance was divided into site variance, tree variance and residual variance:

$$Y = \mu + f(A, B, \dots) + S_i + T_j(S_i) + e \qquad \text{(Equation 1)}$$

Y represents density (ρ_{12}), MOE_{12} or MOR_{12}, μ represents the mean in the variance component analyses or intercept in covariate models, and $f(A, B, \dots)$ represents the fixed-effects part of the model. S_i represents the random site effect, $T_j(S_i)$ represents the nested random tree effect and e represents the residuals. The random effects were assumed to be normally distributed with a mean of zero and variances of σ_S^2, σ_T^2, and σ_e^2, respectively.

The modelling was done in two steps. The first models, including only random effects, describing the between-site variance, between-tree variance (nested under site) and residual variance (within tree variance), were calculated for each property. In the second step, site and tree variables (Table 2) and possible interactions were added to the models. A variance inflation factor (VIF) was used to check for multicollinearity within the models, and covariates were rejected if the VIF was larger than 5. Akaike information criterion (AICc) (Hurvich and Tsai 1989) was used to assess the relative goodness of fit of the models. The models were evaluated by means of coefficient of determination (R^2) and root mean square error (RMSE) of the fixed-effects part of the model. The linear mixed models were calculated using the restricted maximum likelihood method (REML) in JMP software (version 11.0; SAS Institute Inc., Cary, North Carolina) following Littell (2006). Fixed-effects variables were included in the models if the probability of a type I error was smaller than 0.05.

The covariate models were tested on the validation material and were evaluated by coefficient of determination, residual mean square error and mean deviance and deviance for individual sites. The R^2 and RMSE values were calculated from the residuals, i.e. the difference between measured density, MOE_{12}, and MOR_{12} and the predicted values when using the developed models on the validation material.

Results

Density model

The density model (Model 1, Table 5) describes negative effects of altitude, latitude and site index on density. These variables describe differences between the sites only. However, the model also includes a negative effect from DBH and a positive effect from age, describing both variances due to sites and variances due to trees within the site. Further, the model includes a positive effect from relative longitudinal position, describing a negligible vertical increase in density for an average tree (line a, Figure 2). The effect of longitudinal position varied between sites and between trees within the site, described by positive interactions between longitudinal position (LP_{rel}) and site index, altitude and DBH respectively. In Figure 2 the longitudinal changes of density due to changes of the interaction variables are presented and describe greater effects on density for boards from butt logs and minor effects for boards from the upper logs. There was also a negative interaction between LP_{rel} and crown height (KH_{180}), describing a steeper increase with an increase in longitudinal position in boards from trees with lower crown height. The effect of crown height alone was not significant; still we have chosen to keep this lower-level variable in the model. The interactions describe a steeper increase in density with an increased LP_{rel} for higher values of site index, altitude and DBH and lower values of KH_{180}. At lower altitudes, where the site index range is greater, the interactions predicts the largest vertical decrease in small trees with high values of KH_{180} from low site index (line d, Figure 2) and a negligible longitudinal variation in trees from high site index (line c, Figure 2). Site index is limited by altitude, but with a high but realistic site index at high altitude for trees with small KH_{180} and big DBH, the model describes a vertical increase in density (line b, Figure 2).

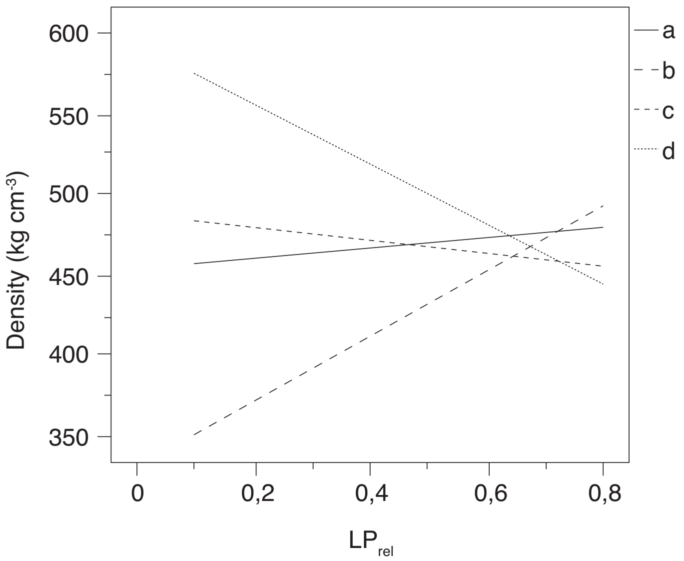

Figure 2. Predicted longitudinal variation of density, as dependent on site index, altitude, DBH, and KH180. Line (a) shows mean values of all fixed effects. Line (b) shows a vertical increase for big trees with small KH_{180} at the highest realistic site index at high altitude. Line (c) shows a vertical decrease for small trees with large KH_{180} at high site index and low altitude. Line (d) shows a vertical decrease for small trees with large KH_{180} at low site index and low altitude.

The fixed-effects part of the model reduced the variance by 56.7%, and the RMSE was 34.45 kg m^{-3}. As compared to the variance component model (Table 6), the model shows a 93.3% lower variance due to site, 15.3% lower variance due to trees, and a 19.6% lower residual variance. The remaining variance not explained by the fixed-effects part of the model is presented in Table 5.

When using the model on the validation data, the predicted values on average were 0.1 kg m^{-3} higher than the observed values. The model reduced the variance by 48.9%, and RMSE was 38.6 kg m^{-3}. The residual of site means was positive for three sites and negative for the other three. The greatest negative deviation of a site mean was 12.1 kg m^{-3} for site 13. The effect of the interaction between LP_{rel} and KH_{180} was minor, and an alternative model without this effect was estimated to check for possible over-parameterization. The reduced model had a higher AIC (9344 vs. 9335) and a slightly lower R-square (r^2= 0.563 vs. 0.567) in the modelling step, but for the validation data the difference was greater (r^2= 0.462 vs. 0.489).

Table 5. Models for density, MOE, and MOR.

SUMMARY OF STATISTICS.			
Model	1	2	3
Property	Density, ρ_{12} (kg m^{-3})	MOE_{12} (kN mm^{-2})	MOR_{12} (N mm^{-2})
Variance components from model step			
σ_S^2	104.88 (7.9%)	0.31 (6.5%)	1.50 (1.6%)
σ_T^2	702.49 (52.7%)	2.12 (44.5%)	31.30 (34.0%)
σ_e^2	526.34 (39.5%)	2.34 (49.0%)	59.41 (64.4%)
Summary statistics from model step			
R^2	56.7%	42.1%	40.0%
RMSE	34.45	2.12	9.47
Parameter estimates and p values and F-ratio for the fixed effects			
Alt	$p<0.001$	$p<0.001$	$p<0.001$
Lat	$p=0.022$		
SI	$p=0.011$	$p=0.301$	
Age	$p=0.021$	$p=0.009$	$p<0.001$
DBH	$p<0.001$	$p<0.001$	$p<0.001$
LP_{rel}	$p<0.001$	$p<0.001$	$p<0.001$
KH_{180}	$p=0.541$		
SI* LP_{rel}	$p<0.001$	$p=0.010$	
Alt*LP_{rel}	$p<0.001$	$p<0.001$	
DBH*LP_{rel}	$p<0.001$		
KH_{180}*LP_{rel}	$p<0.001$		
Summary statistics from validation			
R^2	48.9%	42.4%	35.2%
RMSE	38.64	2.24	10.32

COVARIATE MODELS

1 $\rho_{12} = 1241.96-8.12SI-0.17Alt-9.04Lat+0.40Age-0.39DBH-294.06LP_{rel}+0.11KH_{180} + 11.23SI*LP_{rel}+0.15Alt*LP_{rel}+0.56DBH*LP_{rel}-0.60KH_{180}*LP_{rel}$

2 $MOE_{12} = 20.55-0.15SI-0.01Alt+0.02Age-0.02DBH-6.47LP_{rel}+0.20SI*LP_{rel} +0.01ALT*LP_{rel}$

3 $MOR_{12} = 73.59-0.02Alt+0.12Age-0.10DBH-6.39LP_{rel}$

MOE model

The model describes a negative main effect of altitude on MOE_{12}, while the effect of site index alone was not significant. Like the density model, the MOE_{12} model includes a negative effect from DBH and a positive effect from age, both describing variance due to the trees and variance due to the site. The model includes a negative main effect of relative longitudinal position, describing a slight vertical decrease in MOE_{12} (line a, Figure 3). The effect of longitudinal position depended both on altitude and site index, and was revealed by positive interactions with both. The interaction effect with altitude describes a stronger effect from altitude on timber from butt logs than on timber from upper logs. The interaction between longitudinal position and site index reduces the vertical decrease in MOE_{12} with increasing site index. Since site index is limited by altitude, the effect of the interaction with site index is limited at high altitudes. The model predicts a negligible effect from longitudinal position in trees at a higher altitude when using high but realistic site indices (line b, Figure 3). At lower altitudes, where the site index range is larger, the interaction between site index and LP_{rel} predicts a vertical decrease in trees from low site index (line d, Figure 3) and a negligible longitudinal variation in trees from high site index (line c, Figure 3).

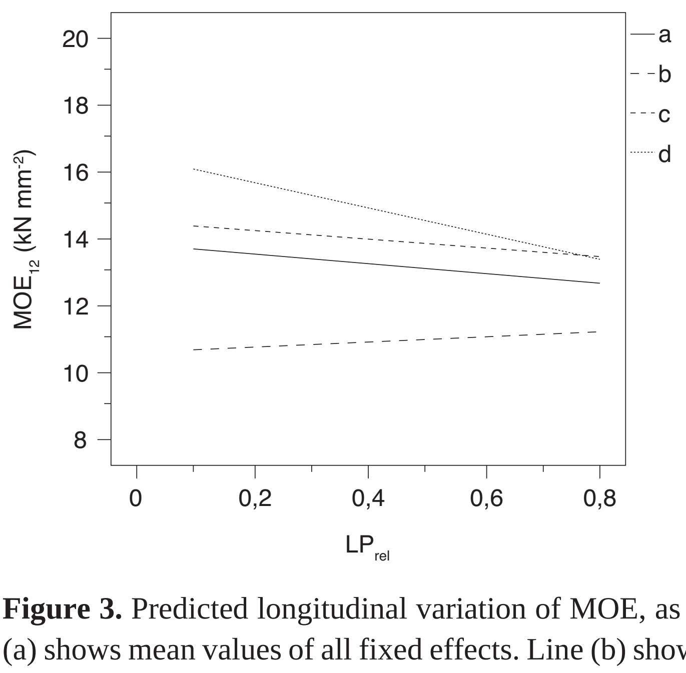

Figure 3. Predicted longitudinal variation of MOE, as dependent on site index and altitude. Line (a) shows mean values of all fixed effects. Line (b) shows a vertical increase at the highest realistic site index at high altitude. Line (c) shows a vertical decrease at high site index and low altitude. Line (d) shows a vertical decrease at low site index and low altitude.

The fixed-effects part of the MOE_{12} model reduced the random variance by 42.1%, and the RMSE was 2.14 kN mm^{-2} (Model 2, Table 5). As compared to the variance component model (Table 6), the model showed an 89.3% lower variance due to site, 25.9% lower variance due to trees and 4.1% lower residual variance.

When using the model on the validation data, the predicted values on average were 0.49 kN mm^{-2} higher than the observed values. The model reduced the validation material variance by 42.4%, and the RMSE was 2.24 kN mm^{-2}. The residual of site means was negative for five sites and positive for only one. The two greatest deviances of site means were site 13 with -1.66 kN mm^{-2} and site 3 with -1.09 kN mm^{-2}.

MOR model

The MOR_{12} model (Model 3, Table 5) describes a negative effect from altitude on MOR_{12}, while the effects of latitude and site index alone were not significant and therefore have not been included in the model. Even though the parameter estimate is greater in the MOR_{12} model than in the MOE_{12} model (Table 5), the relative effect of altitude was smaller on MOR_{12} than on MOE_{12}. As for the other models, the MOR_{12} model also includes a negative effect from DBH and a positive effect from age. These variables describe both variance due to trees and variance due to site. The model also includes a negative effect from longitudinal position, describing a vertical decrease in MOR_{12}, but no interactions between longitudinal position and other variables. Figure 4 shows the negative effects of longitudinal position and altitude for trees with average DBH and Age. The effect of longitudinal position interacted negatively with site index and DBH. However, when checking this three-way interaction effect for possible over-parameterisation, the model with the interaction effect included was found to have a higher AICc (7071 vs. 7066). The three-way interaction effect has therefore not been included in the model presented.

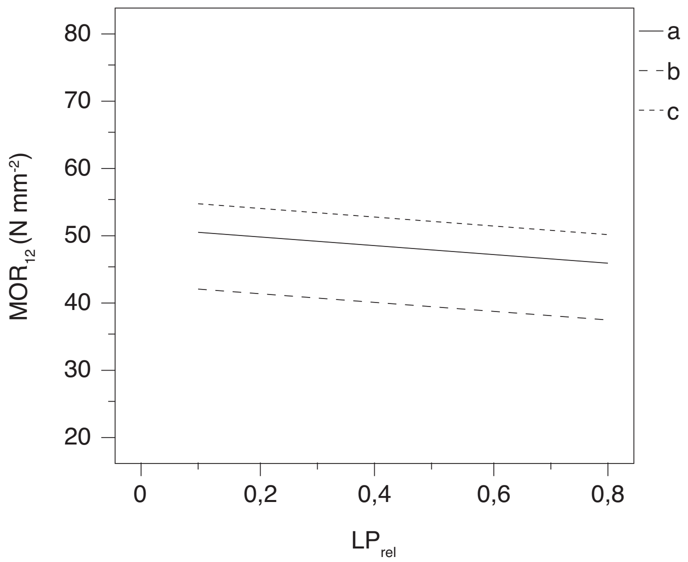

Figure 4. Predicted longitudinal variation of MOR, as dependent on altitude. Line (a) shows mean values of all fixed effects. Line (b) shows the vertical decrease at high altitude. Line (c) shows the vertical decrease at low altitude.

The fixed-effects part of the model reduced the random variance by 35.2%, and the RMSE was 10.32 N mm^{-2}. As compared to the variance component model (Table 6), the model showed 95.3% lower variance due to site, 50.7% lower variance due to trees, and a 2.0% lower residual variance. When using the model on the validation data, the predicted values were on average 1.97 N mm^{-2} higher than the observed values. The model reduced the variance in the validation data by 33.9%, and RMSE was 10.43 N mm^{-2}. The residual of site means was negative for four of the six sites and positive for two. The greatest deviations of site mean were -3.84 N mm^{-2} for site 13 and -7.32 N mm^{-2} for site 3.

Table 6. Variance component model for density, MOE, and MOR.

	σ_S^2	σ_T^2	σ_e^2
Density, ρ_{12} (kg m^{-3})	1575.97 (51.5%)	829.51 (27.1%)	654.65 (21.4%)
MOE_{12} (kN mm^{-2})	2.91 (35.5%)	2.86 (34.8%)	2.44 (29.7%)
MOR_{12} (N mm^{-2})	32.13 (20.6%)	63.54 (40.7%)	60.63 (38.8%)

Discussion

Both the negative effect of site index and the combined effect of DBH and age on density (Model 1, Table 5) correspond with the negative effect of annual ring width on density found in many studies of Norway spruce (Kollmann and Coté 1968, Pape 1999 and Wilhelmsson et al. 2002). The negative effects of altitude and latitude on density, after adjusting for site index, DBH and age (Model 1, Table 5), correspond with results reported by Wilhelmsson et al. (2002), who has found that density increases with temperature sum. They also correspond with results reported by Gindl et al. (2000), who have found a positive correlation between within ring maximum density and temperature in August - September, showing that the autumn temperature is important for density. A similar result was reported by Høibø (1991), who found higher density for a material from the Oslo region (59°N latitude) compared to a material from the latitudes 65.5 – 69.5°N that was studied by Nagoda (1985). The positive effect of age on density and MOE is related to the negative effect of age on annual ring width (Wilhelmsson et al. 2002). The negative effect of annual ring width on density is related to a smaller proportion of latewood (Jyske et al. 2008).

The between-sites variation in bending properties followed the variation in density, and the effects of DBH, age and altitude were significant for both MOE (Model 2, Table 5) and MOR (Model 3, Table 5). The somewhat smaller effect of altitude on MOR than on MOE is in accordance with the hypotheses in the introduction, that altitude has a greater effect on MOE than MOR due to the greater effect of density on MOE than on MOR (Vestøl et al. 2012). In a study of 14 of the sites (Vestøl et al., unpublished) it was found that density explained 68.2% of the site variance of MOR and 78.6% of the site variance of MOE. Besides density, the bending properties are also influenced by other wood properties and defects, of which knots and fibre deviations are the most important (Johansson 2003). These effects vary more within trees and therefore lead to a larger residual variance. According to Vestøl et al. (2012), knot diameter has a larger effect on MOR than on MOE, suggesting that much of the within tree variation in MOR can be attributed to differences in knot size. This explains the differences in the distribution of the unexplained variances of density, MOE, and MOR. It also explains why the effect of latitude was significant only for density and not for the bending properties, and why site index was significant only for density and MOE, and not for MOR.

Within sites, the correlation between annual ring width and density is higher since there is no additional effect of climate (Wilhelmsson et al. 2002). The negative effect of increased diameter growth on density, which is related to DBH and age, also has a significant negative effect on bending properties. This effect is amplified by the additional effect of knot size, which to a great extent is positively correlated with diameter growth (Høibø 1991). The effect of knot size is related to large crowns and longer and thicker branches in dominant trees compared to more suppressed trees (Moberg 2001, Vestøl and Høibø 2001). Since only trees with a DBH of greater than 20 cm were sampled, the trees from sites with a small average diameter were, on average, more dominant than trees sampled from stands with a greater-than-average DBH. This sampling effect may explain why DBH also explained some of the variance due to site.

The positive interaction effect between LP_{rel} and site index on density found in this extended dataset of 17 sites (which also includes the three sites of Høibø et al. (2014)) fits well with the results of Høibø et al. (2014), who found density increasing with height above ground for the richest site and density decreasing with height for the poorest site. The extended dataset shows a similar type of interaction effect of LP_{rel} and DBH on density as Høibø et al. (2014) presented.

The longitudinal variation in bending properties depends on the combined effect of density and knot size. While the longitudinal variation in density is not consistent in Norway spruce (see e.g., Kuçera 1994, Hakkila 1966, Atmer and Thörnqvist 1982, Johansson 1992, Repola 2006, Jyske et al. 2008), an increase in knot diameter together with increasing distance from the ground in the lower part of the stem has been found to be a regular pattern (Mäkinen et al. 2003, Moberg 2001, Colin and Houllier 1991, Wilhelmson et al. 2002). This pattern is a result of increased branch longevity due to declines in stand density with age and the accumulated growth of branches in the living part of the crown. Since the correlation with density is stronger for MOE and the effect of knot size is stronger on MOR (Vestøl et al. 2012), the different longitudinal variations of density and knot size will result in different longitudinal variations in MOE and MOR.

The effect of altitude is mainly climatic and it influences the relation between density and annual ring width (Wilhelmsson et al. 2002). For MOE, the positive interaction effect between altitude and longitudinal position (Model 2, Table 5), showing that the effect of altitude is greater for timber from butt logs than for timber from upper logs, follows the corresponding interaction in the density model (Model 1, Table 5). The positive interaction with site index also shows that the longitudinal variation in MOE in timber from a lower site index follows the same pattern of variation as density with an increasing longitudinal position. For low site indices, both the effect of knot size and the effect of density contribute to a vertical decrease in MOE. However, in timber from a higher site index, it is a vertical increase in density, which is positive for MOE, while the effect of knot size is opposite. The contrary effects result in a negligible longitudinal variation in MOE for higher site indices.

MOR is more dependent on knot size than MOE is (Ranta-Maunus 2009). The greater effect of DBH on MOR in timber from the upper part of trees from a higher site index might be due to a greater effect from knot diameter. In trees from stands with a higher site index, knot diameter varies more in the longitudinal direction (Vestøl and Høibø 2001), and the greatest difference between trees is found in the lower part of the living crown, where the thickest knots are located. The smaller longitudinal variation in knot diameter on trees from a lower site index makes the effect of knot size smaller and the effect of density correspondingly more important. The effect of DBH on density was greater for timber from butt logs, and it thereby has a greater effect on MOR in butt logs when the effect of knot diameter is limited.

The stands appeared to have relatively small differences on knot size, and the site differences were more due to density. The wide range in site conditions for the material studied may cause the relatively greater proportion of site variance as compared to tree variance (Table 6), making between-site variation more pronounced. This may also explain why relatively large proportions of the variance due to site were explained by variables that are independent on silviculture, i.e. site index, latitude and altitude. However, for MOR, a relatively large reduction for variance between trees within a stand was achieved, as compared with density and MOE (Table 5). This probably is due to the greater effect of knot diameter on MOR than MOE (Ranta-Maunus 2009, Vestøl et al. 2012) and a relatively large variation in knot diameter between trees within stands and less variation between stands. DBH within stands is usually well correlated with branch diameter (Loubère et al. 2004) due to the longer and thicker branches of dominant trees as compared to more suppressed trees (Moberg 2001, Vestøl and Høibø 2001). DBH_{rel} was expected to describe the social position within stands, but it turned out to be less important than DBH. This might in part be due to the sampling effect that followed from only selecting trees with a DBH greater than 20 cm. Density is more important for MOE than for MOR (Vestøl et al. 2012), making variation in density between stands important for MOE, and in particular for this material, which has a relatively large range in altitude and latitude.

Liu et al. (2007) have presented models for MOE and MOR with a better fit for black spruce timber from naturally grown forests in eastern Canada than we have obtained in this study. When using only tree and site variables, their MOE model showed a substantial better RMSE than the presented MOE model in our study, while the difference was small for the MOR models. However, their models showed a poorer fit for the validation material for both MOE and MOR. Several studies (Lei et al. 2005, Liu et al. 2007, Haartveit and Flæte 2002, Øvrum 2013) have presented stem taper as an important variable when modelling MOE, MOR and grade yield. However, in this study, stem taper (tree slenderness, H/D) was correlated with DBH, site index, and altitude (Table 3), and it was of minor importance compared to these variables. This probably is related to the wide range in altitudes, latitudes, site index and DBH in this material.

In this study, we have aimed for a large range in altitude, latitude and site index, and it covers the procurement area for most sawmills in Norway. One limitation of the material is the lack of sites at higher altitudes in the northernmost part of the study area, and one should be cautious when using the models for timber from such areas. Considering the distribution of site index in Norway, where over 70% of the forest is found to have a site index between 11 and 20, the study material represents timber used for structural purposes fairly well. However, for modelling purposes it might have been better to have more sites with a higher site index where the timber properties are more dependent on variation in silvicultural regime. The models showed small effects from site and tree variables that depend on silvicultural regimes as judged by greater effect from site variables that depend on climate or other growth conditions. This might be because of small differences in silviculture between sites.

The models presented show that in part the variability of the density and bending properties of Norway spruce structural timber can be explained by geographical data and forest inventory data including external tree measurements. The models were tested on a validation data set and showed a good fit for the validation material. Therefore, it can be concluded that the models give reliable predictions for density, MOE, and MOR within the ranges given for the different variables. The models explained major parts of the site variances of all properties, whereas smaller parts of within tree variances were explained. A substantial part of the between-tree variance in MOR was explained, while smaller parts of the variance due to trees was explained for density and MOE. The models describe both geographical variations and variations due to growth, with altitude, site index and latitude as the most important site variables, and DBH and age as the most important tree variables. The models can be used for estimating the distribution of timber properties in the procurement area of a sawmill or to select stands with timber that is suitable for higher strength classes. The models also describe some of the variation within sites, with diameter at breast height and age as the most important variables, and can be used for pre-sorting of timber, and to some extent also to estimate effects of silviculture on timber properties.

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PAPER V

Site effects in machine strength grading of Norway spruce structural timber

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Abstract

The aim of the study was to assess site effects in machine strength grading of Norway spruce structural timber. Site effects were estimated for grading based on resonance frequency and timber length, and for grading based on dynamic modulus of elasticity. Timber was collected from 14 sites in Norway, and linear mixed models were developed based on 1188 boards. The study showed that strength grading based on resonance frequency and timber length left significant effects of site that were related to altitude, latitude and site index. The site effects were smaller when the grading was based on dynamic modulus of elasticity. For both grading methods, the site effects were smaller for bending strength than for modulus of elasticity and density. Major parts of the site effects were explained by mass density, and simulations showed that it is possible to fulfil the requirements of the strength classes with a higher yield when the sorting is based on a combination of exclusion by mass density and exclusion by the frequency-based indicating property.

1 Introduction

Bending strength and modulus of elasticity are the two most important properties of timber to consider when using in constructions (Glos 1995). In Europe, structural timber is expected to fulfil requirements related to density, stiffness and strength according to EN 338 (Steiger and Arnold 2009). In order to meet the requirements, the timber is graded visually or by machine strength grading. Visual grading of structural timber from the Nordic countries is performed according to INSTA142 (Standard Norge 2009c), and the highest grade is assigned to strength class C30 (Standard Norge 2012a). In order to obtain higher strength classes, timber has to be graded by machine. A common method is based on dynamic modulus of elasticity (E_{dyn}) measured on axial vibration of the boards (Equation 1), where ρ is the mass density, L is the board length and f is the first mode resonance frequency.

$$E_{dyn} = \rho(2Lf)^2 \quad \text{(Equation 1)}$$

Dynagrade, the most common machine for strength grading in Norway, tests timber according to this principle but without measuring mass density. Dynagrade measures the resonance frequencies originating from a strike by a metal hammer to the end of the board (Boström 1997). Together with the length, which is measured by laser, the machine calculates a so-called indicating property (Dyn-IP, Equation 2), as defined in EN14081-2 (Standard Norge 2012c).

$$\text{Dyn-IP} = (2Lf)^2 \qquad \text{(Equation 2)}$$

This IP value is correlated with the strength of the boards with an R^2 value of about 0.5 for Norway spruce (Hoffmeyer 1995; Larsson et al. 1998; Hanhijärvi et al. 2005; Hanhijärvi and Ranta-Maunus 2008; Olsson et al. 2012; Ranta-Maunus 2012). This is an efficient way to grade timber. However, such grading machines are known to be inaccurate when it comes to predicting density (Ranta-Maunus 2012, Lukacevic et al. 2015).

Strength grading is adjusted to geographical region, and the current setting values used for Dynagrade in Norway are common to the Nordic and the Baltic countries (Standard Norge 2009b). Ranta-Maunus (2009) showed that it is reasonable to use different machine settings for Central and Northern Europe due to raw material differences between these regions. However, it was also shown that the variability of timber is much larger than expected. The definition of growth area in European standards is based only on differences between countries. However, it has been shown that the variability of timber properties within a country can be as large as the variation across countries in Europe (Ranta-Maunus 2009, Hautamäki 2013). Further, the incoming timber to a sawmill also shows great variability (Ranta-Maunus and Turk 2010, Ranta-Maunus et al. 2011), making systematical deviances after grading probable; conservative grading is therefore necessary in order to meet the minimum requirements in all subsamples. This leads to poor utilization of the timber properties, compared to a system that is able to grade samples from different regions with the same level of accuracy.

European strength grading standards are based on a proposal by Rouger (1997). Even though many weaknesses of the current strength grading system have been found (Stapel and van de Kuilen 2013) and new methods have been suggested (Sandomeer et al. 2008; Ziethen and Bengtsson 2009; Ranta-Maunus and Turk 2010), none of the newer methods have been implemented yet. Recent studies (Ranta-Maunus et al. 2011; Ranta-Maunus 2012; Lukacevic et al. 2015) suggest using combined IP values, and this approach is already implemented in more accurate machines, i.e. GoldenEye from Microtec. Lukacevic et al. (2015) showed that strength grading done on the basis of a single factor, such as MOE, density or knottiness, gives no reliable prediction of bending strength, while a combination of single IP values achieves better correlations. When two grade-determining properties are poorly correlated, the grading result can be improved by using several indicating properties. Ranta-Maunus (2012) suggested using one IP value for MOE and MOR and another for density. Since a frequency-based IP is poorly correlated with density, density could be used as a separate IP value to obtain more accurate grading. The results of Ranta-Maunus (2012) indicate that the growth area, where the same settings can be used, could be wider when using two separate IP values.

Even though the bending properties are correlated with density, they also depend on other physical wood properties and on defects, of which knots and fibre deviations are the most important. The relative importance of density and knot size is different for MOE and MOR; while knot size has a stronger effect on MOR than on MOE, density is better correlated with MOE than with MOR (Ranta-Maunus 2009; Vestøl et al. 2012). Vestøl et al. (2012) and Høibø et al. (2014) have shown that the variance structures of density and bending properties vary in Norway spruce, and that their relationship depends on the origin of the timber. One important difference is the longitudinal variation within trees. While knot size increases with vertical position in the lower part of the stem (Colin and Houllier 1991; Mäkinen and Colin 1998), the longitudinal variation of density is not consistent (Tamminen 1964; Hakkila 1966; Atmer and

Thörnqvist 1982; Olesen 1982; Kuçera 1994; Repola 2006). This results in a different relationship between density and bending properties depending on whether the timber comes from a butt log or from an upper log (Vestøl et al. 2012.).

Both density and knot size are correlated with annual ring width, but there is an additional effect of climate on density (Ericsson 1960; Wilhelmsson et al. 2002). Variations in annual ring width within a stand are related to stand density, local variations in growth conditions and competition between the trees. Høibø (1991) found that both density and knot size are correlated with relative tree size in a stand, but the effect was larger on knot size. The effect of climate on the relationship between annual ring width and density is described by Ericson (1960) and Wilhelmsson et al. (2002). Temperature is often a limiting factor for spruce grown in Norway, and density is therefore related to altitude and latitude. Klem (1965) found dry density in spruce from western Norway to be correlated with altitude and site index, but not with latitude. Høibø (1991) found higher density in Norway spruce than Nagoda (1985) found in Norway spruce from Northern Norway when the annual ring width was the same.

Due to the long fibres and relatively small knots in Norway spruce grown in Norway, the ratios of strength to density and stiffness to density are relatively high. This is an advantage in many situations, but it may be a challenge to fulfil the density requirements in EN338 (Standard Norge 2009a) without underestimating the strength and stiffness of the timber (Chrestin 2000). The indicating property of Dynagrade favours timber with a high ratio of MOE to density, and the grading result may depend on the origin of the timber since the properties have different variance structures. Høibø et al. (2014) showed in a study of Norway spruce that the relationships between bending properties and indicating property from Dynagrade were different for timber from three sites with different site index. While the indicating property from Dynagrade explained mainly variance between trees, the difference between the sites was explained by density (Høibø et al. 2014). However, the study used samples from a limited area with small variation in altitude and latitude, and a material with a larger geographical variation is therefore required to include climatic effects on density and thereby the bending properties. The first aim of this study is to estimate site effects in machine grading of Norwegian spruce timber and to test whether the site effects are related to the origin of the timber. The second aim is to test whether the site effects can be explained by mass density, and to simulate the potential improvement of grade yield and characteristic properties by using mass density as a second indicating property in addition to the indicating property from Dynagrade.

2 Materials and methods

2.1 Material

The dataset comprises 1188 specimens of Norway spruce (Picea abies) from 14 sites located in Southern Norway, Eastern Norway and Trøndelag. Obtaining samples that reflect a wide range of latitude, altitude and site index values, representing the growing conditions for spruce in Norway, was a goal when choosing the material.

Geographical data and forest inventory data that were used in the statistical analysis are altitude (Alt), latitude (Lat), and site index (SI) (Table 1). Site index, defined as dominant height at age 40 (Tveite 1977), was calculated from age at breast height and the height of the three largest trees sampled from each site.

Table 1 Geographical data and site index

Site	Latitude (°N)	Longitude (°E)	Altitude (m)	Site index (m)	Mean age (years)
1	58.2889	8.1957	170	14	106
2	58.5288	8.4627	210	20	58
3	59.6401	10.4487	150	26	42
4	59.8567	10.3284	380	17	63
5	60.0383	9.1125	700	11	132
6	60.2555	8.9446	800	11	109
7	60.5320	11.3701	370	20	48
8	60.6372	9.7993	544	11	91
9	60.6618	10.8852	220	20	94
10	61.0632	9.5403	845	14	71
11	61.3102	10.2391	630	14	106
12	62.7471	9.9898	470	14	110
13	63.3521	10.2455	150	17	104
14	63.6511	10.9141	100	14	101

2.2 Methods

The methodology of this study follows Vestøl et al. (2012) and Høibø et al. (2014), and the material is the same as used by Fischer et al. (2015). At each site, diameter at breast height was recorded for all trees within a selected area, and trees with breast height diameter larger than 20 cm were classified into five diameter classes with an equal number of trees in each class. Three trees were randomly selected from each diameter class, giving a representative sample of the diameter distribution among trees with DBH larger than 20 cm.

The timber was processed into boards that were dried in industrial kilns and graded with a Dynagrade strength grading machine at three different sawmills. The three sawmills had different drying schedules, and the mean moisture content of the timber at the time of grading was 14%, 16% and 19%, respectively. The indicating property from Dynagrade (Dyn-IP; Eq. 2) was recorded for each board, and the values were adjusted to 12% moisture content according to EN14081-4 (Standard Norge 2009b). E_{dyn} (Eq. 1) was used to estimate indicating property of Precigrader, and it was calculated by multiplying Dyn-IP with mass density, calculated from the average cross section of a sample of boards of each dimension from each sawmill, timber length and the weight. E_{dyn} was adjusted to 12% moisture according to ITT/78/12/04 (CEN 2012). Mass density was also used as a separate indicating property (Den-IP), calculated as the ratio of weight to measured volume of each single board. It was adjusted to 12% moisture content according to EN384 (Standard Norge 2010a). Grade yield for each site was estimated using setting values for single grade C24, C30 and C35 according to EN14081-4 (Standard Norge 2009b). The setting values were $4.30 \cdot 10^6$ for C24, $6.48 \cdot 10^6$ for C30 and $7.78 \cdot 10^6$ for C35 when using Dynagrade, and 8780 for C24, 11180 for C30 and 13250 for C35 when simulating Precigrader. Grade yields for timber from each site are presented in Table 2.

The boards were conditioned at 20 °C and 65% relative humidity before testing. Global MOE and MOR were measured in four-point bending according to the requirements in EN408 (Standard Norge 2012b). The part of each board with the most and the largest knots was chosen for testing, and the boards were shortened to 20 times nominal cross-sectional board height before testing. Density and moisture content were determined from clear specimens of complete cross sections taken close to the failure point. The moisture content at the time of testing varied from 8.9% to 16.2%, with an average of 13.6%. According to EN384 (Standard Norge 2010a), density was adjusted by 0.5% for each percentage point deviation from 12% moisture content and MOE was adjusted by 1% for each percentage point deviation from 12% moisture content. MOR was adjusted for board height according to EN384 (Standard Norge 2010a). All adjustments were made on single observations.

Table 2 Site-specific grade yield for machine strength grading by IP-Dyn and E_{dyn}

Site	N	IP-Dyn			E_{dyn}		
		C24	C30	C35	C24	C30	C35
1	92	92	74	21	92	92	90
2	101	101	60	6	101	95	52
3	103	103	40	2	103	81	24
4	87	87	45	2	87	83	38
5	93	93	60	7	93	85	64
6	52	52	26	-	52	51	21
7	45	45	36	1	45	40	27
8	63	63	40	3	63	58	40
9	119	119	113	51	119	119	112
10	49	48	17	-	48	22	7
11	111	111	69	6	111	103	52
12	76	76	60	11	76	75	54
13	112	112	87	8	112	103	83
14	85	85	80	19	85	85	78

2.3 Statistical analysis

Density, MOE and MOR were analysed in linear mixed models where the random variance was divided into site-, tree-, and residual variance:

$$Y = \mu + f(A, B, \dots) + S_i + T_j(S_i) + e \qquad \text{(Equation 3)}$$

Y represents density (ρ_{12}), MOE_{12} or MOR_{150}, and $f(A, B, \dots)$ represents the fixed effects. S_i (i=1-14) represents the site variance, T_j (j=1-205) represents the tree variance, and e represents the residual variance. The random effects were assumed to be normally distributed with a mean of zero and variances of σ_S^2, σ_T^2, and σ_e^2, respectively.

Initially, models with indicating property from each grading machine as the only fixed effects were estimated, and the random effect of site was tested by a likelihood ratio test. To allow easier computing the Dyn-IP was divided by 10^{-6} before estimating the models. In cases of significant variances due to site, geographical data and site index were added to the covariate model in order to explain some of the site variations. Also models combining Dyn-IP with Den-IP values were estimated, and the random effects of site were tested with likelihood ratio tests.

The linear mixed models were calculated using the restricted maximum likelihood method (REML) in JMP software (version 11.0; SAS Institute Inc., Cary, North Carolina) following Littell (2006). Fixed-effects variables were included in the models if the probability of a type I error was smaller than 0.05.

3 Results and discussion

3.1 Properties of strength-graded timber

Mean values, standard deviations and fifth percentiles of density and bending properties for different strength grades are presented in Table 3. Altogether, the material fulfilled the minimum requirements for the strength classes, both when graded by Dynagrade (Dyn-IP) and when simulating grading by Precigrader (E_{dyn}).

Table 3 Mean values, standard deviations and fifth percentiles of density and bending properties for different strength grades of EN338 (Standard Norge 2009a)

	Grade	N	ρ_{12} (kg m^{-3})			MOE_{12} (kN mm^{-2})			MOR_{150} (N mm^{-2})		
			mean	*s*	$\rho_{0.5}$	mean	*s*	$E_{0.5}$	mean	*s*	$f_{0.5}$
Dyn-IP	C24	1187	450	43	379	12.7	2.6	8.3	46.0	10.9	27.7
	C30	807	459	40	397	13.7	2.2	10.3	49.6	9.6	34.6
	C35	137	478	39	408	15.8	2.2	12.0	57.7	9.4	41.7
E_{dyn}	C24	1187	450	43	379	12.7	2.6	8.3	46.0	10.9	27.7
	C30	1092	455	40	391	13.0	2.3	9.4	47.3	10.2	30.2
	C35	742	469	35	419	14.0	2.0	11.1	50.6	9.3	35.7

3.2 Models based on indicating property from Dynagrade (Dyn-IP)

Dyn-IP reduced the variance of density with only 5%, and RMSE was 42 kg m^{-3} (Table 4; Model 1a). A likelihood ratio test showed that the random effect of site was significant ($p<0.0001$), and it constituted 26.8% of the variance not explained by Dyn-IP. There were significantly negative effects of site index ($F=36.52$, $p=0.0001$), altitude ($F=35.03$, $p=0.0001$) and latitude ($F=10.33$, $p=0.0093$) to the model. Model 1b (Table 4), which includes these covariates in addition to Dyn-IP ($F=6.99$, $p<0.0083$), reduced the random variance with 28%, and RMSE was 37 kg m^{-3}. As compared to Model 1a, the random variance due to sites was reduced with 86.1%. It constituted only 4.9% of the unexplained variance in Model 1b, and it was not significant ($p=0.1617$).

Dyn-IP reduced the variance of MOE_{12} with 49%, and RMSE was 1.9 kN mm^{-2} (Table 4, Model 5a). A likelihood ratio test showed that the random effect of site was significant ($p<0.0001$), and it constituted 22.5 % of the variance not explained by Dyn-IP. There were significantly negative additional effects of site index ($F=535.02$; $p<0.0001$) and altitude ($F=31.63$; $p=0.0001$) (Table 4, Model 5b), while the additional effect of latitude was not significant ($p=0.0524$). Model 5b reduced the variance with 59%, and RMSE was 1.7 kN mm^{-2}. As compared to model 5a, the random variance due to site was reduced with 89.9 %. It constituted only 2.8% of the variance not explained by the covariates in Model 5b, and it was not significant ($p=0.4572$).

Dyn-IP reduced the random variance of MOR_{150} with 39%, and RMSE was 8.6 N mm^{-2} (Table 4, Model 9a). A likelihood ratio test showed that the random effect of site was significant ($p=0.0016$), but it constituted only 4.4% of the variance not explained by Dyn-IP. There were significantly negative additional effects of site index ($F=24.50$, $p<0.0001$) and altitude ($F=11.88$, $p=0.0007$) compared to Model 9a (Table 4, Model 9b), while the additional effect of latitude was not significant ($F=1.12$; $p=0.2922$). Model 9b includes site index, altitude and Dyn-IP as covariates. It reduced the variance with 41%, and RMSE was 8.4 N mm^{-2} (Table 4). The estimated variance due to site was negative and therefore removed before estimating the model.

3.3 Models based on dynamic MOE (E_{dyn})

E_{dyn} explained 45% of the variance in density, and RMSE was 32 kg m^{-3} (Table 4; Model 3a). The likelihood ratio test showed that the random effect of site was significant ($p<0.0001$), and it constituted 17.5% of the variance not explained by E_{dyn}. There were significantly negative additional effects of site index ($F=32.85$, $p=0.0002$), altitude ($F=21.24$, $p=0.0006$) and latitude ($F=7.10$, $p=0.0239$) to the model. Model 3b, which includes these covariates in addition to E_{dyn} ($F=283.49$; $p<0.0001$), reduced the random variance with 53%, and RMSE was 29 kg m^{-3} (Table 4). As compared to Model 3a, the variance due to site was reduced with 82.9%. It constituted 3.5% of the variance not explained by the fixed effects in Model 3b, and it was not significant ($p=0.2360$).

E_{dyn} reduced the MOE_{12} variance with 69%, and RMSE was 1.4 kN mm^{-2} (Table 4; Model 7a). The random effect of site was significant ($p<0.0001$), and it constituted 17.5% of the variance not explained by E_{dyn}. There were significantly negative additional effects of site index

(F=13.21, p=0.0042) and altitude (F=23.71; p=0.0004) to the model, while the additional effect of latitude was not significant (F=3.47; p=0.0932). Model 7b, including site index, altitude and E_{dyn} (F=1120.02; p<0.0001) as covariates, reduced the variance with 73%, and RMSE was 1.4 kN mm^{-2} (Table 4). As compared to Model 7a, the variance due to site was reduced with 71.1%. It constituted 5.7% of the variance not explained by the fixed effects in Model 7b, and it was significant (p=0.0108).

E_{dyn} reduced the variance of MOR_{150} with 45%, and RMSE was 8.1 N mm^{-2} (Table 4; Model 11a). The variance due to site constituted only 1.8% of the variance not explained by the fixed effects in the model, but it was still significant (p=0.0382). There was a significantly positive additional effect of latitude (F=20.09, p<0.0001) to Model 11a (Table 4, Model 11b). Model 11b, including latitude and E_{dyn} as covariates, reduced the variance with 47%, and RMSE was 8.40 N mm^{-2} (Table 4). The estimated variance due to site was negative and therefore removed before estimating the model.

3.4 Models based on mass density (Den-IP) and indicating property from Dynagrade (Dyn-IP)

Den-IP reduced the variance of density with 73%, and RMSE was 22 kg m^{-3} (Table 4; Model 4). The random effect of site constituted 4.5% of the variance not explained by Den-IP, and the likelihood ratio test showed that it was significant (p<0.0001). A model combining Dyn-IP (F=32.74; p<0.0001) and Den-IP (F=1641.78; p<0.0001) as covariates reduced the variance with 74%, and the RMSE was 22 kg m^{-3} (Table 4; Model 2). Even though the variance due to site constituted only 4.7%, it was still significant (p<0.0001). As compared to Model 1a with Dyn-IP as the only covariate, Model 2 reduced the variance due to site with 95.2%.

A model with Dyn-IP and Den-IP as covariates reduced the MOE_{12} variance with 76%, and RMSE was 1.3 kN mm^{-2} (Table 4; Model 6). As compared to Model 5a (Table 4) with Dyn-IP as the only covariate, the variance due to site was reduced with 95.1%, and it was not significant (p=0.0954) anymore. A corresponding result was found for MOR_{150}. A model combining Dyn-IP and Den-IP as covariates reduced the MOR_{150}-variance with 47%, and RMSE was 7.9 N mm^{-2} (Table 4; Model 10). As compared to Model 9a (Table 4) with Dyn-IP as the only covariate, the variance due to site was reduced with 90.9%, and it was not significant (p=0.4221) anymore.

Table 4 Models for density, modulus of elasticity, and bending strength

Y	Model	Fixed effects	R^2	RMSE	Variance components		
					σ_S^2	σ_T^2	σ_e^2
ρ_{12}	1a	424.571 + 3.853Dyn	0.05	42	475 (26.8%)	723 (40.7%)	576 (32.5%)
	1b	952.807 + 3.903Dyn-IP - 5.805SI – 0.095Alt – 6.537Lat	0.28	37	66 (4.9%)	722 (52.9%)	576 (42.2%)
	2	34.755 + 5.649Dyn-IP + 0.829Den-IP	0.74	22	23 (4.7%)	32 (6.7%)	422 (88.6%)
	3a	313.075 + 11.945E_{dyn}	0.45	32	181 (17.5%)	322 (31.2%)	529 (51.3%)
	3b	632.122 + 11.580E_{dyn} - 3.905SI – 0.053Alt – 3.801Lat	0.53	29	31 (3.5%)	329 (37.0%)	528 (59.5%)
	4	65.309 + 0.846Den-IP	0.73	22	22 (4.5%)	41 (8.3%)	429 (87.2%)
MOE_{12}	5a	0.938 + 1.721Dyn-IP	0.49	1.9	0.81 (22.5%)	1.23 (34.3%)	1.55 (43.2%)
	5b	5.931 + 1.708Dyn-IP – 0.200SI – 0.004Alt	0.59	1.7	0.08 (2.8%)	1.24 (43.3%)	1.54 (53.9%)
	6	-12.952 + 1.783Dyn-IP +0.030Den-IP	0.76	1.3	0.04 (2.6%)	0.32 (18.9%)	1.34 (78.5%)
	7a	-0.071 + 1.104E_{dyn}	0.69	1.4	0.38 (17.5%)	0.37 (17.1%)	1.43 (65.4%)
	7b	3.243 + 1.077E_{dyn} – 0.118SI – 0.003Alt	0.73	1.4	0.11 (5.7%)	0.39 (20.4%)	1.43 (73.9%)
MOR_{150}	9a	-4.969+7.516 Dyn-IP	0.39	8.6	3.3 (4.4%)	16.9 (22.7%)	54.2 (72.9%)
	9b	7.077 + 7.474Dyn-IP – 0.560SI - 0.007Alt	0.41	8.4	-	17.0 (23.9%)	54.1 (76.1%)
	10	-37.834 + 7.168Dyn-IP + 0.077Den-IP	0.47	7.9	0.3 (0.4%)	10.5 (16.6%)	52.8 (83.0%)
	11a	0.385 + 3.979E_{dyn}	0.45	8.1	1.8 (2.7%)	9.8 (14.8%)	54.7 (82.5%)
	11b	-53.922 + 4.004E_{dyn} + 0.889Lat	0.47	8.0	-	9.6 (14.9%)	54.7 (85.1%)

3.5 Simulated grade yield and characteristic values

Characteristic values and grade yield were calculated for different combinations of exclusion by Dyn-IP and Den-IP (Figures 1 a-d). The exclusion rates were increased in steps of 10 percentage points from 0% to 50% for both indicating properties. In cases where some of the boards were excluded by both Dyn-IP and Den-IP, the total exclusion rate was smaller than the sum of the two exclusion rates. Figure 1a) shows that this effect is negligible when both exclusion rates are 10% or smaller. When the exclusion rates increase, more boards are excluded by both indicating properties, and the yield is highest for similar exclusion rates based on Den-IP and Dyn-IP. The simulations show that while Den-IP has a stronger effect than Dyn-IP on characteristic density (Figure 1b), the result is the opposite for characteristic MOR_{150} (Figure 1d). When it comes to characteristic MOE_{12}, the effects of exclusion by Dyn-IP and Den-IP are similar, even though the effect of Dyn-IP is slightly stronger on higher exclusion rates (Figure 1c).

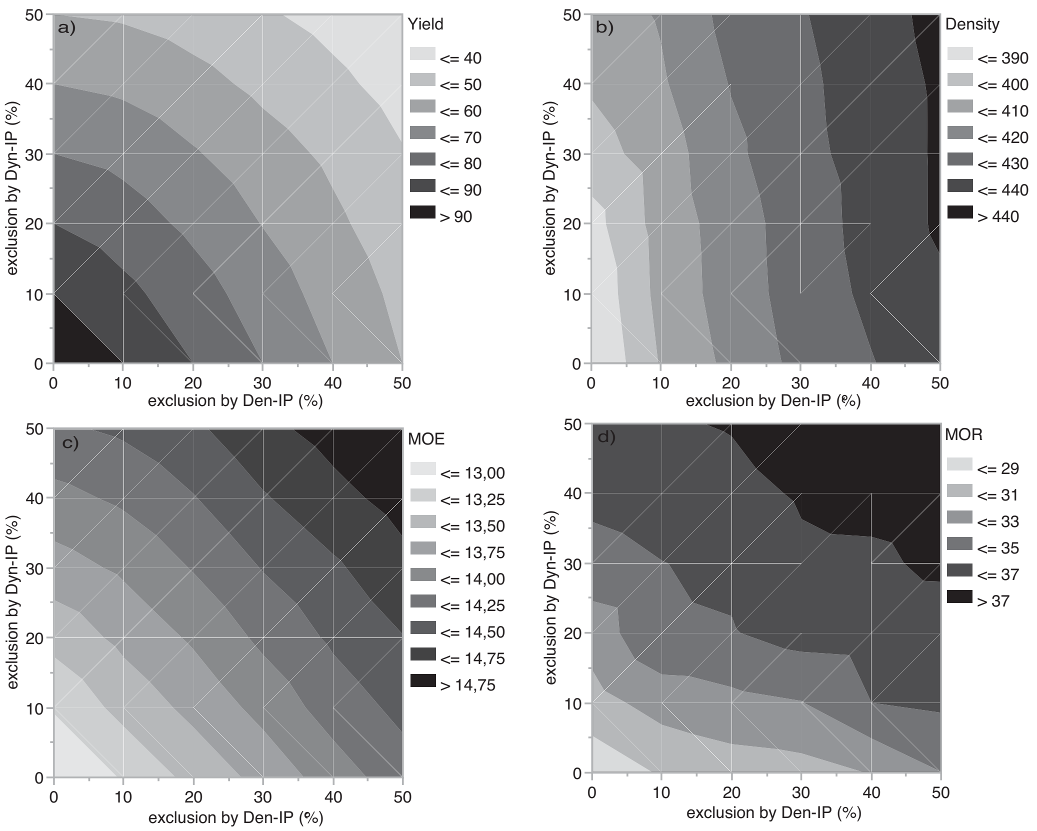

Fig. 1 Yield and characteristic properties of timber for different exclusion rates based on Dyn-IP and/or Den-IP: Yield a), density b), MOE_{12} c), and MOR_{150} d)

3.6 Discussion

Unexplained variances due to site after grading is critical since it may lead to systematical deviance from the correct value of the properties for subsamples of timber coming from a particular area. If there are still large site effects after grading, grading has to be conservative in order to meet the requirements, and the properties of the timber resource is not efficiently utilized. The models show that gradings based on Dyn-IP and on E_{dyn} both leave significant variances due to site (Table 4), and for all properties the unexplained variance due to site was larger for the models based on Dyn-IP. Grading based on Dyn-IP favours timber with a high ratio of MOE to density, and this ratio is influenced by the effect of knot size on MOE. Density and knot size have different variance structures (Vestøl et al. 2012; Høibø et al. 2014). Density depends more on site, and Dyn-IP mainly explains variance within site and less of the variance between sites. Further, knot diameter has a larger effect on MOR than on MOE (Hanhijärvi et al. 2005), and it is more influenced by silviculture than by climate, leading to more variation between trees within site than between sites for MOR (Høibø 1991; Vestøl et al. 2012). The results show that unexplained variance due to site constitutes a smaller proportion of the unexplained MOR variance than it does for the other properties (Table 4). The absolute values are not directly comparable across properties, but the estimated standard deviations due to site were compared with the difference in required characteristic values of strength class C24 and C30 (Standard Norge 2010a). The standard deviation due to site was 72.6% of the difference between the two strength classes for density, 90.0% for MOE, and 30.3% for MOR.

The results show that grading can be more reliable when it is based on E_{dyn} than when it is based on Dyn-IP. E_{dyn} includes a density measurement, and the correlations with density and with MOE and MOR are higher. The differences in r-squares between the models based on Dyn-IP and those based on E_{dyn} are comparable to what Ranta-Maunus et al. (2011) found. The models based on E_{dyn} also left smaller unexplained variances due to site than the models based on Dyn-IP (Table 4). As compared to the required characteristic values of strength class C24 and C30, the standard deviation due to site was 44.8% of the difference between the two strength classes for density, 61.6% for MOE, and 22.4% for MOR.

For both machine types, major parts of the variance due to sites were related to site index, altitude, and/or latitude. The models should only be used to predict trends inside the study area, and not for single stands, since variation between stands are expected due to differences in silviculture, which is not taken into account in the models. For the same indicating property the models predict that timber from lower site index at lower altitudes will have the highest values for timber properties. Even when corrected for expected lower site index with increasing altitude, the models predict a net negative effect of altitude. Altitude is mainly representing a climatic effect, and it influences the relation between density and annual ring width, as earlier described by Wilhelmsson et al. (2002). For the models based on Dyn-IP, the additional effects of site index and altitude were significant for both density and bending properties, while the effect of latitude was only significant for density. Besides density, knots and fibre deviation are the wood properties that most significantly influence bending properties (Johansson 2003). This results in a greater residual variance for bending properties, which may explain why the effect of latitude was significant only for density and not for the bending properties. The additional effect of site index on the relationships between Dyn-IP and the bending properties was also found by Høibø et al. (2014).

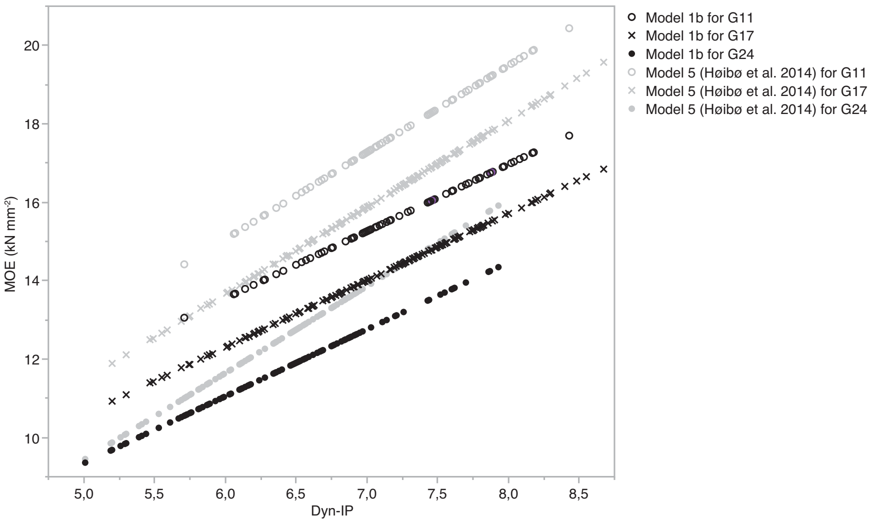

Fig. 2 Site effects on the relationship between indicating property value from Dynagrade (Dyn-IP) and modulus of elasticity (MOE) described by Model 1b on the data-set of Høibø et al. 2014 and compared to Model 5 from Høibø et al. 2014

Testing model 1b and 5b (Figure 5 and 6) on the dataset used by Høibø et al. (2014) showed that the models give the same prediction trends, but in general the models from this study predict lower values for both MOE and MOR, and the estimated differences between the sites are smaller than the differences Høibø et al. (2014) found between the three sites in Østfold county.

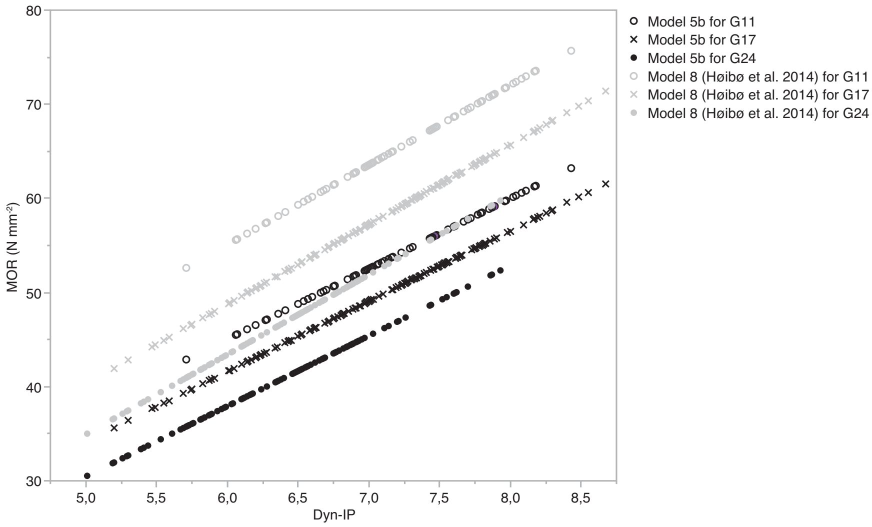

Fig. 3 Site effects on the relationship between indicating property value from Dynagrade (Dyn-IP) and bending strength (MOR) described by Model 5b on the data-set of Høibø et al. 2014 and compared to Model 8 from Høibø et al. 2014

This is natural, since the study by Høibø et al. (2014) included some very old stands where the timber had extraordinarily high density, and density is not accurately predicted by the indicating property of Dynagrade. The difference was smaller for the youngest stand at high site index where the wood density was lower. The differences between the three sites are more pronounced for timber yielding higher strength classes, especially for MOE and timber from higher site index.

Ranta-Maunus (2012) showed that using mass density as a separate indicating property for density improves the results of machine strength grading based on E_{dyn}. This was also found in our study, where density had a much higher correlation with Den-IP than with E_{dyn} (Table 4; Model 4 vs. Model 3a). Høibø et al. (2014) found that differences between sites in the relationship between bending properties and Dyn-IP could be explained by wood density. This is in accordance with our study, where models including mass density as a second covariate explained substantial parts of the variance due to site on density (Model 2), MOE (Model 6a) and MOR (Model 10a) not explained by only using Dyn-IP (Models 1a, 5a, 9a) or E_{dyn} (Models 3a, 7a, 11a). This also corresponds to the results of Hautamäki et al. (2013), who found that regional differences of MOR in Finland and Russia corresponded to differences in wood density. Wilhelmson et al. (2002) showed that the density of spruce in Sweden decreases with altitude and latitude, and that the relationship between density and annual ring width decreases with temperature sum. This means that some of the additional effects of site can be explained by density, and that grading systems that include density recording should be less dependent on the origin of the timber.

The simulations of characteristic properties showed that Dyn-IP and mass density explained different parts of the variability, and that the requirements can be fulfilled with higher yield if the exclusion is based on a combination of Dyn-IP and mass density. This corresponds to Ranta-Maunus (2012), who proposed using mass density as a separate indicating property. The present study also shows that mass density can be used to reduce the site-effects on the bending properties. When models based on E_{dyn} as the only covariate (Models 7a, 11a) were compared with the corresponding models based on Dyn-IP and mass density together (Models 6a, 10a), the latter left smaller MOE variance due to site, while the MOR variances due to site were similar for the two models.

4 Conclusion

The study has shown that strength grading of spruce timber from Norway based on Dyn-IP or E_{dyn} leaves out significant effects of site that are related to altitude, latitude and site index. The site effects are larger for grading based on Dyn-IP than on E_{dyn}, and they are also larger for density and MOE than for MOR. Mass density explains substantial parts of the variance due to site, and by using it as a second indicating property together with Dynagrade IP value it is possible to fulfil the requirements of the strength classes with a smaller exclusion rate than if only one indicating property is used.

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