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

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Draft

Abstract

Density, modulus of elasticity (MOE) and bending strength (MOR) are important properties of structural timber, and knowledge about the variability of these properties is important to make efficient use of the timber. In order to utilize such information in the production of structural timber, the information must be available before sawing. This study presents models describing the variability of density and bending properties of Norway spruce boards within individual trees, as well as 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 in Southern Norway, Eastern Norway and Trøndelag. Important variables describing variation in density, MOE and MOR between sites were site index and elevation. For density, latitude gave additional information. Age, DBH and longitudinal position within the tree were the most important variables at the tree level. The models explained major parts of the site variance of all properties, and for MOR they explained a substantial part of the variance due to trees. In addition to 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

1 Introduction

2 For species in Europe, density, modulus of elasticity (MOE) and bending strength (MOR) vary
3 significantly both between regions (Ranta-Maunus 2009) and within regions (Foslie 1985, Foslie
4 and Moen 1968, Lackner and Foslie 1988, Nagoda 1985, Hautamäki et al. 2013, Moore et al.
5 2013, Gardiner et al. 2011). The large variation found between sites, between trees within sites
6 and within single trees (Zobel and van Buijtenen 1989, Vestøl et al. 2012, Høibø et al. 2014)
7 makes individual strength grading of each single board crucial for achieving effective use of
8 timber as a structural material.

9
10 Today most sawmills use machine strength grading, which is more accurate than visual grading.
11 This has led to greater yields of higher grades, thus increasing the competitiveness of timber as a
12 structural material (Ranta-Maunus 2009). However, most of the strength grading machines used
13 account for only a relatively small part of the total variation. Methods for improved sorting and
14 grading are therefore needed. Predictions of properties based on forest inventory data might be
15 used together with data from strength grading machines to make timber grading more accurate
16 (Stapel and van de Kuilen 2013, Høibø et al. 2014, Lukacevic et al. 2015) and grade yield higher.
17 Incorporating information on the variation between and within trees also makes more optimal
18 crosscutting possible (Høibø et al. 2014).

19
20 Wood density is itself an important timber property (Standard Norge 2009), but it is also widely
21 used as an indicator of timber qualities due to its positive correlations with most mechanical
22 properties. For Norway spruce (*Picea abies* L. Karst), density is negatively correlated with
23 growth rate (Persson 1975), leading to lower density for more dominant trees (Pape 1999). On

the other hand, density has been found to be positively correlated with temperature sum (Wilhelmsson 2001), which fits well with Høibø (1991), who 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 from 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 then 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% of the stem height, 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 that greatly influences timber strength (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 for density, MOE and MOR (Standard Norge 2009), deep knowledge about the relationships between the properties is important for the design of economic and reliable timber structures (Steiger and Arnold 2009). Høibø et al. (2014) found that detailed tree- and log-level information can be used to improve grading accuracy. The relationship between density and bending properties varies considerably among trees, stands and regions, but the importance of these properties also varies 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 elevation on density, leading to a negative effect on MOE. The corresponding effects on MOR may be smaller, given that MOR has been found to be less affected by wood density and more by knot diameter (Vestøl et al. 2012). As described above, 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 but counteracts the effect of knot size on more fertile sites. The total effect of longitudinal position can therefore be expected to be different for MOE and MOR, and 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 tree and stand characteristics that best predicted the bending stiffness of naturally grown black spruce were 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, wood density and knot area ratio, while for MOE, density was the best single predictor, followed by ring width and number of annual rings.

Models describing the properties of structural Norway spruce sawn timber from Norway have so far been limited to certain regions, and they do not represent the wide range of elevations and latitudes at 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 areas for sawmills in Norway. The models should also provide a better understanding of how silviculture affects the properties of structural timber from different regions.

1 **Material and methods**

2 The study was based on timber from 17 sites in Southern Norway, Eastern Norway, and
3 Trøndelag (Figure 1). The sites numbered 1–14 have been described by Vestøl et al. (2016), and
4 sites 15, 16 and 17 were used in an earlier study published by Høibø et al. (2014). The material
5 reflects large variations in latitude, elevation and site index, and represents the growing
6 conditions for spruce in Norway. The sites were randomly divided into 11 modelling sites and
7 six validation sites. The site-level data were elevation (Elev in m.a.s.), latitude (Lat), basal area
8 (BA in m² ha⁻¹) and site index (SI in m). Site index, defined as dominant height at age 40 (Tveite
9 1977), was calculated from age at breast height and the height of the three largest trees sampled
10 from each site. For sites 15, 16 and 17, the site indices were obtained from forest inventory plans
11 and checked for height and age at stump height for the three largest trees sampled, taking the
12 estimated number of years from butt end to breast height into account. The site-level and forest
13 inventory data for each site is presented in Table 1.

14
15 At each site, diameter at breast height (DBH in mm) was recorded for all trees within a selected
16 area. Trees with a DBH larger than 20 cm were classified into five diameter classes with an equal
17 number of trees in each class. Three trees were randomly selected from each diameter class in
18 order to obtain a representative sample for the trees with a DBH greater than 20 cm.

19
20 The tree variables measured were DBH, age at stump height (Age in years), tree height (H in
21 dm), height to the whorl where live branches covered half of the circumference (KH₁₈₀ in dm)
22 and height to the whorl where live branches covered the whole circumference (KH₃₆₀ in dm).
23 Other tree-level variables that were calculated from these were DBH/Age (mm), H/DBH (dm

mm⁻¹) and relative DBH (DBH_{rel}). The latter was defined as the ratio of individual tree DBH to mean DBH of the site. All variables are presented in Table 2, and correlations are presented in Table 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 set to 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 were conditioned in a climate with 65% RH and 20 °C for at least five weeks to a stable moisture content 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). The critical section, i.e. the position at which failure was expected, was located. The boards were shortened to 20 times the nominal height (nominal board width is 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 longitudinal range within 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 15, 16 and 17 were, depending on which log they had been taken from, located systematically within the log, 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.

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 used 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.

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:

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

Y represents density (ρ_{12}), MOE_{12} or MOR_{12} , μ represents the mean in variance component analyses or intercept in covariate models, 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, describing the within-tree 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.

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. The 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 et al. (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

1 Density model

2 The density model (Model 1, Table 5) describes negative effects of elevation, latitude and site
3 index on density. These variables describe differences among the sites only. However, the model
4 also includes a negative effect of DBH and a positive effect of age, describing both variances due
5 to sites and variances due to trees within the site. The effect of longitudinal position varied from
6 a steep increase to a steep decrease (line b and c, Figure 2), but for an average tree from and
7 average stand the model describes a negligible vertical increase in density (line a, Figure 2). The
8 differences in longitudinal variation are described by positive interactions between longitudinal
9 position (LP_{rel}) and site index, elevation and DBH, respectively, and a negative interaction with
10 crown height (KH_{180}). The effect of KH_{180} alone was not significant; we have nevertheless
11 chosen to include this lower-level variable in the model. The interactions describe a steeper
12 increase in density with an increased LP_{rel} for higher values of site index, elevation and DBH and
13 lower values of KH_{180} (Table 5). At lower elevations, where the site index range is large, the
14 interactions predict the largest vertical decrease in small trees with high values of KH_{180} from
15 low site indices (line c, Figure 2), while there is a negligible increase for big trees with low
16 KH_{180} . For high site indices at low elevations the model predicts a vertical increase in density for
17 big trees with low KH_{180} but a negligible longitudinal variation for small trees with high KH_{180} .
18 Site index is limited by elevation, but with a high but realistic site index at high elevation the
19 model describes the largest vertical increase in density for trees with low KH_{180} and large DBH
20 (line b, Figure 2). For small trees, the longitudinal variation is negligible. Altogether, the
21 interaction effects describe much larger variation for density in the lower part of the stems than
22 in the upper part (Figure 2) when comparing timber from trees with different values for the
23 variables interacting with LP_{rel} .

The fixed-effects part of the model reduced the total variance by 56.7%, and the RMSE was 34.5 kg m⁻³. Compared to the variance component model (Table 6), the model showed a 93.4% lower variance due to site, 15.4% lower variance due to trees, and a 19.7% lower residual variance. When using the model on the validation data, the predicted values were on average 0.1 kg m⁻³ higher than the observed values. The model reduced total 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, and the largest negative deviation of a site mean was 12.1 kg m⁻³ for site 13. The effect of the interaction between LP_{rel} and KH₁₈₀ 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 larger ($r^2 = 0.462$ vs. 0.489).

MOE model

The model describes a negative main effect of elevation on MOE₁₂ (Model 2, Table 5), while the effect of site index alone was not significant. Like the density model, the MOE₁₂ model includes a negative effect of DBH and a positive effect of age, both describing variance due to trees and variance due to site. The model includes a negative main effect of relative longitudinal position, describing a slight vertical decrease in MOE₁₂ (line a, Figure 3). The effect of longitudinal position depends both on elevation and on site index, and is revealed by its positive interactions with both. The interaction effect with elevation describes a stronger effect of elevation on timber from butt logs than on timber from upper logs. The interaction between longitudinal position and site index reduces the vertical decrease in MOE₁₂ with increasing site index. Since site index is

limited by elevation, the effect of the interaction with site index is limited at high elevations. The model predicts a negligible effect from longitudinal position in trees at a higher elevation when using high but realistic site indices (line b, Figure 3). At lower elevations, where the site index range is larger, the interaction between site index and LP_{rel} predicts a vertical decrease of MOE_{12} , with the strongest effect in trees from low site indices (line c, Figure 3).

The fixed-effects part of the MOE_{12} model reduced the overall variance by 42.1%, and the RMSE was 2.14 kN mm^{-2} (Model 2, Table 5). Compared to the variance component model (Table 6), the model showed 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 were on average 0.49 kN mm^{-2} higher than the observed values. The model was able to account for 42.4% of the variance in the validation material, and the RMSE was 2.24 kN mm^{-2} . The residual of site means was negative for five sites and positive for only one, and the greatest deviance of site means was found for site 13 with -1.66 kN mm^{-2} and for site 3 with -1.09 kN mm^{-2} .

MOR model

The MOR_{12} model (Model 3, Table 5) describes a negative effect of elevation on MOR_{12} , while the effects of latitude and site index were not significant and are therefore not 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 elevation was smaller on MOR_{12} than on MOE_{12} . As for the other models, the MOR_{12} model also includes a negative effect of DBH and a positive effect of age. These variables describe both variance due to trees and variance due to site. The model

also includes a negative effect of 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 elevation for trees with average DBH and Age. There was a significant negative interaction among longitudinal position, site index and DBH, but when checking this three-way interaction effect for possible over-parameterization, the model where the interaction effect was 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.

The fixed-effects part of the model reduced the total variance by 35.2%, and the RMSE was 10.3 N mm^{-2} . 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 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 overall variance in the validation data by 33.9%, and RMSE was 10.4 N mm^{-2} . The residual of site means was negative for four of the six sites and positive for two, and the greatest deviations of site mean were -3.84 N mm^{-2} for site 13 and -7.32 N mm^{-2} for site 3.

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 Côté 1968, Pape 1999 and Wilhelmsson et al. 2002).

The negative effects of elevation 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 found that density increases with temperature sum. They also correspond with results reported by Gindl et al. (2000), who found a positive correlation between within-ring maximum density and temperature in August–September, which shows that the autumn temperature is important for density. A similar result was reported by Høibø (1991), who found higher density for material from the Oslo region (59°N latitude) compared to 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 elevation were significant for both MOE (Model 2, Table 5) and MOR (Model 3, Table 5). The somewhat smaller effect elevation had on MOR compared to MOE is in accordance with the hypothesis stated in the introduction that elevation has a greater effect on MOE than on MOR due to the greater effect of density on MOE compared to MOR (Vestøl et al. 2012). In a study of 14 of the sites Vestøl et al. (2016) 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 fiber deviations are the most important (Johansson 2003). These effects vary more within trees, leading 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, 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 an 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 greater than 20 cm were sampled, the trees from sites with a small average diameter were, on average, more dominant than the 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 with the results of Høibø et al. (2014), who found density to increase with height above ground for the richest site and decrease with height for the poorest site. The extended dataset shows a type of interaction effect of LP_{rel} and DBH on density similar to the one described in Høibø et al. (2014).

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.

Kučera 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, Høibø et al. 2014), the different longitudinal variations in density and knot size result in different longitudinal variations in MOE and MOR.

The effect of elevation 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 elevation and longitudinal position (Model 2, Table 5), which shows that the effect of elevation 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 lower site indices follows the same pattern as the density variation 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 higher site indices, there is a vertical increase in density, which is positive for MOE, while the effect of knot size is the opposite. The contrary effects result in a negligible longitudinal variation in MOE for higher site indices.

MOR is more strongly 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

1 due to a greater effect from knot diameter. In trees from stands with a higher site index, knot
2 diameter varies more in the longitudinal direction (Vestøl and Høibø 2001), and the greatest
3 difference between trees is found in the lower part of the living crown, where the thickest knots
4 are located. The smaller longitudinal variation in knot diameter on trees from lower site indices
5 makes the effect of knot size smaller and the effect of density correspondingly more important.
6
7 Site variance constituted a larger proportion for density than for the bending properties (Table 6).
8 The sites covered a wide geographical area and also a wide range of site indices, while the
9 silvicultural regime was not taken into account when choosing the sites. The sites appeared to
10 have relatively small differences in knot size but larger differences due to density. This may also
11 explain why relatively large proportions of the variance due to site were explained by variables
12 that are independent of silviculture, i.e. site index, latitude and elevation. However, for MOR a
13 relatively large reduction in variance between trees within a stand was achieved, as compared
14 with density and MOE (Table 5). This is probably due to the fact that the effect of knot diameter
15 is greater on MOR than on MOE (Ranta-Maunus 2009, Vestøl et al. 2012) and to a relatively
16 large variation in knot diameter between trees within stands and less variation between stands.
17 DBH within stands is usually well correlated with branch diameter (Loubère et al. 2004) because
18 dominant trees have longer and thicker branches than more suppressed trees (Moberg 2001,
19 Vestøl and Høibø 2001). DBH_{rel} was expected to describe the social position within stands, but it
20 turned out to be less important than DBH. This might in part be due to the sampling effect that
21 followed from only selecting trees with a DBH greater than 20 cm. Density is more important for
22 MOE than for MOR (Vestøl et al. 2012), making variation in wood density between stands more

important for MOE, and in particular for this material, which has a relatively large range in elevation 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 substantially better RMSE than the MOE model presented in our study, while the difference was small for the MOR models.

However, their models exhibited 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 concluded that stem taper is an important variable when modelling MOE, MOR and grade yield.

However, in this study, stem taper (tree slenderness, H/DBH) was correlated with DBH, site index, and elevation (Table 3), and was of minor importance compared to these variables. This is probably related to the wide range of elevations, latitudes and site indices in this material.

In the present study, we included samples from a large range of elevations, latitudes and site indices in order to cover the procurement area for most sawmills in Norway. One limitation of the material is the lack of sites at higher elevations 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 indices 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 silvicultural regime. The models showed small effects of site and tree variables that depend on silvicultural regime, but a much

greater effect of site variables that depend on climate or other growth conditions. This might be due to the small differences in silviculture among the sites.

The models show that the variability of the density and bending properties of Norway spruce structural timber can in part be explained by geographical data and forest inventory data including external tree measurements. The models were tested and showed a good fit for the validation material. It can therefore be concluded that the models give reliable predictions for density, MOE, and MOR within the range of the sampled material. 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 between-tree variance were explained for density and MOE. The models describe both geographical variations and variations due to growth. Elevation, site index and latitude were the most important site variables and DBH and age the most important tree variables. Since the models describe substantial parts of the between-site variance they can be used to select stands with timber that is suitable for higher strength classes. The models also describe some of the variation within sites, and can be used for pre-sorting timber and to some extent to estimate effects of silviculture on timber properties.

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Tables

Table 1. Geographical and forest inventory data.

Site No.	N trees	Lat (N)	Lon (E)	Elev	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

Table 2. Variables used for modelling.

Variables	Abb.	Unit
Site variables		
Site index, dominant height at age 40	SI	m
Elevation	Elev	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 of the circumference	KH ₁₈₀	dm
Height to the whorl where the 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

Table 3. Correlation matrix for tested variables.

	SI	BA	Elev	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
Elev			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

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	18.2	13.5	2.80
MOR ₁₂ (N mm ⁻²)	984	30.3	70.3	49.6	12.2
Density, ρ ₁₂ (kg m ⁻³)	984	389	561	464	52.4
Validation material					
MOE ₁₂ (kN mm ⁻²)	567	8.74	19.0	13.1	2.96
MOR ₁₂ (N mm ⁻²)	567	27.9	69.7	48.2	12.8
Density, ρ ₁₂ (kg m ⁻³)	567	370	562	455	54.1
All					
MOE ₁₂ (kN mm ⁻²)	1551	9.13	18.4	13.4	2.86
MOR ₁₂ (N mm ⁻²)	1551	29.7	70.2	49.1	12.4
Density, ρ ₁₂ (kg m ⁻³)	1551	382	562	460	53.1

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Table 5. Models for density, MOE₁₂, and MOR₁₂.

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 (7.9%)	0.31 (6.5%)	1.5 (1.6%)
σ_T^2	702 (52.7%)	2.12 (44.5%)	31.3 (34.0%)
σ_e^2	526 (39.5%)	2.34 (49.0%)	59.4 (64.4%)
Summary statistics from model step			
R ²	56.7%	42.1%	40.0%
RMSE	34.5	2.12	9.47
Parameter estimates and p values and F-ratio for the fixed effects			
Elev	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	38.6	2.24	10.3
COVARIATE MODELS			
1	$\rho_{12} = 1241.96 - 8.12SI - 0.17Elev - 9.04Lat + 0.40Age - 0.39DBH - 294.06LP_{rel} + 0.11KH_{180}$ $+ 11.23SI*LP_{rel} + 0.15Elev*LP_{rel} + 0.56DBH*LP_{rel} - 0.60KH_{180}*LP_{rel}$		
2	$MOE_{12} = 20.55 - 0.15SI - 0.01Elev + 0.02Age - 0.02DBH - 6.47LP_{rel} + 0.20SI*LP_{rel} + 0.01Elev*LP_{rel}$		
3	$MOR_{12} = 73.59 - 0.02Elev + 0.12Age - 0.10DBH - 6.39LP_{rel}$		

Table 6. Variance component model for density, MOE₁₂, and MOR₁₂.

	σ_s^2	σ_T^2	σ_e^2
Density, ρ_{12}	1576 (51.5%)	830 (27.1%)	655 (21.4%)
MOE ₁₂	2.91 (35.5%)	2.86 (34.8%)	2.44 (29.7%)
MOR ₁₂	32.1 (20.6%)	63.5 (40.7%)	60.6 (38.8%)

1

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Figures

Figure 1. Sampling areas in Southern Norway, Eastern Norway and Trøndelag.

Figure 2. Predicted relationships of wood density to longitudinal position (LP_{rel}), as influenced by site index, elevation, DBH, and KH_{180} : Line a) for mean values of the fixed effects, line b) for big trees with small KH_{180} at the highest realistic site index at high elevation and line c) for small trees with large KH_{180} at low site index at low elevation.

Figure 3. Predicted relationships of MOE_{12} to longitudinal position (LP_{rel}), as influenced by site index and elevation: Line a) for mean values of the fixed effects, line b) for trees at the highest realistic site index at high elevation and line c) for trees at low site index and low elevation.

Figure 4. Predicted relationship of MOR_{12} to longitudinal position (LP_{rel}), as influenced by elevation: Line a) for mean values of the fixed effects, line b) for trees at high elevation and line c) for trees at low elevation.