Grade yield in sawn timber of Norway spruce (*Picea abies* (L.) Karst.) - modeling the effect of timber length, forest, tree and log variables

Sorteringsutbytte i trelast av gran (*Picea abies* (L.) Karst.) - modellering av effekten av trelastlengde, skog-, tre- og stokkvariabler

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Preface and acknowledgement

This thesis is submitted as partial fulfilment of the degree Philosophiae doctor (PhD) at the Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management. The work has been carried out at Norsk Treteknisk Institutt (NTI). The funding for the work has been provided by the Research Council of Norway through the project "Norwegian timber as raw material, added value and industrial possibilities", "SSFF-prosjektet" in short. The above-mentioned institutions are sincerely thanked for their contribution to making this project possible.

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Audun Øvrum

Summary

Grade yield of sawn timber is a key influence on the profitability of a saw mill since timber grades are the basis for the selling price of boards. In visual grading the grade of a board is determined by the worst part of the board, thus the expected grade will decrease as the length increases. This is a well-known effect, but it has not been investigated to any extent for Norway spruce (*Picea abies* (L.) Karst). To investigate the length's effect on grade yield in sawn timber of Norway spruce, and how this effect is influenced by site, tree and log variables was the aim of this study.

The grading rules applied were appearance grading according to Nordic Timber and visual strength grading according to INSTA 142. First a general description of the distribution of grades in trees of Norway spruce was made. Expected grade showed a decreasing trend from the butt end toward the top end of the trees. This was mostly attributed to the increasing knot diameter upwards in the trees, and to the smaller timber sizes extractable as the distance from stump increases. The decrease in grade was stronger in visual strength grading compared to appearance grading, the main reason being the stronger sensitivity to knot size in strength grading due to the lack of any distinction between sound and dead knots.

In the next step logs from different stem parts were simulated to address the practical implications of the distribution of grades in the trees. A smaller length effect was found upwards in trees, and was explained by the larger knot variation and the higher frequency of other down-grading features than knots in the lower stem parts. The length effect was found to be stronger in strength grading compared to appearance grading, and this was explained by the larger knot size sensitivity in strength grading. In strength grading a smaller length effect in inner boards compared to boards farther from the pith was found, and this was due to the larger knot size in outer boards. Based on current market prices an increase in the log length from 45 dm to 60 dm showed an estimated loss in value of about 6 %.

In the third study the practical effect of cross-cutting trees in different fixed lengths was investigated, and how this turned out at sites with varying quality, and in different tree sizes. Length gave the strongest effect on grade yield in the visual grading rules, and it was concluded that trees from the poorer sites should be cross-cut in shorter logs. Medium-sized trees gave the highest grade yield for both the visual grading rules, while forest quality was most important in machine strength grading.

Finally, the length model was expanded to include objective measures of site, tree, log and board characteristics to make a more general model for the effect of length on grade yield. Still, the length effect was found to decrease upwards in trees, and more strongly so in strength grading than in appearance grading. The largest trees within the stands showed the highest sensitivity to increasing length, implying that the largest trees should be cross-cut in shorter logs in order to obtain a high grade yield. The variation in grade yield within stands was greater than the variation between stands, and the magnitude of the length effect was at the same level as the first investigation. Except from length, the position of a board within a tree turned out to be the most important factor for determining the grade.

The general length models showed a prediction accuracy within a 10 % margin for each grade, indicating a proper fit if the model is used within the range of the observations in the

dataset. A validation is recommended in order to generalise the model. Further enhancement of the models should include data with a larger variation in tree and stand age and sites with higher fertility.

Sammendrag

Sorteringsutbytte er veldig viktig for et sagbruks lønnsomhet siden sorteringsklasse danner grunnlaget for salgsprisen for trelast. I visuell sortering er det den dårligste delen av planken som bestemmer kvaliteten, og således vil sorteringsutbyttet gå ned hvis lengden på trelasten økes. Dette er et velkjent fenomen, men har vært lite undersøkt i gran (*Picea abies* (L.) Karst). Å undersøke trelastlengdens innvirkning på sorteringsutbyttet i gran, og hvordan denne påvirkes av voksested, tre- og stokkvariabler har vært målet for dette arbeidet.

For utseendesortering ble det sortert etter Nordisk Tre, mens styrkesortering ble utført etter INSTA 142. Først ble det utviklet en generell beskrivelse for fordelingen av sorteringsklasser i stammen til grantrær. Et minkende sorteringsutbytte ble funnet oppover i trærne. Hovedforklaringen for dette var den økende kvistdiameteren oppover i trærne og de mindre trelastdimensjonene som er mulig å ta ut mot toppen av trær. Effekten av lavere sorteringsklasser oppover i trærne var kraftigere i styrkesortering enn i utseendesortering, hovedsaklig grunnet den større avhengigheten av kviststørrelse siden en ikke skiller mellom frisk og tørr kvist i styrkesortering.

I neste steg ble stokker fra forskjellige stammehøyder simulert for å finne den praktiske innvirkningen av fordelingen av sorteringsklasser i trærne. En svakere lengdeeffekt ble funnet oppover i trærne, og ble forklart med større variasjon i kvistegenskaper og høyere forekomst av nedklassing for andre årsaker enn kvist i nedre stammedeler. Lengdeeffekten ble funnet å være større i styrkesortering enn i utseendesortering og forklart med den større innvirkningen av kviststørrelse i styrkesortering. I styrkesortering ble det funnet en mindre lengdeeffekt i planker tatt ut nærmest margen enn i planker tatt ut lengre fra marg, noe som skyldtes økende kviststørrelse fra marg mot bark. Ved å øke tømmerlengden fra 45 til 60 dm ble det avdekket et verditap på 6 % ut fra dagen markedspriser for skurlast.

I det tredje arbeidet ble effekten av å kappe trær slavisk i ulike fastlengder undersøkt, og hvordan dette slo ut på ulike skogkvaliteter og i ulike tretyper. Lengde ble funnet å påvirke sorteringsutbyttet mest i de visuelle sorteringsreglene, og det ble konkludert med at trær i bestand med lav skogkvalitet bør kappes i kortere stokker. Mellomstore trær ga høyest sorteringsutbytte for begge de visuelle sorteringsreglene, mens skogkvalitet var det viktigste for utbyttet i maskinell styrkesortering.

Til slutt ble lengdemodellen utvidet til å inkludere objektive målbare egenskaper på bestands-, tre-, stokk- og plankenivå for å utvikle en mer generell modell for lengdens innvirkning på sorteringsutbyttet. Fortsatt ble lengdeeffekten funnet å minske oppover i trær, og mer i styrkesortering enn i utseendesortering. De største trærne i bestandene viste størst lengdeeffekt, noe som indikerer at disse bør kappes kortere for å opprettholde et godt sorteringsutbytte. Variasjonen i sorteringsutbytte var større innen bestand enn mellom bestand, og størrelsen på lengdeeffekten var på nivå med det som ble funnet i den første studien. Bortsett fra lengde var plankeposisjon i treet den viktigste faktoren for forventet sorteringsklasse.

De generelle lengdemodellene viste en prediksjonsnøyaktighet med en feilmargin på 10 %, og viste et rimelig prediksjonsnivå hvis modellen brukes innenfor området det er observasjoner fra i datasettet. Det anbefales å validere modellene for å gjøre dem mer

generelle. I en utvidelse av modellen bør en inkludere data med større variasjon i bestands- og trealder, samt finne voksesteder med høyere bonitet.

List of papers

The thesis is based on the following papers, which will be referred to in the text by their Roman numerals:

I. Øvrum, A, Vestøl, GI, and Høibø, OA (2008) Modeling the longitudinal variation of sawn timber grades in Norway spruce (*Picea abies* (L.) Karst.). Holz als Roh- und Werkstoff 66(3):219-227

II. Øvrum, A, and Vestøl, GI (2008) Modeling the effect of length on yield of sawn timber grades in Norway spruce (*Picea abies* (L.) Karst.). Manuscript submitted to Holz als Roh- und Werkstoff

III. Øvrum, A, Høibø, OA and Vestøl, GI, (2008) Grade yield of sawn timber in Norway spruce (*Picea abies* (L.) Karst.) as affected by forest quality, tree size and cross-cutting length. Manuscript submitted to Forest Products Journal

IV. Øvrum, A, Vestøl, GI, and Høibø, OA (2008) Modeling the effects of timber length, stand- and tree properties on grade yield of Norway spruce (*Picea abies* (L.) Karst.) timber. Manuscript submitted to Canadian Journal of Forest Research

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Work of present author

The present author was the primary author of all papers.

Paper I — The present author designed the experimental work together with the second author. Reporting and analysis of the results was the work of the present author, and so was writing the paper, to which also the second and third author contributed.

Paper II — The present author designed the experimental work together with the second author. Reporting and analysis of the results was the work of the present author, and so was writing the paper, to which also the second author contributed.

Paper III — The present author designed the experimental work together with the third author. Reporting and analysis of the results was the work of the present author, and so was writing the paper, to which also the second and third author contributed.

Paper IV — The present author designed the experimental work together with the second author. Reporting and analysis of the results was the work of the present author, and so was writing the paper, to which also the second and third author contributed.

Contents

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1 Introduction

1.1 Timber use and the importance of length

The length of timber is an important consideration for the Norwegian sawmilling industry. Timber length is limited by the log length, which is usually decided during the logging process. The stems are cross-cut according to price lists, where the price of a log per cubic meter is determined by the saw log grade, the top diameter and the length of the log, yielding a variety of log lengths. The traditional Norwegian cross-cutting regime was developed in the late 1960s, and it was based on the grades of inner centreboards according to the old grading rules for sawn timber in Norway called "ØS-rules"(Anonymous 1981). These defined two saw log classes, prima and sekunda (Anonymous 1994a). The best class, prima, was meant to give two centre boards in the grade US (unsorted grade 1-4) according to the "ØS-rules", and boards of fifth grade from sekunda logs, alternatively one board of US and one of sixth grade (Müller 1984). Since then, the grading rules for saw logs have been modified several times without testing the consequences on sawn timber quality. In addition, the sawing pattern is quite different from what it was in the late 1960s; boards in the centre yield are thinner, 38 and 50 mm thick, compared to the commonly used thicknesses of 63, 75 mm and 100 mm in the 1960s, and a stricter requirement on wane today. This has diminished the ability to predict quality on sawn timber in the traditional cross-cutting scheme (Dalen and Høibø 1985; Haugen 1996; Müller 1984).

Until 1989, Norway had national price lists for saw logs, one for prima and one for sekunda. The price list tabled basis prices per cubic meter for each combination of lengths and top end diameters of logs. The final price was based on the price list, adding a percentage of the basis price and a certain amount per cubic meter, distinguishing between "prima" and "sekunda". The additional amounts were negotiated at a national level. Today, there are no general restrictions on which grading rules or price lists to use. Many sawmills still follow the aforementioned system, whereas others have only one quality class for saw logs, where normally the quality requirements are similar to the lowest class from the old saw log rules (sekunda) (Anonymous 1994a). The buyers of sawn timber are to an increasing degree requiring cut to length timber, or at least sufficiently long pieces of timber. This is due to the increased focus on costs in the housing industry, which will be minimised both in regards of time consumption and waste if the timber is adjusted to the length it will have in the final construction. Cut to length is hence increasingly important in order to maintain and strengthen the position of timber as a building material. Hence, most larger sawmills have their own unique price lists, which are intended to reflect the sale of sawn timber in terms of dimensions and lengths. These sawmill specific price lists often have a stronger length appreciation than the old standard lists, and together with the fact that one saw log class gives longer logs on average, many sawmills report that the mean length of logs has increased. This improves the sawmills efficiency because most of the operations happen with transverse transportation of the timber. It is also an advantage to the transport process in the forest, from forest to sawmill and from saw mill to customer.

1.2 Implication of length for the quality of timber

The commercial expression of quality in the sawmilling industry is grades. Often buyers can buy batches which include several grades, depending on the processing of the sawn timber (Lycken 2006). However, for the saw mills, grades are the most consistent quality separation and the factor for pricing of the boards.

Grading by visual inspection is a method commonly used to assess the quality of sawn timber in Norway. Appearance grading of Nordic softwoods is performed according to Nordic Timber (Anonymous 1994b). Although many sawmills determine their grades based on customer demands (Lycken 2006), Nordic Timber (Anonymous 1994b) decides how to measure features and how to grade the timber. Visual grading of structural timber of Nordic softwood is standardised in INSTA 142 (1997) in accordance with EN 518 (1995). Common to the different grading rules is the assessment of grade based on the worst part of each piece. Since the features vary along the timber, grade yield will decrease if the average length of timber increases, since no piece can be upgraded after first being down-graded.

The grade yield of sawn timber is affected by many different factors related to variations in wood properties, how logs are cross-cut from stems, the sawing pattern and how timber is graded. Also, grading of the logs will influence sawn timber grade since some features are visible on the stem surface. The cost of increasing timber length is a reduction in grade yield. This effect is parallel to the size effect applied in structural timber. Size effect is based on the "Weakest link theory" developed by Weibull (1939) in his studies of brittle materials (ref. by Rouger and Barrett 1995). The size effect is due to increased probability of finding a strength reducing component in a larger piece of timber than in a smaller piece of timber. This aspect has been used for decades and is implemented in standards for structural timber, for instance in EN 384 (2004), to determine bending and tension strength for different sizes of timber. The main difference between the length effect in grading and the size effect in structural timber is that in grading, the grades will have the shape of absolute threshold values for different features, while for the size effect both a variation in stress within the construction member due to the loading, and the variation in strength properties in the timber member must be addressed, making the investigation of size effect in structural timber more complicated.

To properly address the effect of length on timber grade is not a straightforward task, and compromises are inevitable. Orvèr (1973) studied the effect of length in terms of the value of the logs cut from Scots pine (*Pinus sylvestris* L.) stems. He found a significant trend of an increased value of cross-cutting in shorter lengths. A continuous expression of the length effect in sawn timber is not really attainable since timber sizes are dependent on log diameter, which will create a stepwise size increase in timber widths, typically in inches increments in commercial timber production. Furthermore, a change of length in one log will affect the other logs in the tree, and to address all these factors is very hard.

1.2.1 Influence of variation in wood properties

The most frequent reason for down-grading timber is knots, but grade can also be affected by the slope of grain, annual ring width, reaction wood, resin wood or resin pockets, biological defects like rot, and mechanical injuries. Some of the features can be taken into account when the trees are cross-cut, while others are not visible before the timber is sawn.

Knots are occluded branches and the diameter of a knot at a radial distance from the pith depends on the branch diameter and branch angle. Branch diameter of Norway spruce increases upwards in the lower part of the stem (Abetz and Unfried 1983; Bues 1996; Colin and Houllier 1991; Moberg 2001, 2006; Mäkinen et al. 2003; Vestøl and Høibø 2001), and the maximum branch diameter of a tree is found in the lower part of the living crown (Colin and Houllier 1991; Vestøl and Høibø 2001). Complete vertical profiles of branch- or knot diameter in Norway spruce have been reported by Colin and Houllier (1991) and Moberg (2001, 2006). Since the dimension of sawn timber is limited by the diameter of the log and the allowed knot size depends on the timber dimension (Nordic Timber & INSTA 142), the expected grade is reduced upwards in a tree. The log diameter is mainly a restriction to the timber width, whereas the thickness is less affected. Therefore, the effect of reduced log diameter is stronger if the grade is limited by face knots than if it is limited by edge knots. The quality of a knot, that is whether it is sound or dead, is not taken into account in visual strength grading (INSTA 142 1997). However, appearance grading according to Nordic Timber (Anonymous 1994b) allows larger sound knots than dead knots in a grade. Vertical profiles of sound knot length in Norway spruce have been presented by several authors (Moberg 2001, 2006; Mäkinen et al. 2003; Vestøl and Høibø 2000; Øyen 1999). Moberg (2001) found the sound knot length to increase from the stump towards the crown, while Vestøl and Høibø (2000) found that the sound knot length increases up to 40 % of tree height. Øyen (1999) described a sound knot cylinder based on the assumption that sound knot length is relatively constant from 10 % to 20 % of tree height up to the living crown.

Most coniferous species from the northern hemisphere have a grain angle clearly to the left near the pith with a gradual change turning to the right as the tree grows older (Panshin and De Zeeuw 1980). Both Säll (2002) and Bramming (2006) found this trend in Norway spruce with the highest grain angle close to the pith and the culmination point being somewhat farther from the pith higher up in trees (Säll 2002).

The radial variation in ring width, especially in the lower parts of the stem, is influenced by stand density. Pressler's rule has been used to describe the annual increment in basal area for trees as demonstrated by Deleuze and Houllier (1995) and Houllier et al. (1995) in their studies of Norway spruce. Pressler's rule states that the basal area increment is constant from the stump up to the base of the functional part of the crown. Since the girth of the stem decreases from the stump upwards, annual rings will be widest at the crown base, with a sharper decrease upwards in the crown than downwards towards the stump.

Reaction wood is a response to external impacts primarily caused by slope, wind, injuries, branches and insect attacks (Zobel and Van Buijtenen 1989). Compression wood is most frequent in the first few growth rings near the pith, but there is no clear conclusion concerning the longitudinal variation within trees since the reasons for the formation of reaction wood are so numerous (Timell 1986). Perstorper et al. (1995) found more compression wood in top logs compared to butt logs in Norway spruce, but no radial variation. Öhman (2002) concluded that the sweep will give good indications about the frequency of compression wood in Norway spruce logs, and will as such be a better predictor than position in the stem.

The occurrence of resin pockets in Norway spruce was described by Temnerud (1997). His conclusion was that the probability of occurrence of resin pockets was lowest in the innerwood of butt logs. The probability of occurrence of resin pockets increased with distance from pith and declining top diameter, indicating an increase towards the top of the tree. This was confirmed by both Herb and Becker (2006) and Gjerdrum and Bernabei (2007). However, the variation is great, and the differences between trees within a stand and between stands are of such magnitude that resin pockets might be considered to be randomly distributed in sawn timber of Norway spruce.

Biological damages and damages due to wind, snow, thinning, etc. are hard to model because of extreme local variations, and also because the silvicultural program for the stand influence these variables (Braastad 1979; Persson 1972, 1976). Damages from the production process will depend on the specific sawmill's equipment and logistic.

1.2.2 Influence of cross-cutting and sawing

Features visible on the stem surface will be possible to address in the cross-cutting, and sweep, crook and mechanical injuries in particular are considered in the cross-cutting today and are important for the sawn timber grade yield. Visible knots on the stem surface, however, are not very good grade indicators, something indicated by the aforementioned poor relationship between prima and sekunda in the Norwegian grading rules for saw logs (Anonymous 1994a).

The position of a feature in a board will strongly influence grade since features are assessed differently on the different sides of the boards, and the size limitations, at least for knot properties, are linked to the timber size. As an example, a sound knot with a diameter of 23 mm, which is a normal-sized knot in Norway spruce (Vestøl and Høibø 2001) will give grade A in Nordic Timber (Anonymous 1994b) in boards thicker than 32 mm if it is situated on the edge of the board. Placed on the face the width has to exceed 115 mm to obtain grade A. However, a knot of 23 mm in diameter will only be judged to be 23 mm if it is sawn perpendicular to the branch angle, and this will often not be the case. This means that it will be defined as being of a larger size if it is sawn diagonally, and may even lead to down-grading to grade C in Nordic Timber (Anonymous 1994b) in a worst-case scenario. The transition of knots from sound knots near the pith to dead knots closer to the bark in lower stem parts will also cause a higher risk of down-grading towards the bark, since the tolerance for dead knots is lower than for sound knots in most appearance grading rules. Both Nordic Timber (Anonymous 1994b) and INSTA 142 (1997) allow larger face knots than edge knots. Which side the knots appear on is mostly random unless one is able to detect knots in the logs and make sawing pattern based on that information. Björklund and Juhlin (1998) found no practical effect of rotation of logs according to knots for Scots pine (*Pinus sylvestris* L.). Johansson and Liljeblad (1988) found some impact of optimising log position due to geometrical and knot features in Scots pine, but pointed out that it is difficult to achieve this in sawmills today, while Nordmark (2005) on the other hand claimed that it is in fact, possible with new measuring equipment like 3D scanners and X-ray scanners for Scots pine. Even if knot variation is smaller for Norway spruce than Scots pine, Lemieux et al. (1997) pointed out that 50 % of the total knot volume is concentrated in one third of the log in Norway spruce, this being the sectors pointing towards southeast in the standing tree. This indicates a potential for sawing according to knots. However, most sawmills in Norway focus on sweep in the rotation of the log, and knots are generally ignored in the sawing process of Norway spruce. However, when focusing on sweep in the rotation, the most knotty side will normally appear in planks containing the compression wood, since the knots to a greater extent are located at the outside of the sweep. Nevertheless, the position and shape of the knots on the sawn surface will lead to random variation in grade along the stem.

1.3 Models for grade yield

During the last decades different models for predicting sawn timber grade have been developed. As Nordmark (2005) points out, there are three different approaches to this topic:

1. Use of growth models for taper, live crown and branching to simulate stem shape and knot structure at the time of harvesting.

2. Model the structure directly from site, stand and tree characteristics.

3. Predict grade from measurements of log characteristics by scanners, shape or interior properties (X-ray), sound waves, microwaves or other measuring techniques.

Growth models applied to predict grade yield have been introduced for Scots pine by Väisänen et al. (1989). Models for prediction of grade yield from site, stand and tree descriptors are more numerous, e.g. Scots pine (Ikonen et al. 2003; Moberg and Nordmark 2006; Uusitalo 1994, 1997; Uusitalo et al. 2004), Radiata pine (Beauregard et al. 2002) and Black spruce (Liu et al. 2007). Models to predict grade yield based on measurement on the logs exist for Douglas fir (Todoroki et al. 2005) and larch (Petutschnigg and Katz 2005).

The variation in grades in Norway spruce might seem too small to conduct any work on sophisticated grade yield models, as pointed out by Verkasalo et al. (2002). They think that it is feasible to just cut Norway spruce stems into saw logs with fixed lengths and diameters according to saw mills orders. However, their investigations were only on trees which satisfied the Finnish grading rules for saw logs with the exception of knottiness. Moreover, Birkeland and Øvrum (2005) found no effect in cross-cutting Norway spruce according to the Norwegian grading rules for saw logs, and actually found a higher value for the stems that had been cross-cut in fixed lengths when the value was calculated as the sum of the market price for different standard Nordic Timber grades and pulp wood.

Houllier et al. (1995) and Kantola et al. (2007) made models for several aspects of timber quality in Norway spruce based on growth models, but not grade directly. Høibø (1991) and Johansson(1992) conducted spacing trials to investigate the influence of planting distance on grade yield and found the grade yield to decrease by increasing planting distance. Malinen et al. (2003) and Verkasalo et al. (2002) predicted internal quality and value of Norway spruce trees through sophisticated models including a number of stand and tree descriptors. Included in their work were models for grade yield.

Several log models for grade yield in Norway spruce have been developed, and Jäppinen (2000) investigated the potential for predicting sawn timber grade of Norway spruce based on external features of logs measurable in different types of log scanners. He developed models with high accuracy for various grading rules like Nordic Timber (Anonymous

1994b) and Gröna boken (Anonymous 1976). Models for the strength properties in boards based on log parameters have also been developed (Brännström et al. 2007; Edlund et al. 2006; Jäppinen 2000; Oja et al. 2001). Jäppinen (2000) found that through a pre-sorting of logs based on variables from a 3D scanner the yield of glulam lamellas could be improved significantly. Oja et al. (2001) found that data from an X-ray logscanner could give good indications about the stiffness in the centre boards graded by a Cook-Bolinder machine (Boström 1994). Brännström et al. (2007) found that an X-ray logscanner predicted the strength in centre boards with the same accuracy as a standard strength grading machine (Goldeneye 902). Edlund et al. (2006) showed that by measuring the MOE in saw logs by resonance frequency and exclude the saw logs with lowest MOE, a significant improvement in the higher machine strength grades as measured by a Cook Bolinder (Boström 1994) strength grader was obtained. Even if such systems establish a good relationship between log variables and different sawn timber properties, usually the cross-cutting is carried out before these optimising processes, and some economic yield is lost.

It is common to find that timber grade yield is reduced with height within a stem. Rikala (2003) found a decrease in grade yield in appearance grading and in strength grading in logs extracted higher up in the trees in his studies of Norway spruce. Blomqvist and Nylinder (1988) did not find any difference in appearance grade between logs of Norway spruce, only more homogenous grades in butt logs. Høibø (1991), on the other hand, found a trend towards an increasing grade yield higher up in trees in appearance grading, but a decreasing trend in strength grading of Norway spruce. However, he only extracted two boards from each log, and these were thicker than those extracted in a saw mill today, thus leading to more dry knots down-grading for the butt logs as compared to (Rikala 2003). The deviance in results indicates that the last decades' changes in sawing pattern influence the grade yield.

Models including forest parameters need some kind of logistic system to maintain the information of the trees and logs into the sawing process. Simple models which allocate logs to only a few classes may just need some kind of colour marking or equivalent to be able to address the information in the conversion. More sophisticated models, however, need a more advanced system, but it is very difficult to track logs back to origin in an industrial saw mill today. Methods for making traceability possible through the wood-value chain have been investigated by (Uusijärvi 2000), and through the LINESET project (Uusijärvi 2003) a potential for better utilisation of the forest raw material was revealed, and some traceability applications were tested. One example is the fingerprint approach developed by Chiorescu (2003) and further developed by Flodin et al.(2007, 2008). Methods for making traceability possible are currently being developed further through the project Indisputable Key (Anonymous 2006), which aims to enable a tracking back to the raw material by using existing equipment and developing new systems for obtaining data backwards in the value chain. This will increase the potential for implementing models for wood properties making the processing of wood more adapted to obtaining desired end product properties, and stimulate and facilitate more advanced and precise models for wood properties.

Øyen (1999) introduced the system of an industrial sound knot cylinder (SKC) in Norway spruce trees as a cylinder from 10 % of tree height to crown base where the wood would satisfy the sound knot requirements for most appearance products, i.e. panelling, floor boards and so on. He found DBH to be the most important variable for predicting the SKC in individual Norway spruce trees, and the best model also included crown height and age.

Further developed models for SKC (Anonymous 1998) were used in harvesters to optimise the cross-cutting of stems into logs suitable for appearance wood (few dead knots), and logs suitable for structural timber, where there are no distinction between dead and sound knots. The sound knot prediction in this system worked well, but a challenge to this work was that even if a model is capable of describing the systematic variations in different stem properties like knots, there will still be random defects like ramicorn branches, resin pockets, compression wood and top breakage present. This makes the grade yield more unpredictable, and as such will make the implementation of such cross-cutting systems hard.

None of the models and investigations on grade yield in Norway spruce have treated length as a separate factor for influencing grade yield. In Birkeland and Mjåland (2001) and Birkeland and Øvrum (2005) for example, differences in grade yield were investigated for different cross-cutting systems, but the comparisons will not be totally correct before the length of the timber in the cross-cutting systems is adjusted for.

1.4 Objectives and overview of work

The objectives of this thesis were to investigate the variation in, and to quantify the effect of timber length on, the expected grade of sawn timber produced from Norway spruce. In order to achieve this, the work was separated into the following tasks:

1. Describe and analyse the longitudinal variation of sawn timber grade (Paper I)

2. Analyse the effect of length on grade yield of timber from different stem parts (Paper II)

3. Investigate the effects of forest quality, tree size, cross-cutting length and the interactions between these on grade yield (Paper III)

4. Expand the model for length effect in paper II with the input from paper III by including measurements on site, tree, log and boards to develop a more general length effect model for Norway spruce (Paper IV)

5. Estimate the cost of reduced grade yield due to increased length (Paper II and IV)

The tasks were performed in the sequence described above, and an overview of the experimental work is shown in Table 1.

Table 1. Overview of the experimental work

Objective	Work	Data	Main conclusions
Describe and analyse the longitudinal variation of sawn timber grade	Paper I	Continuous grade in 100 cm sections of 768 boards originating from 56 trees from four different sites	Expected grade showed a decreasing trend from the butt end towards the top end of the trees, with a stronger trend in strength grading than in appearance grading.
Analyse the effect of length on grade yield of timber from different stem parts, and estimate the cost of reduced grade yield due to increased length.	Paper II	As in paper II	A smaller length effect upwards in trees, and a smaller length effect in inner boards compared to boards farther from the pith for IN-grading was found. Based on current market prices an increase in the log length from 45 dm to 60 dm showed an estimated loss in value of about 6 %.
Investigate the effects of forest quality, tree size, cross-cutting length and the interactions between these on grade yield	Paper III	Boards from all logs extracted from 160 trees from six different sites	Length gave the strongest effect on grade yield in the visual grading rules, and the poorer sites should be cross-cut in shorter logs. Medium-sized trees gave the highest grade yield for both the visual grading rules, while forest quality was most important in machine strength grading.
General model for length effect including measurements of site, tree, log and board variables	Paper IV	Boards from the saw logs in the data defined for paper III	The length effect was strongest at stump level, and decreased upwards in trees. Trees with a large relative diameter at breast height had the strongest length effect. The variation in grade yield within stands was greater than between stands, and the magnitude of the length effect was at the same level as in paper II.

2 Materials and methods

2.1 Materials

The work of this thesis was based on analyses of two data sets. The first comprised 768 boards originating from the centre yield of 56 trees of Norway spruce from four different sites located within a small area in south-eastern Norway. Site 1 and 2 were selected due to variation in site index, while site 3 and 4 had the same site index, but the trees in site 4 was of a much more even age than those in site 3. The sites were selected in order to investigate the effect of cross-cutting systems, and the trees were selected based on their high quality and consisted almost entirely of logs satisfying the requirements for saw logs (Anonymous 1994a) in Norway. The overall features for the sites and trees are shown in Table 2, and detailed information about the sites, samples and cross-cutting is presented in paper I.

Table 2. Whole tree attributes of the sample trees in data set 1 (numbers in brackets are the standard deviation)

Site	No. of trees	Site index H_{40} [m]	Age [yrs.]	Diameter at breast height [mm]	Tree height [dm]	Height to the crown base (180º of the whorl living) [dm]
1	8	23	57 (2)	296 (30)	262 (13)	134 (12)
2	8	17	94 (4)	304 (33)	233 (21)	114 (19)
3	20	17	112 (27)	389 (27)	269 (11)	114 (29)
4	20	17	112 (6)	418 (30)	291 (20)	120 (27)

The second data set comprised boards from 160 Norway spruce trees from six different sites which were cross-cut in fixed lengths of 20, 40 or 60 dm respectively. The sites were selected based on general forest quality, i.e. occurrence of splay knots and crook caused by top breakage. The reason for this approach was to reflect the variation within the procurement area of a medium-sized sawmill in Norway. Data for the different recorded features on stand level are shown in Table 3. The definitions of the features are presented in table 3 in paper IV.

Table 3. Mean values (standard deviation) in the stands for the different features recorded in data set 2

Site	Site index H_{40} [m]	Altitude [m]	Forest quality	Saw log classification [%]	Age [yrs.]	DBH [cm]	H [dm]	HC360 [dm]	HC180 [dm]	HLB [dm]	HDB [dm]
1	G17	450	Medium	P: 48.6 S: 17.6 R: 33.7	99 (16)	28.2 (8.0)	201.2 (41.1)	115.3 (35.5)	81.0 (24.3)	42.5 (16.8)	9.4 (7.9)
2	G14	470	Good	P: 68.6 S: 15.8 R: 15.6	117 (9)	26.0 (5.3)	213.7 (23.6)	140.1 (26.8)	104.7 (28.7)	51.9 (13.9)	16.8 (10.0)
3	G14	620	Medium	P: 61.3 S: 9.7 R: 29.0	106 (30)	24.1 (5.4)	191.8 (24.8)	128.3 (38.5)	99.3 (29.9)	61.2 (24.4)	9.3 (5.8)
4	G11	630	Poor	P: 32.8 S: 30.0 R: 37.2	100 (27)	24.9 (6.0)	162.5 (24.3)	997 (32.5)	59.5 (27.9)	30.9 (23.3)	6.3 (4.3)
5	G20	350	Good	P: 76.4 S: 7.1 R: 16.5	102 (16)	28.9 (7.1)	252.3 (30.3)	167.0 (35.9)	134.8 (34.0)	73.7 (31.3)	14.2 (6.9)
6	G11	770	Poor	P: 50.6 S: 25.4 R: 24.0	119 (15)	27.3 (7.3)	155.5 (30.8)	83.1 (45.3)	50.7 (19.5)	25.1 (10.0)	8.6 (5.8)
Tot.				P: 60.0 S: 15.6 R: 24.4	107 (21)	26.6 (6.7)	196.1 (43.9)	122.1 (45.0)	88.2 (39.6)	47.2 (26.7)	10.7 (7.8)

The trees were cross-cut into 529 logs, which yielded a total of 2141 boards. For detailed information of the sampling see paper III.

The analyses in paper III were performed by including all of the boards in data set 2, while in paper IV only the boards from logs satisfying the lowest saw log class (Anonymous 1994a) were included in the analyses. Furthermore, no boards starting higher up than 120 dm from the stump end were included in paper IV.

2.2 Methods

2.2.1 Sawing

In both data sets the sawing was carried out according to Nordic practice as defined in Anonymous (1994b), with heart splitting giving either 2, 4 or 6 ex-log in the centre yield depending on the small end diameter of the log processed (Figure 1).

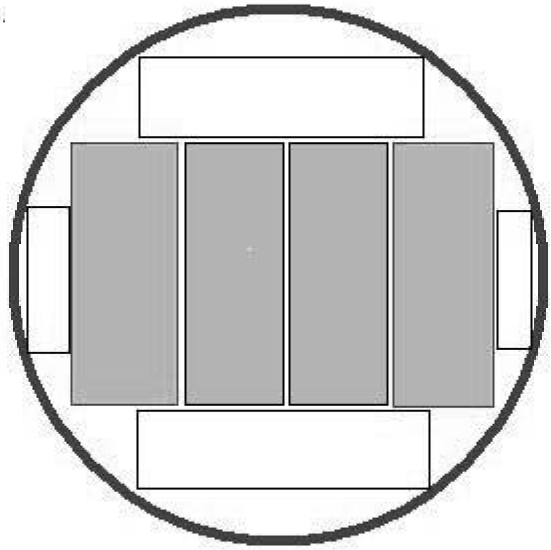


Figure 1. Sawing pattern with boards from centre yield in grey, and side yield in white

Board dimensions were commercial dimensions determined by the sawing pattern giving the maximum volume yield from each log.

2.2.2 Grading

In data set 1 (paper I and II) all features that could lead to down-grading were recorded with size, type and position of features in boards from the centre yield. In total 10 368 features were recorded. Afterwards the grades in Nordic Timber (Anonymous 1994b) and INSTA 142 (1997) were assessed for 100 cm sections, the first starting from the butt end and a new section starting every 10 cm upwards. This was done automatically by a program developed in SAS. This means that there was a 90 % overlap between any two neighbouring sections. Up to 100 centimetres from the butt end was denoted “Section 1”, the section from 10 cm to 110 cm was denoted “Section 2” and so on (Figure 2). This was continued along all boards upwards in the tree, relating all sections to the distance from the butt end. The analyses were limited to “Section 155” since only a few trees had sawn timber above this level, and a total of 28 896 sections were graded.

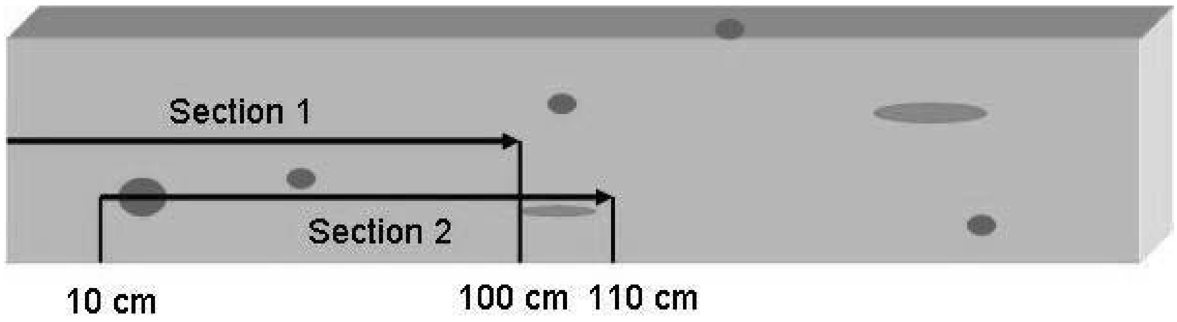


Figure 2. Division of a board into sections

In data set 2 the boards were graded as they were, and no recordings on the actual features were performed except for the down-grading feature if applicable.

In both data sets the boards were graded for appearance according to Nordic Timber (Anonymous 1994b), and strength according to INSTA 142 (1997). In addition a sub-sample of 576 planks from data set 2 was machine strength graded by a Dynagrade (Boström 1997) for paper III.

Nordic Timber (Anonymous 1994b) utilises four grades A, B, C and D with A as the best, and D as reject. It is possible to divide grade A into four different subclasses A1-A4, but this was not done except in paper III where A3 was graded. In INSTA 142 (1997) the grades T3 (C30), T2 (C24), T1 (C18) and reject were used, the strength class in brackets referring to the EN 1912 (2005) assigned strength class defined in EN 338 (2003). The Dynagrade graded the strength classes C30, C24, C18 and reject based on the standard setting values according to EN 519 (1995).

All boards were graded in green state except for the machine grading, which must be performed on timber with a moisture content below 20 % for Dynagrade (Boström 1997).

2.2.3 Statistical modeling

In all the papers ordinal multinomial regression was applied due to the ranked nature of the grade categories.

The general form of logistic regression is a generalised linear model using logit, which is the logarithm of the odds as its link function (Agresti 2002). In ordinal multinomial logistic regression, *Y* (grade in this work) takes on one of *k*+1 possible values denoted by 1, 2, ..., *k*, *k*+1, and there is an inherent ordering in the response values. This is expressed as:

$$p_i = P(Y_i \leq k|x) \qquad (1.1)$$

where x is a vector of explanatory variables. The specific model becomes:

$$logit\ (p_i) = \ln\left(\frac{p_i}{1-p_i}\right) = \alpha + \beta x \qquad (1.2)$$

where α is a vector of intercept parameters and β is a vector of slope parameters. This is a parallel lines regression model based on the cumulative probabilities of the response categories, also known as the proportional odds model. This logit model is called a cumulative logit. Another way of expressing this is:

$$P(Y \le k) = \frac{e^{\alpha + \beta x}}{1 + e^{\alpha + \beta x}} \qquad k = \text{grade 1, grade 2, grade 3, grade 4} \qquad (1.3)$$

A possible dependence between the sections within trees and boards was suspected in data set 1, and hence a violation of the independence criteria assumed in generalised linear models. This meant that the general requirements in logistic regression would not be satisfied, and in particular the tests of significance would be erroneous. A solution to this was to treat the constant introduction of new sections within a tree to have the form of repeated measures. Repeated measures are common in social and medical studies, where the same subjects are measured at different points in time. Liang and Zeger (1986) and Zeger and Liang (1986) introduced Generalized Estimating Equations (GEE) as a solution to this. The principle behind this approach is to introduce a working generalised model for the marginal distribution of Y_i. No specification of the joint distribution of the repeated measures is made, but merely estimating equations that give consistent estimates of the regression parameters, and of their variances under weak assumptions about the joint distribution (Agresti 2002). In such an approach, independence between the subjects is required, but the distribution in the response and predictors is not as important (Agresti 2002). The subject of the correlation structure was defined as tree in paper I, and board in paper II, and the parameter estimates were calculated with the correlation within these subjects taken into consideration.

Several authors have stated that a miss-specified correlation structure will not greatly affect the estimates with the GEE-approach (Agresti 2002; Hardin and Hilbe 2003; Liang and Zeger 1986; SAS 2000) and that the efficiency in specifying the correlation structure exactly is slight. However, Agresti (2002) noted that this is under the assumption that the correlation within the responses is quite small. A large correlation was suspected in data set 1, and as such lead to an investigation of how different correlation structures affected the parameter estimates. The software used (SAS) only allows for independent correlation structure in multinomial models, while for binomial models a choice of several correlation structures is present. Hence a binary response was defined as the probability of attaining the highest grade, namely A or T3, in order to be able to compare correlation structures. The tested and compared correlation structures were as follows:

- Independence (IND), which assumes no correlation between zones.
- Exchangeable (EXCH), which assumes that each response in the cluster is equally correlated
- Autoregressive (AR), which is developed from studies of time series, and assumes that responses are dependent "on their past", so that the correlation between responses diminishes as the distance between them increases.

A normal generalised binomial model without the implementation of GEE in the form of a logistic regression was also included in the comparison and the estimates from the multinomial model. To rank the correlation structures, the Quasilikelihood under the

Independence model Criterion (QIC) statistic proposed by Pan (2001) were calculated for each correlation structure. The correlation structure with the lowest QIC should then be chosen if the choice happened to be unobvious (Hardin and Hilbe 2003). The results showed that the most obvious correlation structure of autoregressive showed almost identical value for QIC as independent, and also the parameter estimates were furthermore identical in practice. Hence, the use of multinomial analyses with the use of independent correlation structure in the GEE-analyses was claimed to be justified. The actual correlation was found to be quite small in paper I, and hence no correlation structure was imposed in the analyses on data set 2 in paper III and IV since these analyses were based on individual boards as responses.

In paper IV the prediction accuracy of the models developed in paper II was compared to the general model developed in paper IV. This was done on the boards which satisfied the constraints of the model in paper II, i.e. logs which were extracted 0 m, 4 m or 8 m from the stump. This comprised 687 boards in total. The testing was performed as a comparison of yield computed by multiplying the probability of the different grades for every board with the board volume, and then sum the total volume of each grade and divide that sum by the total sum of board volume. Classification tables were not used due to the low probabilities in the lowest grades, which make a classification table unfit to check the prediction abilities of the models (Hosmer and Lemeshow 2000).

In paper III and IV odds ratios were introduced to show the trends and relations within and between the variables. In principle, "odds ratio" is defined as the "odds for success" (Agresti 2002). The interpretation of odds ratio for continuous variables was the odds of retaining the grade by increasing the variable with an increment of one. This means that an odds ratio of 0.9 is interpreted as a 10 % chance of a decrease in grade by increasing the variable with an increment of 1. Oppositely, an odds ratio of 1.1 is interpreted as a 10 % chance of increase in grade by increasing the variable with an increment of 1. The odds ratio for categorical variables is the odds of getting a higher grade in one category compared to another category of the variable.

3 Results and discussion

3.1 Longitudinal variation of sawn timber grade (Paper I)

Due to the increased knot diameter towards the crown base (Moberg 2001, 2006; Vestøl and Høibø 2001), and the smaller extractable timber sizes higher up in the trees, a lower probability of the better grades was expected at higher positions in the trees. This effect was found in paper I, and it was more pronounced in grading according to INSTA 142 (IN-grading) (Figure 3) compared to grading according to Nordic Timber (NT-grading) (Figure 4).

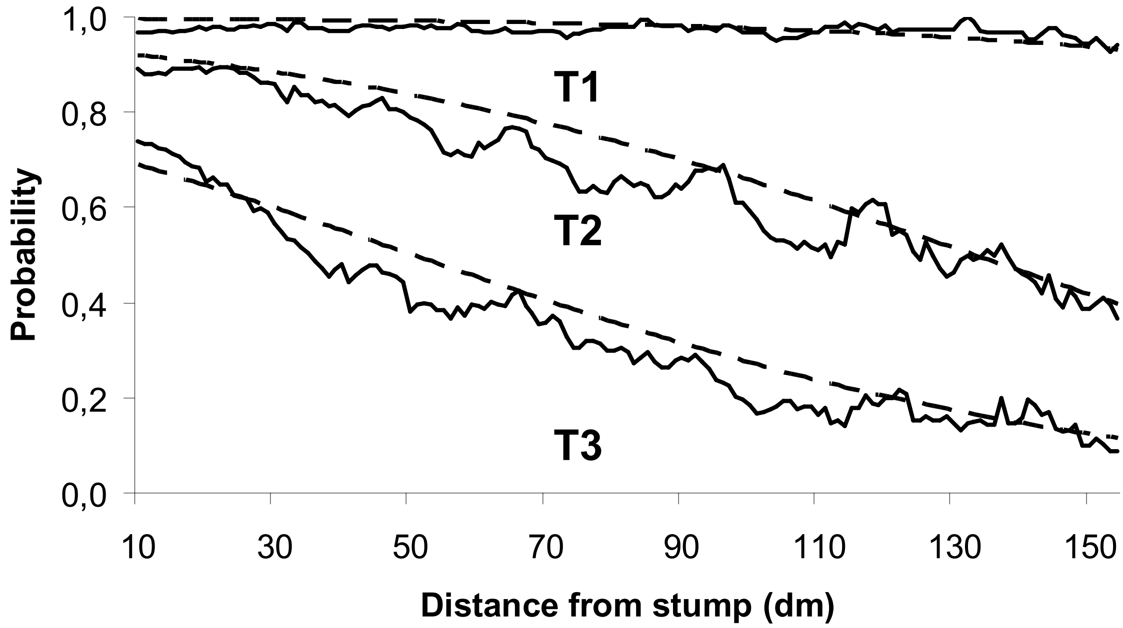


Figure 3. The model (dotted lines) for the INSTA 142 grades compared to the actual frequency (solid-drawn lines) of the grades in the trees (from paper I)

In IN-grading the allowed knot size is independent of whether the knot is sound or dead. Edge knots were utterly dominant as down-grading feature in IN-grading, and the thickness was 50 mm for most of the boards in paper I. The increasing knot size was hence attributed to the stronger decrease in higher grades upwards in the stem for IN-grading. Down-grading to reject in INSTA 142 is more often caused by other features than knots (table 4 in paper I), which may be judged as randomly distributed in the stems. This explained the rather constant percentage of reject throughout the stems (Figure 3).

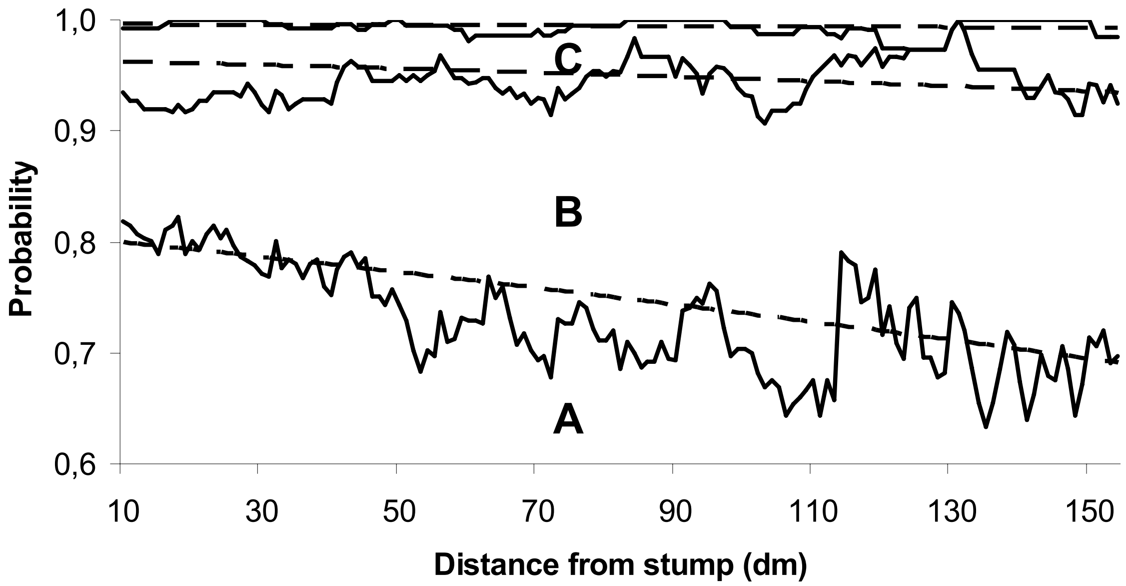


Figure 4. The model (dotted lines) for Nordic Timber grades compared to the actual frequency (solid-drawn lines) of grades in the trees (from paper I)

Nordic Timber(1994b) allows smaller sizes of dead knots than sound knots, and relatively larger knots in the smaller timber sizes. This corresponds quite well to the knot pattern in Norway spruce trees with increasing knot size and sound knot length up to the lower part of the living crown with a following decrease in the crown region, and with a high occurrence of dead knots in the lower parts of the stem (Moberg 2001, 2006; Vestøl and Høibø 2000, 2001). This will cause frequent down-grading for dead knots in the lower stem parts. As the sound knot frequency increases towards the crown base, the knot size will also increase, yielding more down-grading for sound knots. In the crown region the knot size will decrease towards the top end, and this will correspond to the decreasing timber size. The grading rules do, however, not fully compensate for the knot pattern, but the trend of decreasing grade upwards in the stems is diminished compared to IN-grading. Similarly to the results of IN-grading the lower grades of NT-grading (C and D) are often caused by other features than knots (table 2 in paper I), and this made the effect of longitudinal position for these grades almost insignificant, as shown in Figure 4.

3.2 Effect of length on grade yield of timber from different stem parts (Paper II)

In paper II boards were simulated having lengths ranging from 20 dm to 60 dm starting at stump level, 4 m above stump level and 8 m above stump level respectively. Both a “board model”, where board position in the cross section was included, and a “log model”, where the effect of type of board was ignored, were developed for both grading rules. As expected from the results of paper I, the effect of length on grade yield was larger in IN-grading than in NT-grading. A decreasing length effect upwards in the tree was found for IN-grading. For NT-grading a similar trend was found, but it was not statistically significant. The smaller decrease in length effect upwards in the tree in NT-grading compared to IN-grading was attributed to the more uniform distribution of down-grading by knots throughout the trees for NT-grading, as found in paper I.

The NT-board model showed that the length effect was constant throughout the trees (see Figure 5), while the log model suggested decreasing length effect upwards in the trees. This discrepancy was explained by general lower grades higher up in the trees, and also the very large difference in grade yield between board types in logs starting at 8 m.

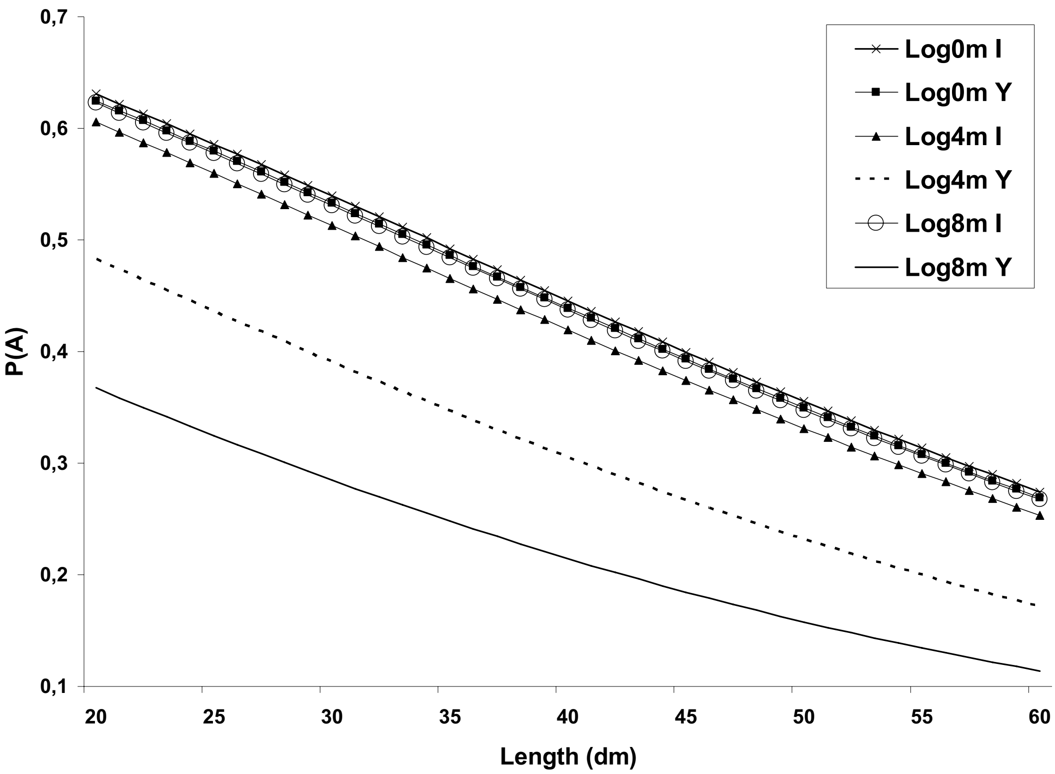


Figure 5. Probability for grade A in the Nordic Timber board model of paper II. I indicates inner boards and Y other boards

A smaller length effect in IN-grading for inner boards was found (see Figure 6) and explained by the larger knot size in general in outer boards, since the knot size increases from the pith towards the bark as long as the knots are still sound.

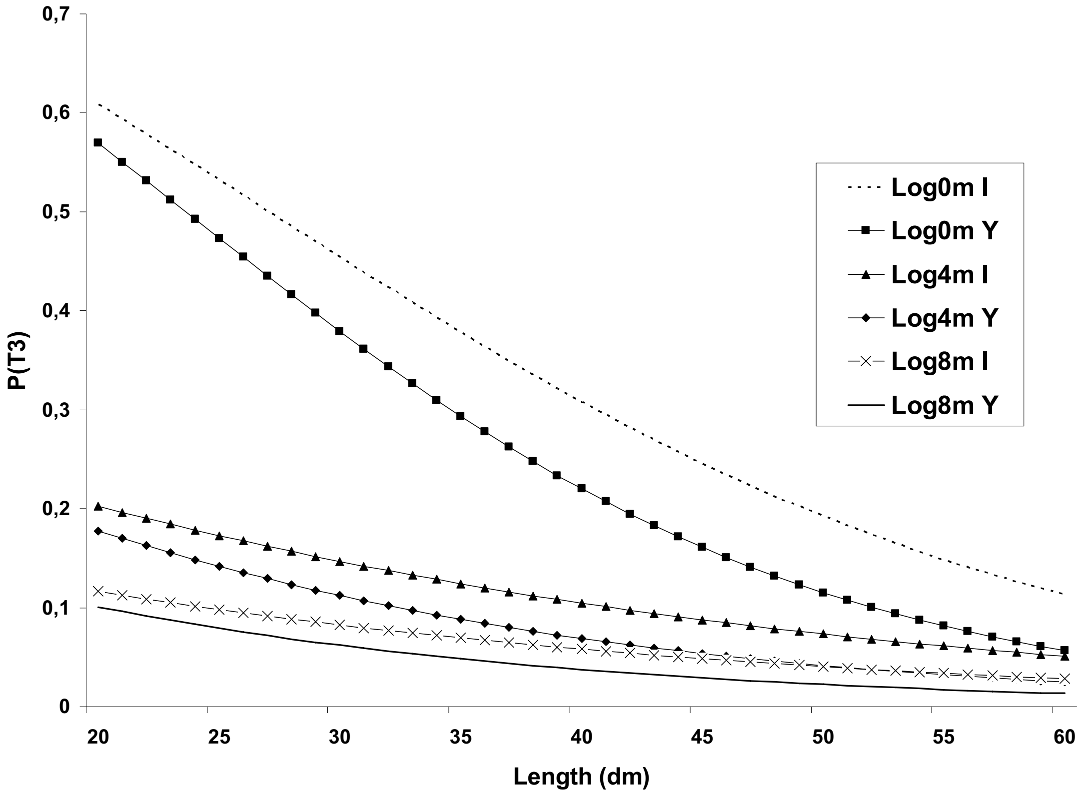


Figure 6. Probability for grade T3 in the INSTA 142 board model of paper II. I indicates inner boards and Y other boards

In NT-grading a decrease in grade yield was found in logs extracted higher up in the trees, something which Rikala (2003) also found in his studies of Norway spruce. Blomqvist and Nylinder (1988) did not find any difference in grade between logs of Norway spruce, only more homogenous grades in butt logs when grading after "Grøna boken" (Anonymous 1976). Høibø (1991), on the other hand, found an increasing trend in grade yield higher up in trees when grading Norway spruce according to the "ØS-rules"(Anonymous 1981). However, he only extracted two boards from each log, and these were thicker boards than those used in this study, namely 75 mm thick, leading to increased down-grading for dry knots in butt logs compared to the results found in paper II, where the boards were 38 and 50 mm thick.

The type of board gave a strong effect in NT-grading in logs starting at 4 m and 8 m, resulting in higher grade yield of inner boards in these logs. For logs starting at stump level, the effect could in practice be disregarded. This was attributed to the inner boards having very few dead knots, which NT-rules grade very strictly, and the larger size of these as the distance from stump increases.

IN-grading yielded significantly higher grades in logs starting at stump level compared to logs starting at 4 m, which again had higher yield than logs starting at 8 m. This was also shown for visual strength grading of Norway spruce by Høibø (1991) and Rikala (2003). The board type did not have any significant effect for grade yield in IN-grading, which was attributed to a more frequent down-grading due to edge knots in inner boards counterbalancing the larger knots in outer boards.

3.3 Effects of forest quality, tree size, cross-cutting length on grade yield (Paper III)

For the visual grading rules, cross-cutting length had the strongest effect on grade yield, while tree size and forest quality were shown to be equally important for grade yield. The decrease in grade yield was stronger from 20 to 40 dm than from 40 to 60 dm. 20 dm is shorter than the normal lengths of Norway spruce logs and represent an extreme way of cross-cutting. The effect of increasing from 40 dm to 60 dm, however, is within the range of normal log lengths. The anticipated stronger effect of length on grade yield in large trees was found, but only for IN-grading. This was explained by the higher dependency on the knot size in strength grading.

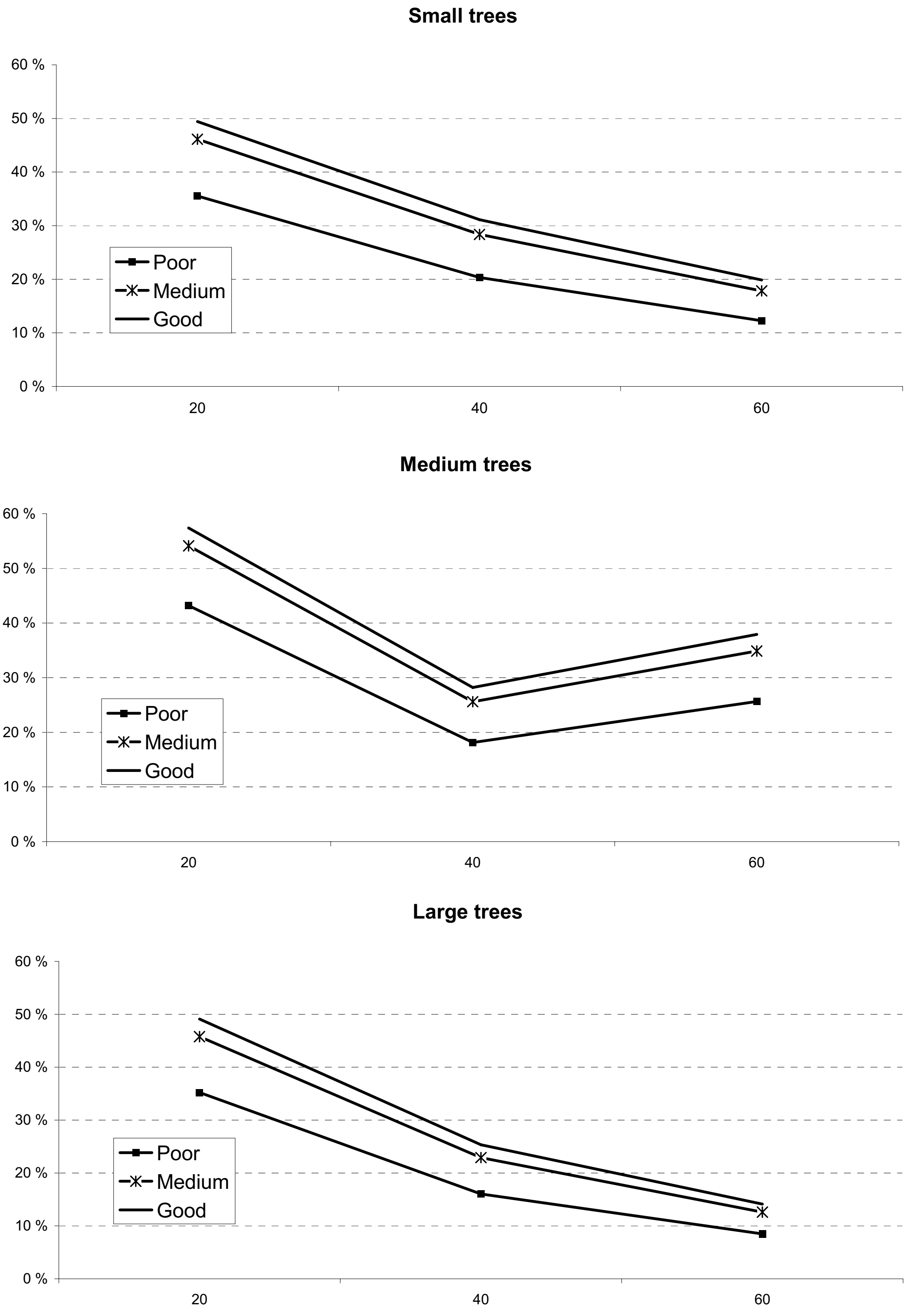


Figure 7. The predicted percentages of grade A in Nordic Timber for the different combinations of cross-cutting length, tree sizes and forest qualities in paper III

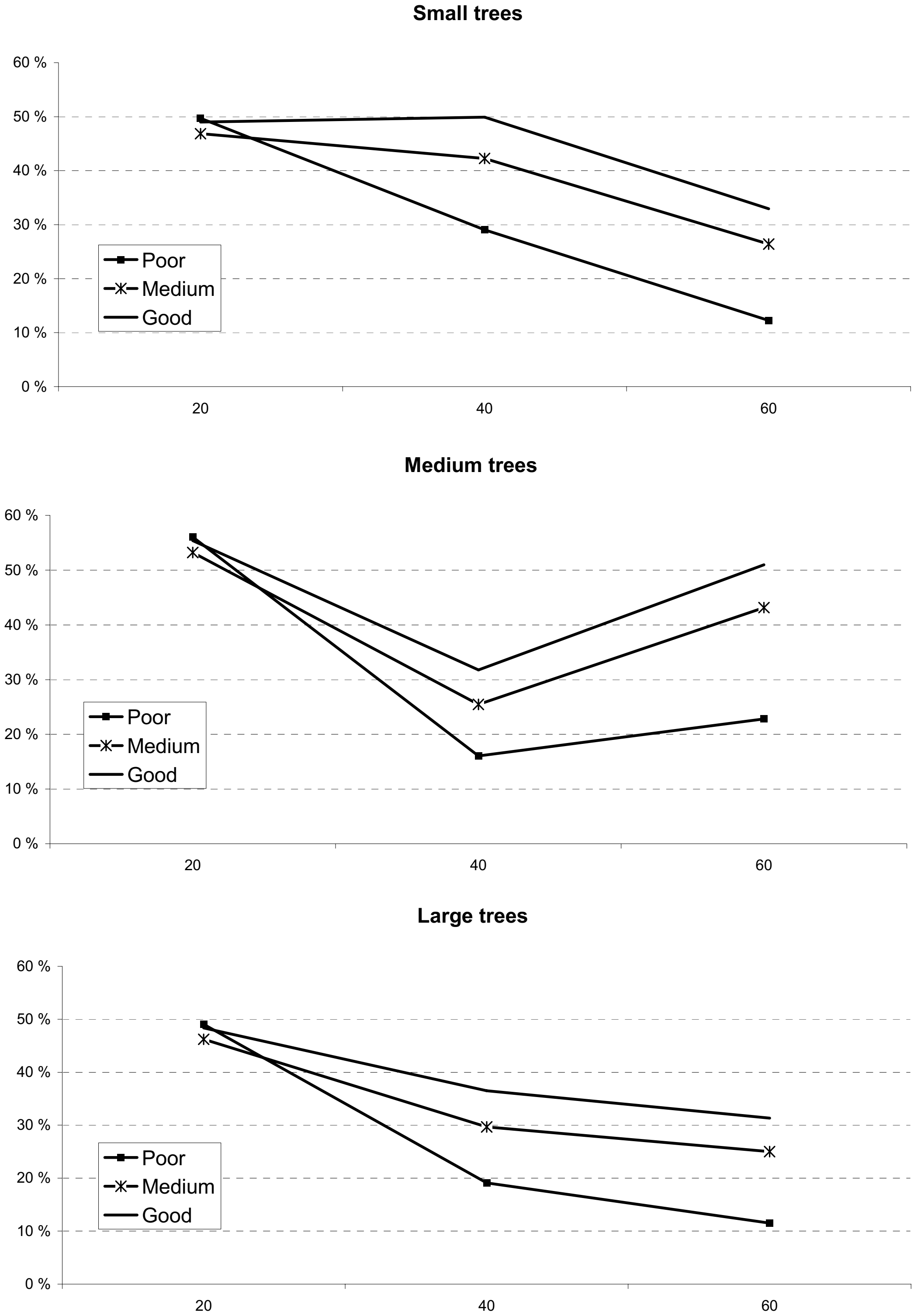


Figure 8. The predicted percentages of T3 in INSTA 142 for the different combinations of cross-cutting length, tree sizes and forest qualities in paper III

For medium-sized trees the grade yield actually increased when the length increased from 40 to 60 dm in both NT and IN-grading (see Figure 7 and Figure 8). This contradicted the hypothesis and was explained by several factors. The trees which were cross-cut in 40 dm lengths have more logs from higher up in the stem represented, which generally yield lower grades as shown by paper II. According to this explanation the suppressed trees cross-cut in 20 dm lengths would be suspected to first encounter the effect of increased grade yield with increasing length, since such trees often will have only one log extractable when cross-cutting in 60 dm lengths. However, the butt logs of smallest trees generally had lower quality due to higher frequency of down-grading for other factors than knots, i.e. rot, compression wood and fibre deviations due to a higher percentage of logs not satisfying the saw log requirements (Anonymous 1994a). This was thought to diminish the effect of overrepresentation of butt logs for the longer lengths in the smallest trees, and as such may explain that it is medium-sized trees that show this increased grade yield by increasing length from 40 to 60 dm. It was also emphasised that all variables were treated as categories, hence threshold values, making the resolution of the scales quite coarse. Combined with few observations in each group, this would make the chance of effects coincidentally working together to make unexplainable statistical inferences possible. Grade yield clearly decreased with increasing length for both the small and the large trees, and for all tree sizes when cross-cutting was increased from 20 to 40 dm lengths. The lesser effect of forest quality with shorter cross-cutting lengths, which was significant in IN-grading and a trend in NT-grading, was in line with the assumption that at sites with low forest quality trees should be cross-cut in shorter lengths. The effect of decreasing grade yield with increasing cross-cutting length was stronger for NT-grading than for IN-grading, which contradicted the results of paper II. This was explained by the material which only includes saw log quality logs in paper II, in addition to the fact that five grades were used for NT-grading in paper III, making the scale of NT and IN-grading not directly comparable since only four grades were used in IN-grading.

Medium-sized trees gave the best grade yield for both NT and IN-grading, which was somewhat in dispute with Høibø (1991), who found a decreasing trend of grade yield for all grading rules by increasing DBH. However, his conclusions were based on measuring DBH at different points in a tree’s life. He found that the effect of DBH on grade yield decreased as the trees got older, and the age at final felling in his study was a mere 51 years. Furthermore, the site fertility was very high, and the stands were intensively managed in his study, making a direct comparison somewhat biased. Since knots were the most frequent down-grading factor, the combination of relatively small knot size, and the fairly high occurrence of sound knots is the most probable reason for the medium-sized trees giving the highest grade yield in NT-grading. For IN-grading however, the smallest trees were thought to give the best grade yield because of the smaller knot size, and did so for cross-cutting length of 40 dm, but not for 20 and 60 dm. The small trees did yield most boards in the highest grade (T3), but they also had the largest reject percentage due to a higher frequency of down-grading to reject because of rot, compression wood and fibre deviations. This was connected to the fact that the smallest trees had the highest frequency of logs not satisfying the saw log grading rules (Anonymous 1994a). This overcompensated the effect of smaller knots in the smallest trees.

Decreasing forest quality gave decreased grade yield, but with an insignificant odds ratio between good and medium forest quality for NT- and IN-grading. The difficult delimitation between “good” and “medium” forest quality in the forest was the explanation for this. The effect of forest quality was clearly most important in the machine grading, where it was the only significant effect. The reason for this very strong forest quality effect was attributed to factors not possible to assess by visual strength grading, most probably density and fibre deviations. Also, the Dynagrade assigns a continuous E_{dyn}, to each board, which in turn assigns them to a strength class. It is well known that the modulus of elasticity gives a better accuracy in the grading process compared to visual grading rules (Johansson 2003), and as such might explain the strong effect of forest quality in machine grading. To examine if this corresponds to an actual difference in strength properties between the sites would require real testing of the strength properties in the boards.

3.4 General model for length effect (Paper IV)

A stronger length effect was found in bigger trees and was explained by the larger knots due to the larger crowns in bigger trees (Vestøl and Høibø 2001). The same decrease in the length effect upwards in the trees as found in paper II was discovered, but in addition this effect was statistically significant for NT-grading as well. The length effect was slightly stronger in IN-grading compared to NT-grading, as in paper II. An expression of the effect of length on grade yield is shown in Figure 9 and Figure 10 by the development of the odds ratios for length. Odds ratio in this case is the odds of retaining the grade by increasing the length with one dm.

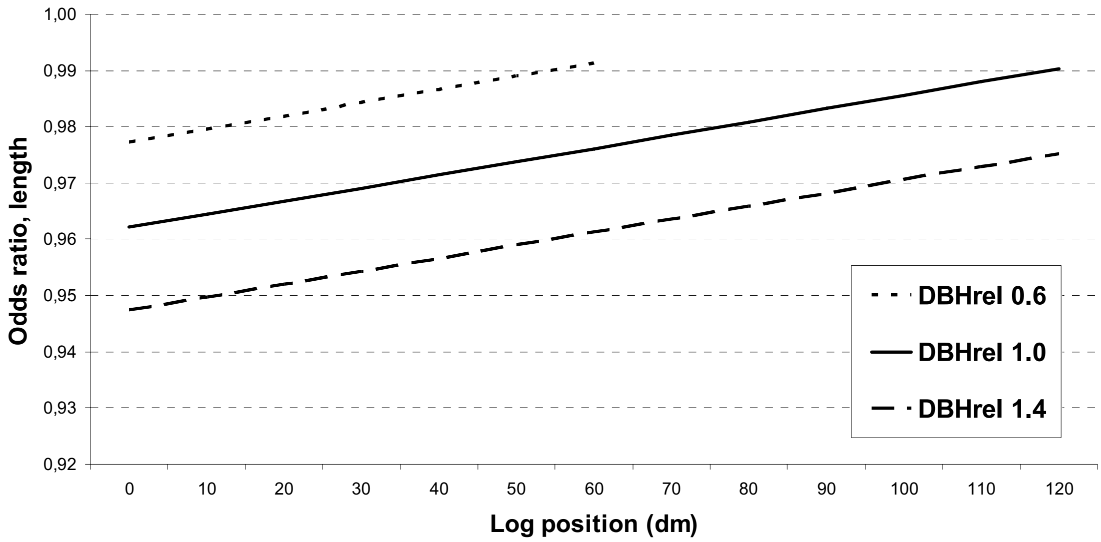


Figure 9. Odds ratio for the length effect in Nordic Timber as affected by log position and relative DBH from paper IV

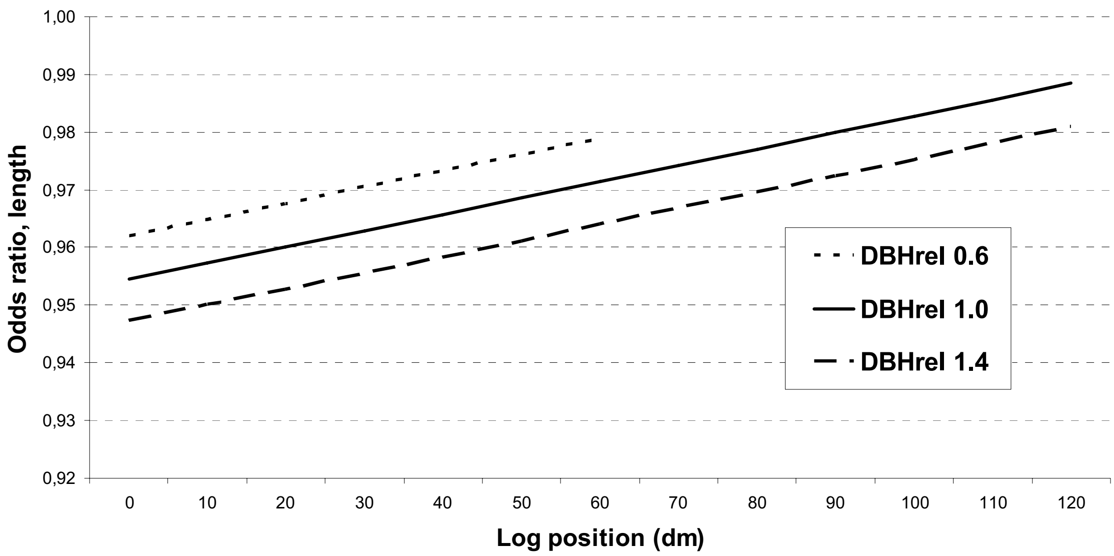


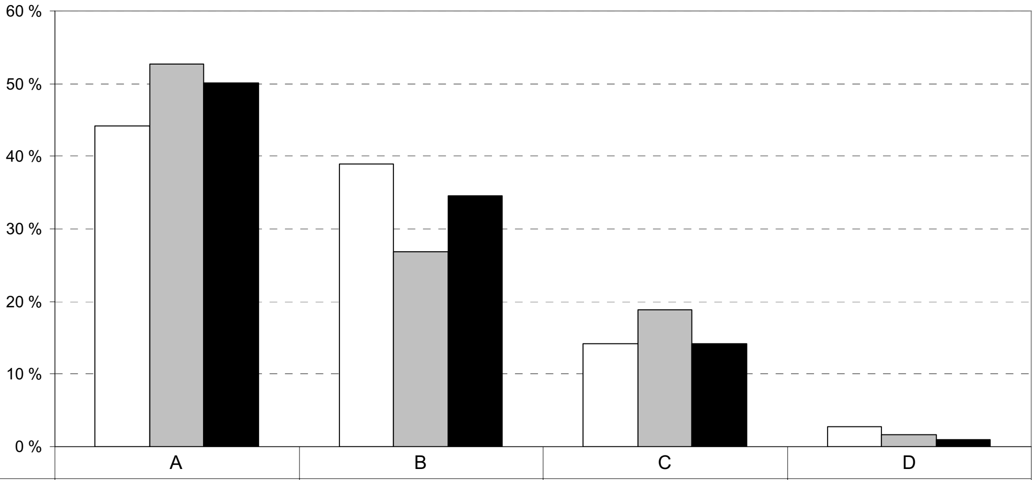
Figure 10. Odds ratio for the length effect in INSTA 142 as affected by log position and relative DBH from paper IV

Parallel to the results shown in paper II a decrease in grade yield in logs extracted higher up in the trees was found, and the reasons for this are outlined in chapter 3.2. A higher grade yield in inner boards compared to other boards was found, an effect which grew stronger towards the top end for NT-grading, also shown in paper II. This effect was mostly attributed to the smaller timber sizes in other boards in NT-grading.

A better grade yield in smaller trees was found, and it was explained by the smaller knot size in such trees. In paper III the best grade yield was found in the medium-sized trees, but in that study all logs were included. Since the smallest trees had the highest frequency of logs not satisfying the saw log grading rules (Anonymous 1994a), the omission of such logs lead to an improvement of grade yield in the smallest trees compared to relatively larger trees, giving a continuous increase in grade yield by decreasing tree size within the stand. Tree height gave a positive effect on grade yield when adjusting for relative DBH, which is to be expected in virtue of the fact that slender trees will have a better quality due to smaller knot proportion and knot diameter (Gislerud 1974). The decreasing grade yield found by increasing mean DBH of the site will be part of the same connection.

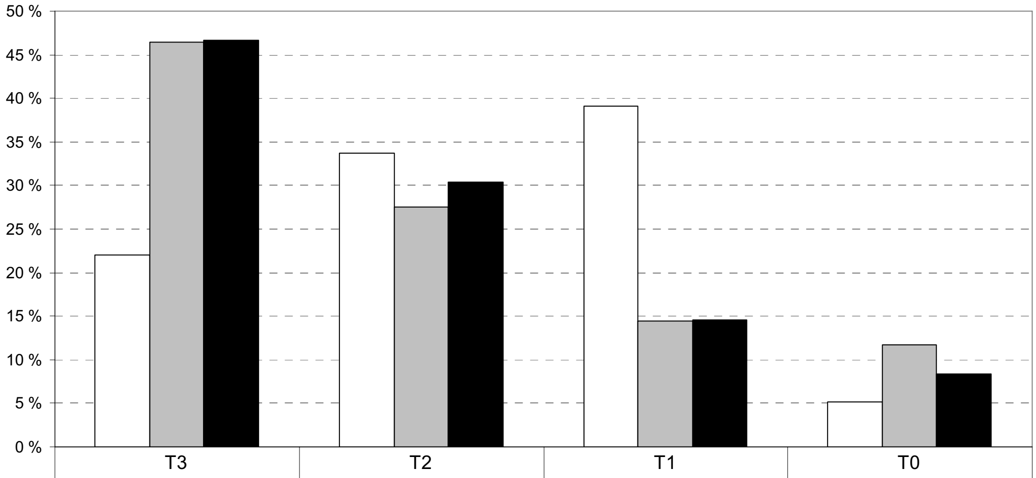
Tree variables, i.e. tree height and $DBH_{rel,}$ were found to be more important than site variables for grade yield, implying a higher variation within stands than between stands. This indicates the same relationship as for knot size (Vestøl and Høibø 2001) and fibre properties (Molteberg 2006) in Norway spruce. However, position of the board within the tree, both longitudinally and in the cross section, was the most important factor for grade yield except for length, and inner boards in butt logs yielded the highest grades.

The general models of paper IV fitted the data much better than the models of paper II (see Figure 11 and Figure 12), which was expected since more variables were included and because of the larger variation in data set 2.



	A	B	C	D
Model paper II	44,1 %	39,0 %	14,2 %	2,7 %
Observed	52,7 %	26,8 %	18,9 %	1,6 %
Model paper IV	50,1 %	34,6 %	14,2 %	1,0 %

Figure 11. Predicted and observed Nordic Timber grade yield for the boards from paper IV satisfying the requirements of the models in paper II



	T3	T2	T1	T0
Model paper II	22,1 %	33,7 %	39,1 %	5,2 %
Observed	46,4 %	27,5 %	14,4 %	11,7 %
Model paper IV	46,6 %	30,4 %	14,6 %	8,3 %

Figure 12. Predicted and observed INSTA 142 grade yield for the boards from paper IV satisfying the requirements of the models in paper II

The models of paper IV will be good enough to assess size and trends of grade yield in planning and budgeting of timber production, and they seemed to predict grade probabilities within a 10 % margin used within the range of the observations in the dataset. However, a validation on a new data set will be needed to ensure prediction accuracy.

3.5 Cost of reduced grade yield due to increased length (Paper II and IV)

In paper II the cost of reduced grade yield due to increased length under different price assumptions was evaluated. The assumptions were parallel to the theory of size effect in structural timber (Rouger and Barrett 1995). The principle laid out was that the value of the total volume of sawn timber should be constant, implying balancing a decrease in grade yield with increasing log length by increasing the value of longer logs (eq. 2.1).

$$P_{L1} \times Y_{L1} = P_{L2} \times Y_{L2} \qquad (2.1)$$

where:

P denoted average price,

Y denoted yield, and was given by the frequency of the different grades at the actual length multiplied by the relative ranking between the different grades,

L1 denoted the length (baseline length) to which a new length *L2* was compared.

The size of the length effect was expressed as the relative price (*RP*) of the new length compared to the baseline length (eq. 2.2). RP will depend on the price gap between the grades of sawn timber, and whether the price gap is to be constant or dependent on length.

$$RP = \frac{P_{L2}}{P_{L1}} = \frac{Y_{L1}}{Y_{L2}} \qquad (2.2)$$

From this, RP was derived with different assumptions about price gaps between the grades by using the various models. In Figure 13, RP is shown for the NT-log model from paper II on butt logs (Log0m) with different assumptions. L1 was set to 45 dm representing the average log length in Norway. *Pricegap 10%* means that there was a constant ten percent difference in value between the NT grades by saying the price of grade A, B, C and D was 1, 0.9, 0.8 and 0.7 respectively. In *Pricegap 25 %,* the grades were set to 1, 0.75, 0.5 and 0.25 respectively. In *Market,* the current market prices in Norway were used, and they were 1, 0.875, 0.625 and 0.4375 respectively. In *A=0,7 X Rest,* the price of the grades B, C and D was set to 0,7 X grade A at the length 45 dm. This meant that for this particular assumption, the RP was the difference in value for grade A alone, treating the price of grades B, C and D as independent of length.

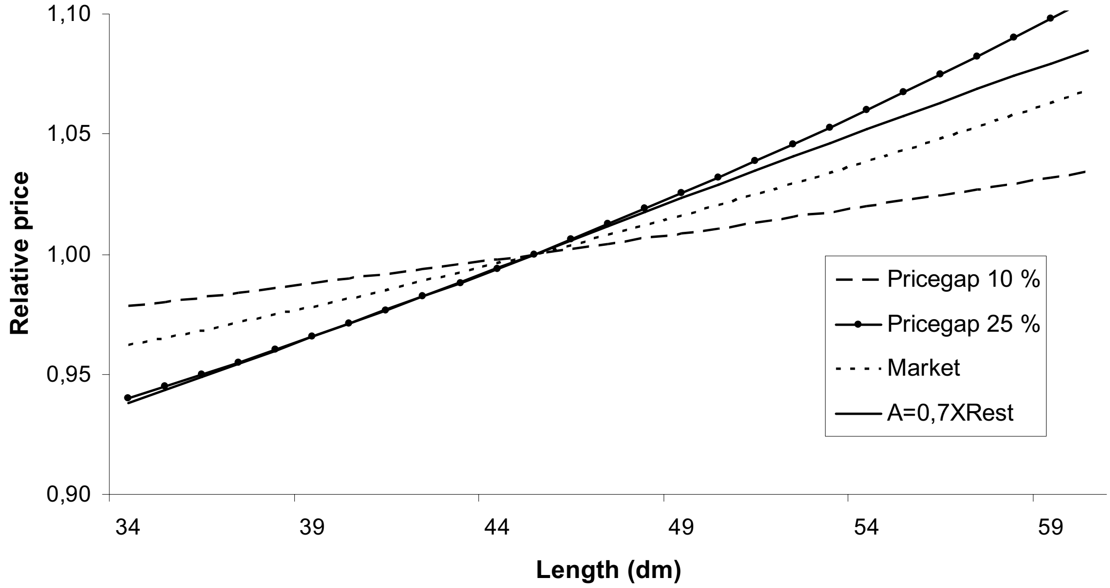


Figure 13. Relative Prices with different assumptions about the price gap between grades for butt logs in the Nordic Timber log model in paper II

In Figure 14, the RP is shown for the different logs in the IN-log model from paper II keeping the price gap constant on all the boards by ranking grade T3, T2, T1 and reject as 1, 0.9, 0.85 and 0.5 respectively. This reflected the current market prices of the grades, and the increasing frequency of reject in logs higher up in the tree counterweighted the stronger length effect in the logs closer to the stump resulting in an almost equal RP-development in the logs.

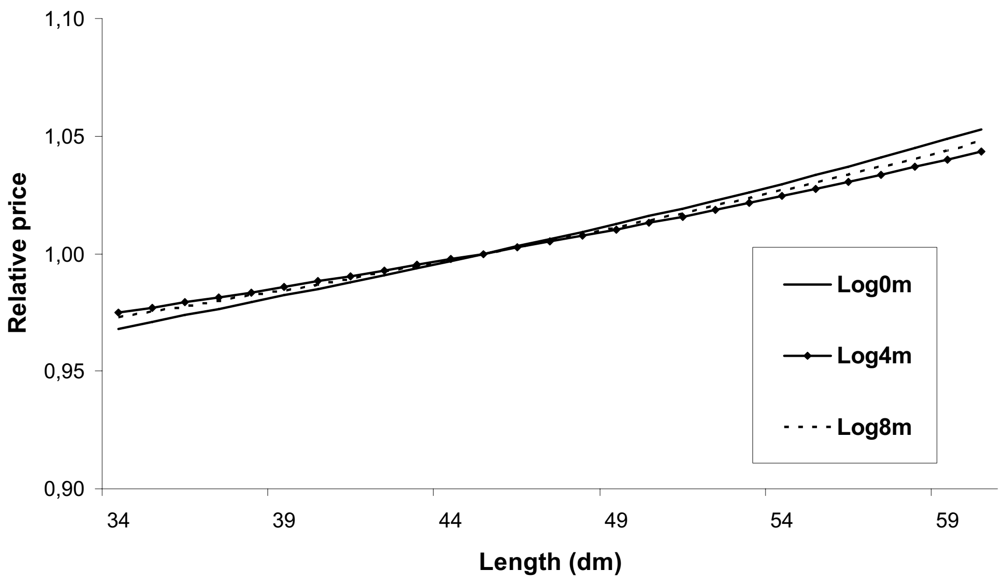


Figure 14. Relative Prices for the logs in the INSTA 142 log model from paper II

The size of RP will depend on the assumptions about the price gap, but showed that from current market prices an increase in the log length from 45 dm to 60 dm will decrease the value of the sawn timber in stock by about 6 %. The size of the length effects found in paper IV was on the same level as that found in paper II, implying that the level of the cost of increasing length seems quite general with a 4 % decrease by 1 meter increase in length being the rule of thumb.

4 Conclusions and final remarks

A decreasing trend in grade from the butt end towards the top end of Norway spruce trees was evident. Moreover, this effect was more pronounced in visual strength grading than in appearance grading. The effect of length on grade yield was strongest in the trees with the highest DBH within the stands, and poorer forest quality also indicated a stronger sensitivity to length increase. This indicates that the biggest trees within a stand, and stands on sites with low forest quality, should be cross-cut in shorter logs in order to obtain high grade yield.

The difference in grade yield between sites of different forest quality was large in machine grading, while for the visual grading rules the effect was significant but not very strong.

Grade yield decreases upwards in the stem, and inner boards give better grade yield than other boards, an effect which is increasing towards the top end in NT-grading. Increasing tree height had a positive effect on grade yield given the same relative DBH of the tree within the stand. The mean diameter at breast height of the stand affected the grade yield negatively given the same tree height. In addition to length, position of a board within a tree is the most important factor for grade yield, and the variation in grade yield within stands is greater than between stands for the grading rules used in this study. The models for predicting grade probabilities seem to fit within a 10 % margin used within the range of the observations in the dataset. A validation is recommended in order to generalise the model. In further studies on this topic, a larger variation in tree and stand ages should be emphasised, in addition to including sites with higher fertility, i.e. site indices of G23 and G26.

The cost of the decreased grade yield by increasing length will depend on the price gap between the grades, and in current market prices a rule of thumb of a 4 % decrease by 1 meter increase in length was found both in strength and appearance grading. The size of the length effect is not the only variable to assess in a sawmill when making decisions on price lists for saw logs and sawn timber and the length appreciation in these. Sawmilling in general is complicated with regards to the definition of saw logs, sawing pattern according to different top diameters, which dimensions to produce, and which grades to use. In this work these things have not been taken in to consideration, since this would have complicated the task of investigating the effect of length on timber grade, and possibly rendered it impossible. Obviously, grades are seldom applied as categorically as in this work, and the older grading rules like “Gröna boken” (Anonymous 1976) had passages saying that the piece of timber had to be graded as a whole. This practice is still embedded in many graders of sawn timber, and may seem reasonable since a couple of millimetres in knot size will rarely diminish the performance of a timber product. A more loose definition of grades would, however, have done the work on investigating the length effect very hard, probably impossible. Another fact is that an increasing portion of timber is graded automatically by scanners, which do require absolute boundaries between the grades.

Hopefully this work will be useful to the sawmilling industry in their planning and budgeting of their production. This work may also be applied in the making of price lists for saw logs, and in the sales of sawn timber there should definitely be a length factor in the selling price, especially for the higher grades.

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Paper I

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ORIGINALARBEITEN · ORIGINALS

Modeling the longitudinal variation of sawn timber grades in Norway spruce (*Picea abies* (L.) Karst.)

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Abstract Grades derived from visual assessments of sawn timber are determined by the worst part of each piece. Since grade varies longitudinally in timber, grade yield will decrease if the average length of timber increases. The variation in grade is caused by longitudinal variation in knot properties and other features as they appear on the sawn surface taken into account during grading. The objective of this study is to describe and analyze this variation in *Picea abies*.

The study consisting of 768 boards for which all features that could lead to downgrading were recorded noting position, type and size. Based on this information, all boards were graded according to appearance by Nordic Timber, and strength by INSTA 142. Logistic regression models of grade as a function of position in the stem were developed, and the dependence between responses was taken into consideration by using General Estimating Equations (GEE). The models showed a decreasing trend in grade from the butt end toward the top end of the trees, and the effect was more pronounced in strength grading than in appearance grading. Models with binomial response and different correlation structures were tested, and it was shown that both independent and autoregressive correlation structures could be used. This suggests that a multinomial ordinal logistic regression with a GEE-approach with an independent correlation structure is appropriate for modeling grade in this study.

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Modellierung der Veränderung der Sortierklassen von Fichtenschnittholz (*Picea abies* (L.) Karst.) in Stammlängsrichtung

Zusammenfassung Bei der visuellen Sortierung wird Schnittholz anhand des größten Fehlers im jeweiligen Stück in eine Sortierklasse eingestuft. Da die Sortierklasse innerhalb eines Holzes in Längsrichtung variiert, nimmt die Ausbeute in den Sortierklassen mit zunehmender Holzlänge ab. Die Veränderungen der Sortierklasse beruhen auf den Veränderungen der Asteigenschaften und anderen sortierentscheidenden, visuell erkennbaren Merkmalen in Längsrichtung. Ziel dieser Studie ist es, diese Veränderungen in *Picea abies* zu beschreiben und zu untersuchen.

Untersucht wurden 768 Schnitthölzer, 38–50 mm dick und 100–225 mm breit, von denen alle sortierrelevanten Merkmale bezüglich Lage, Art und Größe bestimmt wurden. Alle Schnitthölzer wurden nach dem Aussehen gemäß Nordic Timber sowie nach der Festigkeit gemäß INSTA 142 sortiert. Spezielle Regressionsmodelle wurden unter Berücksichtigung der Autokorrelation der Daten entwickelt. Die Modelle zeigten einen Trend zu niedrigeren Sortierklassen vom Fällschnitt bis zum Zopf des Stammes, und dieser Effekt war bei der Festigkeitssortierung stärker ausgeprägt als bei der Sortierung nach dem Aussehen. Verschiedene Modelle mit unterschiedlichen Korrelationsansätzen wurden untersucht und es wurde gezeigt, dass sowohl Modelle mit einfacher Korrelation als auch mit Autokorrelation verwendbar sind. Daraus folgt, dass der hier verwendete multinominale Regressionsansatz ohne Berücksichtigung der Autokorrelation zur Modellierung des Verlaufs der Sortierklassen geeignet ist.

1 Introduction

Grading by visual inspection is a common method used to assess the quality of sawn timber in Norway. Appearance grading of Nordic softwoods is performed according to Nordic Timber (Anonymous 1994). Although many sawmills determine their grades based on customer demands (Lycken 2006), Nordic Timber (Anonymous 1994) decides how to measure features and how to grade the timber. About 80% of the structural timber is machine graded; the rest of the structural timber in Norway is graded by visual inspection. Visual grading of structural timber of Nordic softwood is standardized in INSTA 142 (1997) in accordance with EN 518 (1995). The assessment of the grade based on the worst part of each piece is common to the different grading rules. Since the features vary along the timber, grade yield will decrease with increasing average length of the timber. Orvèr (1973) described this effect in a study of Scots pine. The Nordic timber market demands longer timber, and the saw mills transfer this demand to the forestry through the price system for saw logs. The cost of increasing timber length causes a reduction in grade yield, which raises the question how large this reduction is compared to the gain in increased length.

To answer this question, the first step is to describe the longitudinal variation of sawn timber grades within trees. Longitudinal variation in grades is due to natural variations in features along the stem and how they appear on the sawn surfaces. The most frequent cause for down grading timber is knots, but the grade can also be affected by the slope of grain, annual ring width, reaction wood, resin wood or resin pockets, biological defects like rot, and mechanical injuries. Some of the features may be taken into account when the trees are crosscut, but others are not visible before the timber is sawn. Most knots are visible on the stem surface, but how knots appear on the sawn surface influence the effect on timber grade. Both Nordic Timber (Anonymous 1994) and INSTA 142 (1997) allow larger face knots than edge knots, and the side on which the knots appear is mostly random unless one is able to detect knots in the logs and make sawing patterns based on that information. Björklund and Julin (1998) found no practical effect of this for *Pinus sylvestris.* Johansson and Liljeblad (1988) found some impact of optimizing log position due to geometrical and knot features, but stated that it is difficult to achieve in saw mills today, while Nordmark (2005) claimed that it is possible with new measuring equipment for logs like 3D scanners and X-ray scanners. Most sawmills in Norway focus on sweep in the rotation of the log and knots are generally ignored in the sawing process of *Picea abies*. As a result, the position of knots on the sawn surface will lead to random variation in grade along the stem.

Knots are occluded branches and the diameter of a knot at a radial distance from the pith depends on the branch diameter and branch angle. Branch diameter of *Picea abies* increases upwards in the lower part of the stem (Abetz and Unfried 1983, Braastad 1979, Bues 1996, Colin and Houllier 1991, Handler 1988, Moberg 2001, Vestøl and Høibø 2001), and the maximum branch diameter of a tree is found in the lower part of the living crown (Colin and Houllier 1991, Vestøl and Høibø 2001). Complete vertical profiles of branch- or knot diameter in *Picea abies* have been reported by Colin and Houllier (1991) and Moberg (2001). Since the dimension of sawn timber is limited by the diameter of the log and the allowed knot size depends on the timber dimension (Nordic Timber and INSTA 142), the expected grade is reduced upwards in a tree. The log diameter is mainly a restriction for the timber width, while the thickness is less affected. Therefore, the effect of reduced log diameter is stronger if the grade is limited by face knots than if it is limited by edge knots.

The quality of a knot, namely whether it is sound or dead, is not taken into account in visual strength grading (INSTA 142 1997). However, appearance grading according to Nordic Timber (Anonymous 1994) allows larger sound knots than dead knots in a grade. Vertical profiles of sound knot length in *Picea abies* have been presented by several authors (Moberg 1999, Moberg 2001, Vestøl 1998, Vestøl and Høibø 2000, Øyen 1999). Moberg (2001) found the sound knot length to increase from the stump towards the crown, while Vestøl and Høibø (2000) found that the sound knot length increases up to 40% of tree height. (Øyen 1999) described a sound knot cylinder based on the assumption that sound knot length is relatively constant from 10% of tree height up to the living crown.

Most coniferous species from the Northern Hemisphere have a grain angle clearly to the left near the pith with a gradual decrease turning to the right as the tree grows older (Panshin and De Zeeuw 1980). Both Säll (2002) and Bramming (2006) also found this trend in *Picea abies* with the highest grain angle close to the pith and the culmination point being somewhat farther from the pith higher up in trees (Säll 2002).

The radial variation in ring width, especially in the lower parts of the stem, is influenced by stand density. Pressler's rule has been used to describe the annual increment in basal area for trees as demonstrated by Deleuze and Houllier (1995) and Houllier et al. (1995) in their studies of *Picea abies.* Pressler's rule states that the basal area increment is constant from the stump up to the base of the functional part of the crown. Since the girth of the stem decreases from the stump upwards, annual rings will be widest at the crown base with a sharper decrease upwards in the crown than downwards towards the stump.

Reaction wood is a response to external impacts primarily caused by slope, wind, injuries, branches and insect attacks (Zobel and Van Buijtenen 1989). Compression wood is most frequent in the first few growth rings near the pith, but there is no clear conclusion about the longitudinal variation within trees since the reasons for the formation of reaction wood are so numerous (Timell 1986). Perstorper et al. (1995) found more compression wood in top logs compared to butt logs, but no radial variation. Öhman (2002) concluded that the sweep will give good indications about the frequency of compression wood in *Picea abies* logs, and will be a better predictor as such than the position in the stem.

The occurrence of resin pockets in *Picea abies* was described by Temnerud (1997). His conclusion was that the probability of occurrence of resin pockets was lowest in innerwood of butt logs. The probability of occurrence of resin pockets increased with the distance from the pith and declining top diameter, indicating an increase towards the top of the tree. This was confirmed by both Herb and Becker (2006) and Gjerdrum and Bernabei (2007). The variability is however great, and the differences between trees within a stand and between stands are of such magnitude that it might be considered as random in sawn timber.

Biological damages and damages due to wind, snow, thinning, etc. are hard to model because of extreme local variations, and also because the silvicultural program for the stand influences these variables (Braastad 1979, Persson 1972, Persson 1976). Damages from the production process will depend on the specific saw mill's equipment and logistic.

It is common to find that timber grade yield is reduced as stem height increases. This is mainly due to increasing knot diameter and decreasing log diameter. This trend was found by (Høibø 1991) in his study of *Picea abies,* and by Blomqvist and Nylinder (1988b) for *Pinus sylvestris*. Blomqvist and Nylinder (1988a) found greater homogeneity in grade in butt logs of *Picea abies,* but not a significantly better yield. This vertical variation has to be taken into account when analyzing the effect of length on visual grading of sawn timber. The objective of this paper is to describe and analyze the longitudinal variation of sawn timber grade in *Picea abies*.

2 Materials and methods

2.1 Grading

The longitudinal variation in grade was measured by grading longitudinal sections of sawn timber. All features were recorded as described in Nordic Timber (Anonymous 1994) and INSTA 142 (1997) in boards from the centre yield (Fig. 3). The data included size, type and position of features which may lead to downgrading by one of the grading rules. In total, 10 368 features were recorded, and Fig. 1 shows the frequency of the different features.

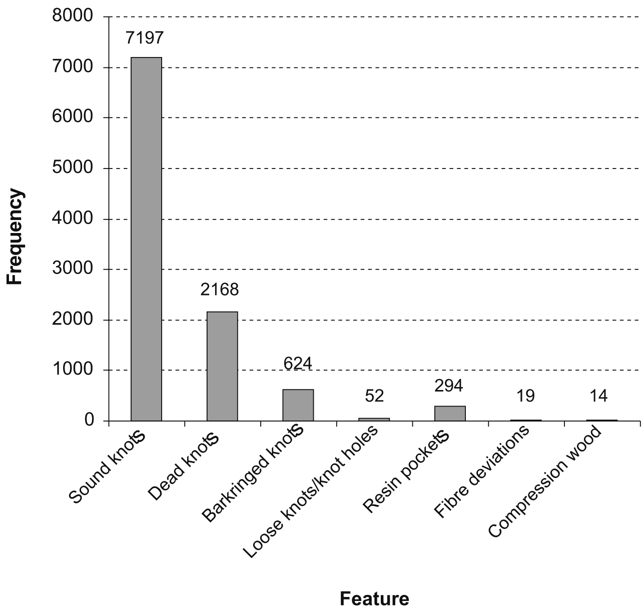

Fig. 1 Frequency of the recorded features
Abb. 1 Häufigkeit der erfassten Merkmale

The grades were assessed for 100 cm sections, the first starting from the butt end and a new section starting every 10 cm upwards. This means that there was a 90% overlap between two neighbouring sections. Up to 100 centimetres from the butt end was denoted "Section 1", the section from 10 cm to 110 cm was denoted "Section 2" and so on (Fig. 2). This was continued along all boards upwards in the tree, relating all sections to the distance from the butt end. The analyses were limited to "Section 155" since only a few trees had sawn timber above this level.

Nordic Timber (Anonymous 1994) utilizes four grades A, B, C and D with A as the best, and D as reject. It is possible to divide grade A into four different subclasses called A1 to A4, but that was not done in this study. According to Nordic Timber (Anonymous 1994) each section was graded based on data from all four sides.

According to INSTA 142 (1997) each feature is graded independently in order to isolate the weakest part of the board, which decides the strength property of the whole board. The rules specify four grades, and using the standard EN 1912 (2005) each grade is assigned to strength classes defined in EN 338 (2003). The grades used in this study

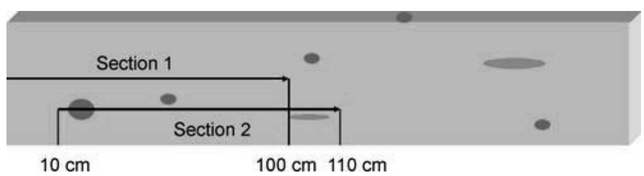

Fig. 2 Division of a board into sections
Abb. 2 Einteilung der Schnitthölzer in Abschnitte

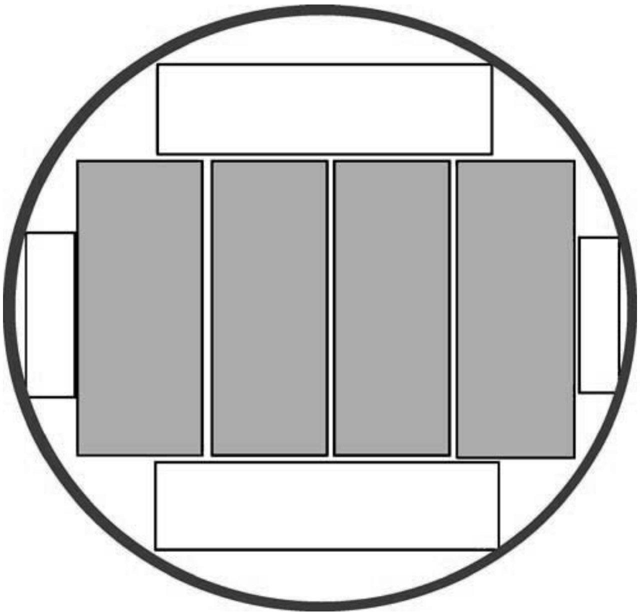

Fig. 3 Sawing pattern with boards from centre yield in *grey*
Abb. 3 Schnittbild mit den Schnitthölzern des Hauptproduktes in *grau*

(strength class in brackets) were T3 (C30), T2 (C24), T1 (C18) and reject.

2.2 Material

The study was based on data collected from 768 boards originating from the centre yield (Fig. 3) of 56 trees of *Picea abies* from four different sites in south-eastern Norway. Sample 1 and 2 each included eight trees. The trees in sample 1 were cross-cut according to the standard log quality system used in Norway assigning saw logs to one of two different grades. Sample 2 was cross-cut based on a method seeking to optimize the production of timber with sound knots (Øyen 1999). The trees in samples 1 and 2 came from two different sites (site 1 and 2 in Table 1) with site index 17 m and 23 m according to the H_{40} system of Tveite (1971). Sample 3 and 4 each included 20 trees from two sites (site 3 and 4 in Table 1) with site index 17 m. The trees from sample 4 were crosscut in the same way as sample 1, while the trees from sample 3 were cross-cut with fixed lengths of 4.0 m in butt logs and the rest of the logs cut to a length of 5.0 m (Birkeland and Øvrum 2005). This is due to the dimensions of the boards and their length as a final product. All trees were sampled due to diameter, and the main aim was to compare effects of different cross-cutting on same diameter trees. Whole tree attributes of the sampled trees from the different sites are presented in Table 1.

Each tree was cross-cut into 3 to 5 logs depending on the size of the tree and the length of the logs in the cross-cutting, resulting in 207 logs altogether. The sawing was done according to Nordic practice as defined in Anonymous (1994), with heart splitting giving either 2, 4 or 6 ex-logs depending on the diameter of the log processed. This means that either 2, 4 or 6 boards from each log were analysed, and the thickness of the centre yield was 38 or 50 mm, with widths in inches intervals ranging from 100 to 225 mm depending on log diameter.

2.3 Statistical analysis

The within-tree variation in timber grade was described using logistic regression with grade as a categorical response and distance from stump as a continuous predictor. The general form of logistic regression is a generalized linear model using logit, which is the logarithm of the odds as its link function (Agresti 2002). The model has the form:

$$\operatorname{logit}(p_i) = \ln\left(\frac{p_i}{1-p_i}\right) = \alpha + \beta_1 x_{1,i} + \ldots + \beta_k x_{k,i},$$
$$i = 1, \ldots, n\,,$$

where

$$p_i = \Pr(Y_i = 1)\,.$$

The logarithm of the odds of the outcome is modelled as a linear function of the predictors, X_i. The basic form of logistic regression is modelling of a binary outcome where the response has no individual ranking. Since both grading rules have four classes with a distinct ranking, the model was expanded to address this. A multinomial distribution was chosen, and because these levels are ranked an ordinal approach was most appropriate. In ordinal multinomial logistic regression Y takes on one of $k+1$ possible values, denoted by 1, 2, ..., k, $k+1$, and there is an inherent ordering in the response values. This is expressed as

$$p_i = P\,(Y_i \le k|\,x)\,,$$

Table 1 Whole tree attributes of the sample trees (numbers in brackets are the standard deviation)
Tabelle 1 Merkmale der Probebäume (Zahlen in Klammern geben die Standardabweichung an)

Site	Site index H_{40} [m]	Age [yrs.]	Diameter at breast height [mm]	Tree height [dm]	Height to the crown base (180° of the whorl living) [dm]
1	23	57 (2)	296 (30)	262 (13)	134 (12)
2	17	94 (4)	304 (33)	233 (21)	114 (19)
3	17	112 (27)	389 (27)	269 (11)	114 (29)
4	17	112 (6)	418 (30)	291 (20)	120 (27)

where $\boldsymbol{x}$ is a vector of explanatory variables. The specific model becomes

$$\text{logit}(p_i) = \ln\left(\frac{p_i}{1-p_i}\right) = \alpha + \boldsymbol{\beta}\boldsymbol{x}' ,$$

where $\alpha_1, \alpha_2, \ldots, \alpha_k$ are intercept parameters and $\boldsymbol{\beta}$ is a vector of slope parameters. This is a parallel lines regression model based on the cumulative probabilities of the response categories, also known as the proportional odds model. This logit model is called a cumulative logit.

Since the different sections within a tree may be dependent, one would suspect that the independence criteria assumed in generalized linear models might be violated. This means that the general requirements in logistic regression will not be satisfied, and especially the tests of significance will be erroneous. Constantly introducing new sections within a tree is assumed to have the form of repeated measures. Repeated measures are common in social and medical studies, where the same subjects are measured at different points in time. A solution for such problems was presented by Liang and Zeger (1986) and Zeger and Liang (1986) by implementing Generalized Estimating Equations (GEE). The principle of this approach is to introduce a working generalized model for the marginal distribution of Y_i. No specification of the joint distribution of the repeated measures is made, but merely estimating equations that give consistent estimates of the regression parameters, and of their variances under weak assumptions about the joint distribution (Agresti 2002). In such an approach, independence between subjects is required, but the distribution in the response and predictors is not that important (Agresti 2002). Fitting a GEE model requires the user to specify the link function, the distribution of the dependent variable, and the correlation structure of the dependent variable (Ballinger 2004). In this study, the subject of the correlation structure was defined as a tree, and the parameter estimates were calculated taking the correlation within trees into consideration.

The analysis was performed with the GENMOD procedure in SAS, which allows the use of GEE, and the algorithm is based on the work by Liang and Zeger (1986). The distribution was assumed multinomial, and the link function as cumulative logit. The only correlation structure available under these specifications in SAS is independent (SAS 2000). In binomial cases, one may choose between various correlation structures like exchangeable, m-dependent, autoregressive or unstructured. Several authors have stated that a miss-specified correlation structure will not greatly affect the estimates with the GEE-approach (Agresti 2002, Hardin and Hilbe 2003, Liang and Zeger 1986, SAS 2000), and that the efficiency in exactly specifying the correlation structure is slight. A notion was expressed by Agresti (2002) that this is under the assumption that the correlation within the responses is quite small. This is not the case in this study leading to an investigation of how different correlation structures affect the parameter estimates. Since this is only possible for binary responses, a binary variable was defined as the probability of attaining the highest grade, namely A or T3, respectively. The different correlation structures tested and compared were as follows:

- Independence (IND), which assumes no correlation between zones.
- Exchangeable (EXCH), which assumes that each response in the cluster is equally correlated.
- Autoregressive (AR), which is developed from studies of time series, and assumes that responses are dependent "on their past", so that the correlation between responses diminishes as the distance between them increases.

A normal generalized model without the implementation of GEE in the form of a logistic regression was included in the comparison, and also the estimates from the multinomial model. In all the models, each response was weighted for the overlapping sections, namely 1/9, and divided by the number of boards in each section of the tree. This means that each 1 meter segment of every tree gives one degree of freedom for the models. Hardin and Hilbe (2003) suggested using the Quasilikelihood under the Independence model Criterion (QIC) statistic proposed by Pan (2001) to discern the best choice of correlation structure unless the choice is obvious. A comparison by calculating the QIC for the different correlation structures was therefore made by using the SAS-macro "*%QIC macro*", where the best choice of correlation structure is indicated by the lowest QIC. The significance of variables was evaluated by a type 3 score test, which is the only available test of significance for the variables, when GEE is used in SAS.

3 Results

3.1 Nordic Timber (NT) grading

Table 2 shows a summary of the NT grades and the frequency of down grading features when each section was

Table 2 Summary of grades and downgrading features after NT
Tabelle 2 Sortierklassen und sortierentscheidende Merkmale bei der Sortierung nach dem Aussehen (NT)

Grade	Number of sections	Downgrading features Knots	Other
A	21585 (74.5%)		
B	5616 (19.4%)	5204 (92.7%)	412 (7.3%)
C	1508 (5.2%)	1269 (84.2%)	239 (15.8%)
D	187 (0.7%)	142 (75.9%)	45 (24.1%)
Total	28896	6615	696

Table 3 Parameter estimates for α, β and QIC for different correlation structures in the GEE-model
Tabelle 3 Schätzwerte für die Parameter α, β und QIC bei verschiedenen Korrelationsansätzen

Model	Correlation structure	α	β (SE β)	p-value type 3 test	QIC
Multinomial	Independent	1.3845	−0.0040 (0.0016)	0.0210	
Binomial	None	1.4223	−0.0045 (0.0018)	0.0118	
Binomial	Independent	1.4223	−0.0045 (0.0016)	0.0103	1008.55
Binomial	Exchangeable	2.1730	−0.0070 (0.0027)	0.0017	1093.19
Binomial	Autoregressive	1.4317	−0.0047 (0.0016)	0.0086	1008.56

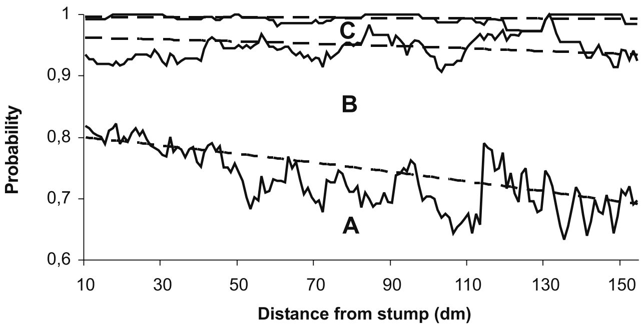

Fig. 4 An ordinal multinomial regression model (*dotted lines*) compared to the actual frequency (*solid-drawn lines*) of grades after NT
Abb. 4 Verlauf der Ausbeuten in den Sortierklassen A, B, C (NT). Regressionsmodell (*gestrichelte Linien*), Messwerte (*durchgezogene Linien*)

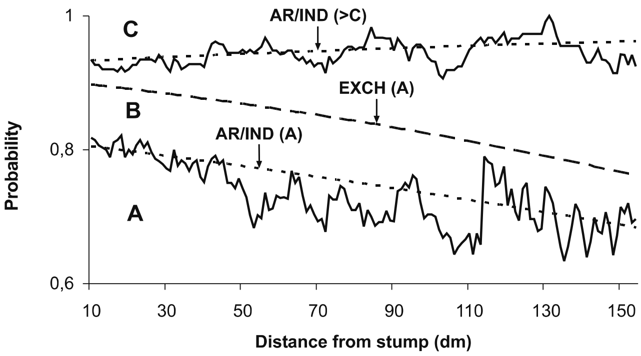

Fig. 5 The distribution of $P(A)$ and $P(>C)$ (*solid-drawn lines*) compared to the estimates from the different GEE-models (*dotted lines*). The AR and IND lines are overlapping
Abb. 5 Verlauf der Ausbeuten der Klassen (A und $>C$) (*durchgezogene Linien*). Schätzwerte der verschiedenen statistischen Modelle (*gepunktete Linien*). Die AR und IND Linien liegen übereinander

graded independently. The number of graded sections in each board was given by board length in dm –9, giving for instance 41 sections in a 50 dm long board (50–9). In total 28 896 sections were graded.

A multinomial ordinal logistic regression with grade of the different sections as the response, and the distance from the stump as the predictor using a GEE approach with the tree as the subject of the correlation gave a type 3 score test with a p-level of 0.021, and a parameter estimate for α of -0.0040. This suggests a decreasing trend in grade upwards in the tree when grading according to NT. The model is presented in Fig. 4.

The results of a binomial ordinal logistic regression of the probability of attaining grade A with different correlation structures in the GEE approach are presented in Table 3.

A similar study was made for the possibility of attaining grade A or B, namely $P(>C)$, and in this case none of the GEE-models gave a significant effect of distance from stump for the $P(>C)$, suggesting that the probability of attaining a better grade than C is equal throughout the tree. A comparison between the actual frequency of $P(A)$, and $P(>C)$ to the models obtained from an independence correlation structure (IND), an autoregressive correlation structure (AR), and an exchangeable correlation structure (EXCH) is shown in Fig. 5.

3.2 INSTA 142 (IN) grading

Table 4 shows a summary of the IN grades and the frequency of downgrading features in the sections when each section was graded independently.

A multinomial ordinal logistic regression with grade of the different zones as response, and the distance from the stump as predictor using a GEE approach with the tree as the subject of the correlation gave a type 3 score test with a p-level of < 0.0001, and a parameter estimate for α of -0.0197. This suggests a stronger decreasing trend in grade upwards in the tree when grading according to IN rather than NT. The model is presented in Fig. 6.

The results of binomial ordinal logistic regression for the probability of attaining grade T3 with different correlation structures in the GEE approach are presented in Table 5.

A similar study was made for the probability of attaining grade $T3$ or $T2$, namely $P(>T1)$, and the pattern was similar to that of $P(T3)$. A comparison between the actual frequency of $P(T3)$, and $P(>T1)$ to the models obtained

Table 4 Summary of grades downgrading features after IN
Tabelle 4 Sortierklassen und sortierentscheidende Merkmale bei der Sortierung nach der Festigkeit (IN)

Grade	Number of sections	Downgrading features	
		Knots	Other
T3	12 109 (41.9%)		
T2	8919 (30.9%)	8820 (98.9%)	99 (1.1%)
T1	7089 (24.5%)	6745 (95.1%)	344 (4.9%)
R	779 (2.7%)	546 (70.1%)	233 (29.9%)
Total	28 896	16 111	676

Table 5 Parameter estimates for α, β and QIC for different correlation structures in the GEE-model
Tabelle 5 Schätzwerte für die Parameter α, β und QIC bei verschiedenen Korrelationsansätzen

Model	Correlation structure	α	β (SE β)	p-value type 3 test	QIC
Multinomial	Independent	0.8109	−0.0197 (0.0014)	< 0.0001	
Binomial	None	0.9527	−0.0223 (0.0020)	< 0.0001	
Binomial	Independent	0.9527	−0.0223 (0.0020)	< 0.0001	1022.47
Binomial	Autoregressive	0.9657	−0.0225 (0.0020)	< 0.0001	1022.51
Binomial	Exchangeable	0.7558	−0.0229 (0.0022)	–	1056.36

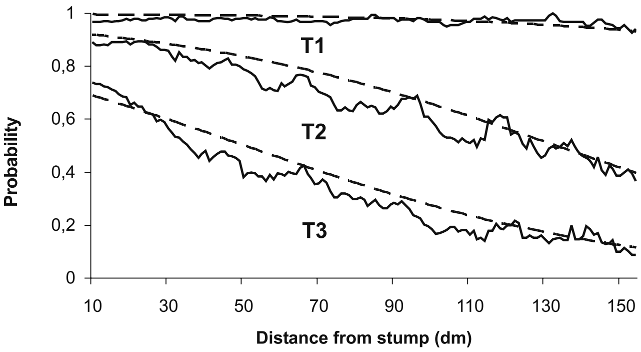

Fig. 6 An ordinal multinomial regression model (*dotted lines*) compared to the actual frequency (*solid-drawn lines*) of grades after IN
Abb. 6 Verlauf der Ausbeuten in den Sortierklassen A, B, C (IN). Regressionsmodell (*gestrichelte Linien*), Messwerte (*durchgezogene Linien*)

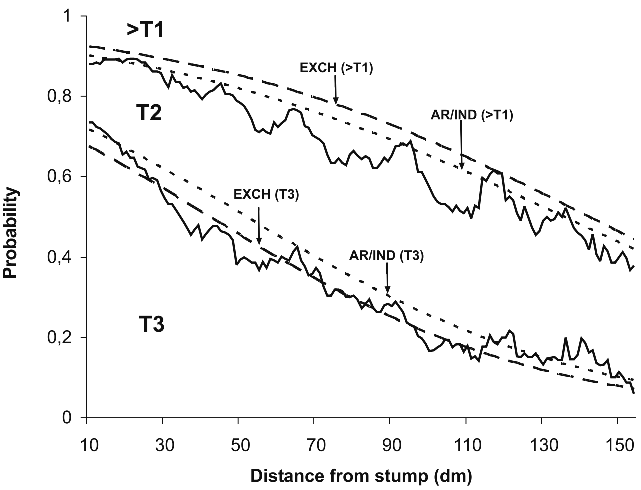

Fig. 7 The distribution of $P(T3)$ and $P(>T1)$ (*solid-drawn lines*) compared to the estimates from the different GEE-models (*dotted lines*). The AR and IND lines are overlapping
Abb. 7 Verlauf der Ausbeuten der Klassen ($T3$ und $T1$) (*durchgezogene Linien*). Schätzwerte der verschiedenen statistischen Modelle (*gepunktete Linien*). Die AR und IND Linien liegen übereinander

from an independence correlation structure (IND), an autoregressive correlation structure (AR), and an exchangeable correlation structure (EXCH) is shown in Fig. 7.

4 Discussion

As shown in Table 2, downgrading from A to B in NT is mainly caused by knots. Since knot diameter increases with increasing distance from stump (Moberg 2001, Vestøl 1998, Vestøl and Høibø 2001), a lower probability of the better grades is expected at higher positions. In the lower part of the stem where most of the knots are dead, P(A) decreases as the dry knots prominently increase in size. Closer to the crown base, the increase in knot size is not as strong, and there is also an increasing proportion of sound knots. Since the allowed size of sound knots is larger than it is for dead knots in NT, longitudinal variation in grade is moderate. Downgrading to C and D is often caused by features other than knots (Table 2) which occur randomly in the stems. This explains the insignificant effect of longitudinal position for these grades.

For IN-grading, the decreasing trend in grade from the butt end and upwards is more pronounced than it is for NT-grading, especially up to 11 meters for T3. Since the allowed knot size is independent of whether the knot is sound or dead, the vertical variation is mainly due to the vertical variation in knot size and to the dimension of sawn timber. The increase in knot size is largest in the lower part of the stems and it continues up to the lower part of the living crown (Moberg 2001, Vestøl 1998, Vestøl and Høibø 2001). The crown base, defined as the position where the living crown covers 180°, is about 12 meters on average (see Table 1). In IN-grading, edge knot is a frequent down grading feature, and since the thickness was 50 mm for most of the boards in this study, the increasing knot size towards the crown base had a direct effect on the frequency of T3 towards the crown.

To use the tree as a subject in the GEE-analysis, and hence claim that all trees are independent might be disputed. Trees from the same stand may be dependent to some extent (Moberg 2001) especially if the stand has been intensively managed giving trees with uniform branching. However, the stands in this study were not intensively managed, and quite similar, and, considering the objective of this study, independence between trees can be justified. Nevertheless, the samples were not representative for the stands and it was not possible to analyze this effect in this study.

To use GEE in the logistic regression models gives no additional impact other than more efficient and unbiased estimators (Ballinger 2004), and secures that the chance of making type II errors are minimized. The strength of GEE is that the variation is calculated while the correlation is considered (Hardin and Hilbe 2003). The parameter estimate is similar to that of the normal generalized linear models, but the variance differs compared to an assumption of independent responses. This compensates for the potential underestimation of variance, and gives a more correct variance estimation leading to safer conclusions about the significance of variables. Agresti (2002) noted that some researchers are critical of GEE for lack of likelihood, and that some consider it more of an estimation method rather than a model. With the introduction of QIC, a comparison between models is present, and makes GEE a suitable tool in this study.

Choosing a correlation structure is not intuitive but AR would be the most obvious choice. However, the results show that AR and IND give approximately the same estimates, and overall better results than EXCH. This suggests that using a multinomial ordinal logistic regression with a GEE-approach with an independent correlation structure is an appropriate choice for ascertaining significance and trends in this study. Since the study was based on limited data, the results cannot be generalised without further studies. The sites were located within a small geographic area with limited variations in growth conditions, and the sampling within sites was restricted to specific diameter intervals. This means that the samples do not represent the variability within sites, and cannot be used in studies of variations among trees at a site and between sites. Such variations may also influence the within-tree variability and particularly the influence of correlation structure. Further studies will be made to investigate these variations.

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Paper II

Modeling the effect of length on yield of sawn timber grades in Norway spruce (*Picea abies* (L.) Karst.)

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Abstract

The aim of the study was to model and analyse the effect of length on grade yield of timber from different stem parts in *Picea abies*, and to use the models to simulate the cost of reduced grade yield due to increased length.

The boards were simulated having lengths ranging from 20 dm to 60 dm starting at stump level, 4 m above stump level and 8 m above stump level respectively.

Logistic regression models showed that length had a significant effect on grade yield, and this length effect was stronger in strength grading according to INSTA 142 (IN) compared to appearance grading according to Nordic Timber (NT). The length effect was most pronounced in butt logs, and somewhat greater in middle logs compared to top logs. Also a smaller length effect in inner boards compared to boards farther from the pith was found for IN-grading.

The cost of the decrease in grade yield with increasing length will depend on the assumptions about the price gap between the grades. Current market prices in both grading rules gave a decrease in value of the sawn timber in stock by about 6 % with an increase in the log length from 45 dm to 60 dm. In addition, a decrease in yield of timber in longer logs will amplify this effect, while a higher efficiency in the production process will diminish it.

Introduction

Length of timber is an important consideration for the Norwegian sawmilling industry. The timber length is limited by the log length, which is usually decided during the logging process. The stems are cross-cut according to price lists, where the price of a log per cubic meter is determined by the saw log class, the top diameter and the length of the log, resulting in a variety of log lengths. The traditional Norwegian cross cutting regime was developed in the late 1960s, and was based on the grades of inner centre boards according to the old grading rules for sawn timber in Norway called “ØS-rules”(Anonymous 1981). It defined two saw log classes called prima and sekunda (Anonymous 1994a). The best class, prima, was meant to give two centre boards in the grade US (unsorted) according to the “ØS-rules”, and boards of fifth grade from sekunda logs, alternatively one board of US and one of sixth grade (Müller 1984). Since then the grading rules for saw logs have been modified several times without testing the consequences on sawn timber quality. In addition, the sawing pattern is quite different from what it was in the late 1960s, namely boards in the centre yield are thinner, 38 mm and 50 mm thick, compared to the commonly used thicknesses of 63 mm and 75 mm in the 1960s, and a stricter requirement on wane today. This has decreased the ability to predict quality on sawn timber in the traditional cross-cutting scheme (Dalen and Høibø 1985; Haugen 1996; Müller 1984).

Until 1989, Norway had national price lists for saw logs, one for prima and one for sekunda, and prices were negotiated at a national level. Today, there are no general restrictions regarding which grading rules or price lists one must use. This has resulted in many sawmills having just one quality class for saw logs, where the quality requirements normally are similar to the lowest class from the old saw log rules (sekunda). Most larger sawmills also have their own unique price lists, which are meant to reflect the sale of sawn timber in terms of dimensions and lengths. Often these lists have a stronger length appreciation than the old standard lists, and together with the fact that one saw log class gives longer logs on average, most sawmills report that the mean length of logs has increased. This improves the sawmill’s efficiency because most of the operations happen with transverse transportation of the timber. It is also an advantage in the transport process in the forest, from the forest to the sawmill and from the sawmill to the customer. A variety of log lengths is the result, which can be a challenge both logistically and in the sales process. The buyers of sawn timber specify their needs for accurate lengths based on their customers' needs, and it is vital for timber as a product to give the end-customer an appropriate product length that is "long enough". A higher mean length is an advantage in market access, but so far not in price.

As pointed out by Øvrum et al. (2008), increased length will give a decrease in grade yield since the worst part of a board determines the grade. Former grading rules used in Norway like the "ØS-rules" (Anonymous 1981) and "Gröna bokan" (Anonymous 1976), included a clause saying that "a board which otherwise clearly satisfy the grade may have occasional features over the limit for the grade". This is not the case in modern rules for appearance grading like Nordic Timber (Anonymous 1994b) and EN 1611-1 (2000), and thus emphasize the effect of decrease in grade.

In grading of structural timber the worst part has always determined the grade, since failure may be expected to occur in the weakest point. This is also taken into account by the size effect used in structural engineering. Size effect is based on the "Weakest link theory" developed by Weibull (1939) in his studies of brittle materials (ref. by Rouger and Barrett 1995). The size effect is due to increased probability of finding a strength reducing component in a larger piece of timber than in a smaller piece of timber. This has been used for decades and is implemented in standards for structural timber, for instance in EN 384 (2004), to determine bending and tension strength for different sizes of timber. The model for size effect in structural timber consists of a probability model of failure as a function of stress and a probability of failure depending on the number of independent elements. The size effect can be divided in to a depth factor and a length factor, and the length factor have been investigated by many workers, i.e. (Barrett and Fewell 1990; Isaksson 1999; Lam and Varoglu 1990; Madsen 1990; Rouger and Fewell 1994).

The effect of length on timber grades from Scots pine (*Pinus sylvestris* L.) in Sweden was investigated by Orvèr (1973). To the authors' knowledge, such studies have not been performed on Norway spruce. Since several Norwegian sawmills want to increase the average timber length, it is of interest to quantify what effect this will have on the expected grade yield. Such information may be used to develop a price system for sawn timber that favours length as well as grade, and it may also be used to develop price lists for saw logs.

The aim of this study is to model and analyse the effect of length on grade yield of timber from different stem parts of Norway spruce, and to use the models to simulate the cost of reduced grade yield due to increased length.

Material and methods

The basis for the analysis was the material presented by (Øvrum et al. 2008), where every 1 meter section in 1 dm intervals in centre boards of 56 Norway spruce trees were appearance graded according to Nordic timber (Anonymous 1994b), and strength graded according to INSTA 142 (1997). Based on these sections, grading of boards from three different logs of each tree were simulated, i.e. logs with butt end at stump level (*Log0m*), logs with butt end 4 m above stump level (*Log4m*) and logs with butt end 8 m above stump level (*Log8m*) (Figure 1). All logs were simulated with lengths ranging from 20 dm to 60 dm with 1 dm intervals.

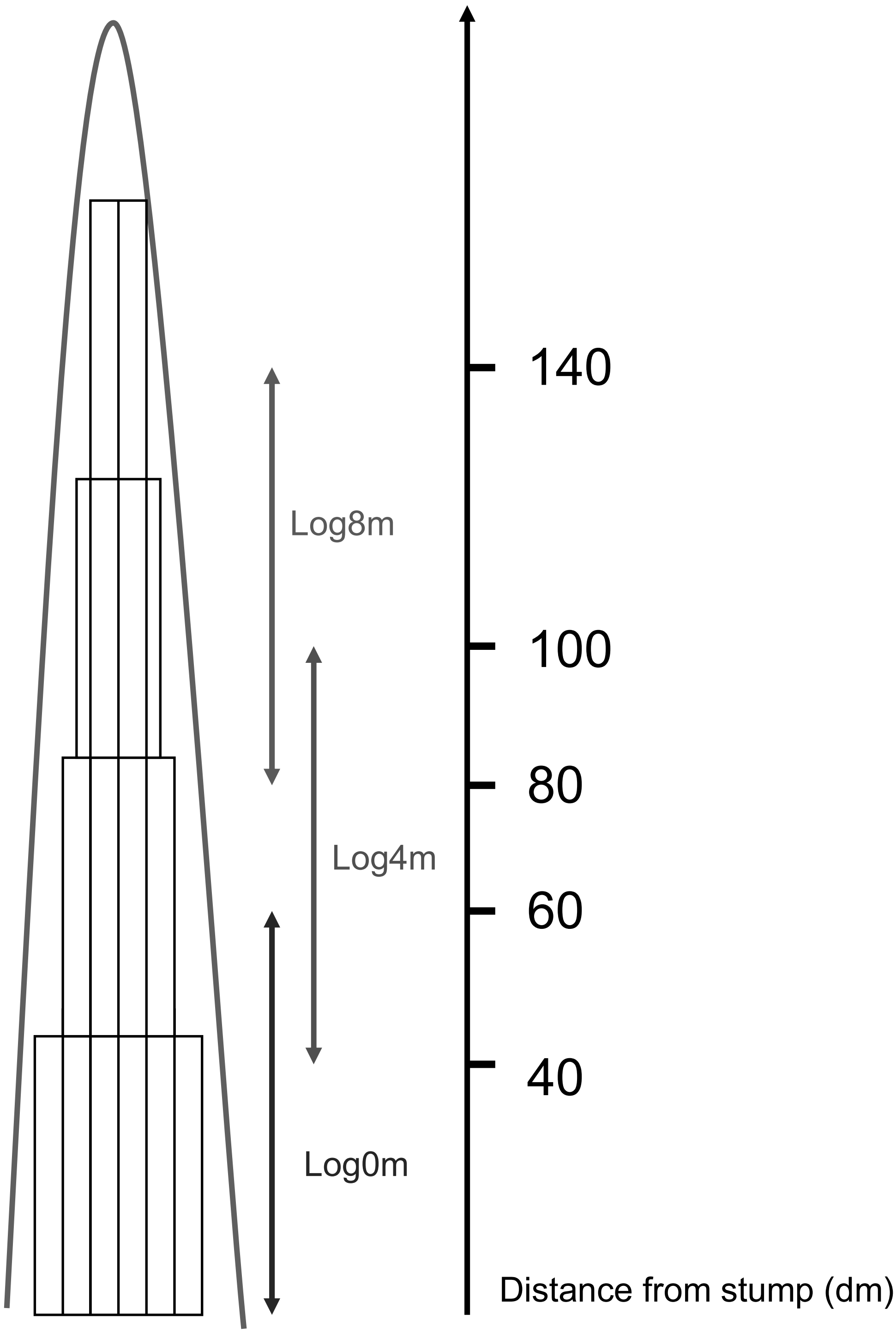

Figure 1. The simulated logs in the stems together with actual logs and boards

The accumulated probability of grade in each board at the various lengths was regarded as response in logistic regression models, and the predictors were both continuous and discrete.

The following variables were tested for significance in different models:

- Length of board was regarded as a continuous variable ranging from 20 dm to 60 dm with intervals of 1 dm.
- Type of log was regarded as a categorical variable: *Log0m, Log4m* or *Log8m.*
- Type of board was regarded as a categorical variable: *I* for inner board, defined as boards on each side of the pith, and *Y* for other boards.

Effects were removed from the models if the p-values of the type 3-test exceeded 0.05.

Boards from the centre yield of a log have the same length unless they have been cut after sawing. In order to investigate the effect of cross cutting on timber grade yield, one may simplify the model by ignoring type of board. However, since inner and outer boards are used for different products, it may be of interest to know the length effect in different boards to be able to assess the price of different products. To be able to address both these questions effectively, both a "board model" where the effect of type of board was tested, and a "log model" where the effect of type of board was ignored were developed.

The analyses were performed as multinomial logistic regression, using GEE-approach with independent correlation structure and weighting as described in a previous study (Øvrum et al.(2008), except with boards from the measured sample as the subject of the correlation structure. This means that the parameter estimates were calculated taking the correlation within boards into consideration. Odds ratios are presented for the length effect to show the decrease in odds of obtaining the same grade if the length is increased by 1 dm.

Results

Grading after Nordic Timber (NT)

NT-log model

Log type (p-value = 0.0086) and the interaction effect of length and log type (p-value = 0.046) were found to be significant together with the length (p-value < 0.0001). The log model for NT-grading is stated in equation 1, and parameter estimates are given in Table 1.

$$P(Y \leq k) = \frac{e^{\alpha_k + \alpha_L + (\beta_L + \beta_0) \times length}}{1 + e^{\alpha_k + \alpha_L + (\beta_L + \beta_0) \times length}}, \text{ k=A, B, C} \qquad (1)$$

Table 1: Parameter estimates for the NT-log model where α_k is dependent on the grade, α_L and β_L on the log type

Parameter		**Estimates**	**Odds ratios**
α_k	α_A	0.3744	
	α_B	2.2886	
	α_C	4.3027	
	β_0	-0.0265	
α_L	α_{Log0m}	0.8418	
	α_{Log4m}	0.0637	
	α_{Log8m}	0	
β_L	β_{Log0m}	-0.0197	0.9549
	β_{Log4m}	-0.0043	0.9697
	β_{Log8m}	0	0.9738

Figure 2 shows the models together with the actual frequency of the NT-grades.

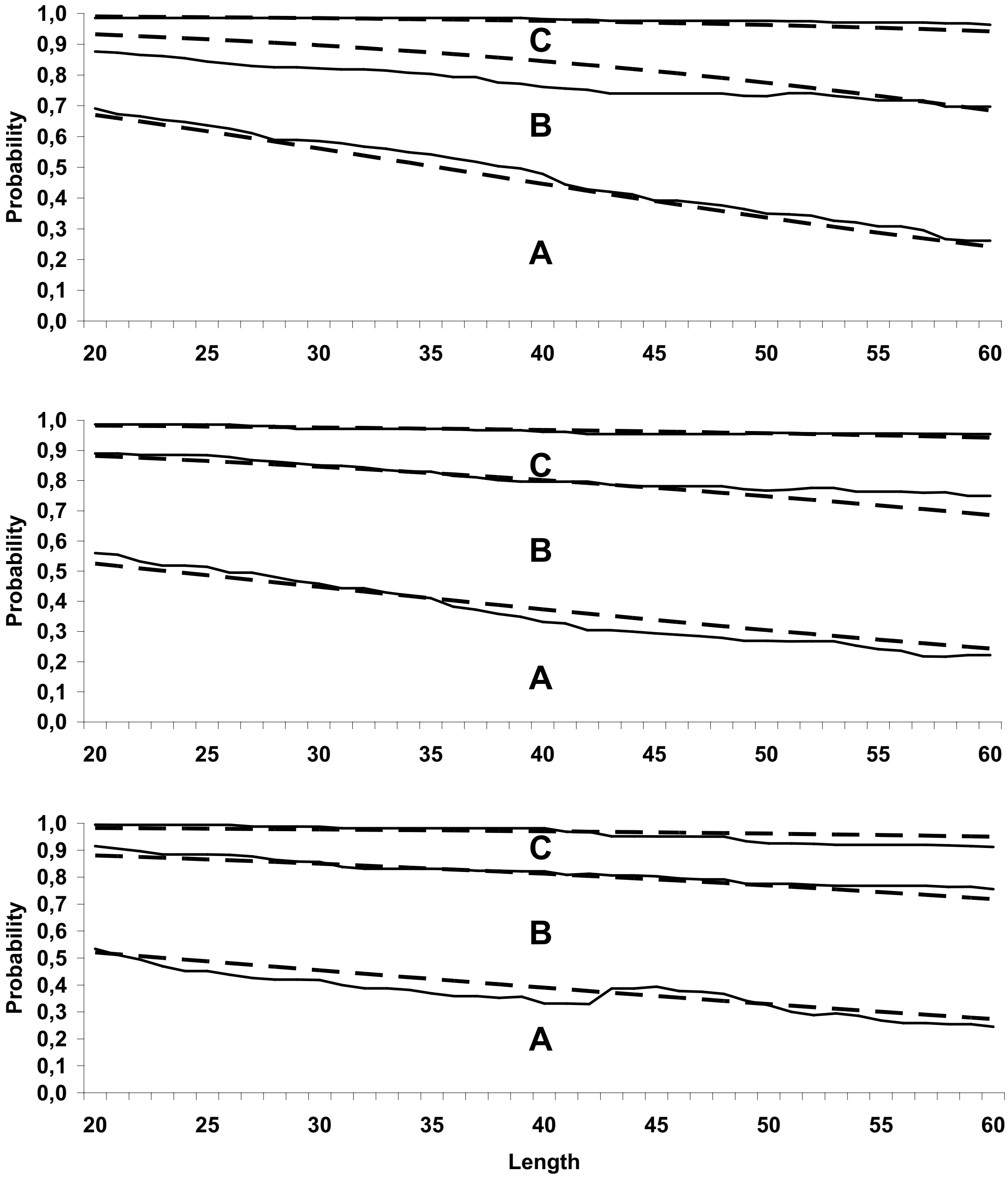

Figure 2. Log models for NT-grades (dotted lines) together with the frequency of NT-grades (solid lines). From the top, Log0m, Log4m and Log8m.

NT-board model

For the board model, neither the interaction boardXlength (p-value=0.18) nor logXlength (p-value=0.17) were significant, indicating that the length effect is constant throughout the stems for NT-grading. Log type (p-value = 0.0016), board type (p-value < 0.0001) and their interaction effect (p-value = 0.0046) were found to be significant together with the length (p-value <0.0001). The board model for NT-grading is stated in equation 2 and parameter estimates are given in Table 2.

$$P(Y \leq k) = \frac{e^{\alpha_k + \alpha_{LB} + \beta \times length}}{1 + e^{\alpha_k + \alpha_{LB} + \beta \times length}}, \text{ k=A, B, C} \qquad (2)$$

Table 2. Parameter estimates for the NT-board model, where α_k is dependent on the grade and α_{LB} on the log x board combination

Parameter		Estimate	Odds ratios
α_k	α_A	-0.1290	
	α_B	1.8191	
	α_C	3.8472	
	β	-0.0377	0.9630
α_{LB}	$\alpha_{Log0m\ I}$	1.0789	
	$\alpha_{Log0m\ Y}$	1.0533	
	$\alpha_{Log4m\ I}$	0.9719	
	$\alpha_{Log4m\ Y}$	0.4752	
	$\alpha_{Log8m\ I}$	1.0454	
	$\alpha_{Log8m\ Y}$	0.0000	

Figure 3 shows the probability for grade A in the different log and board combinations.

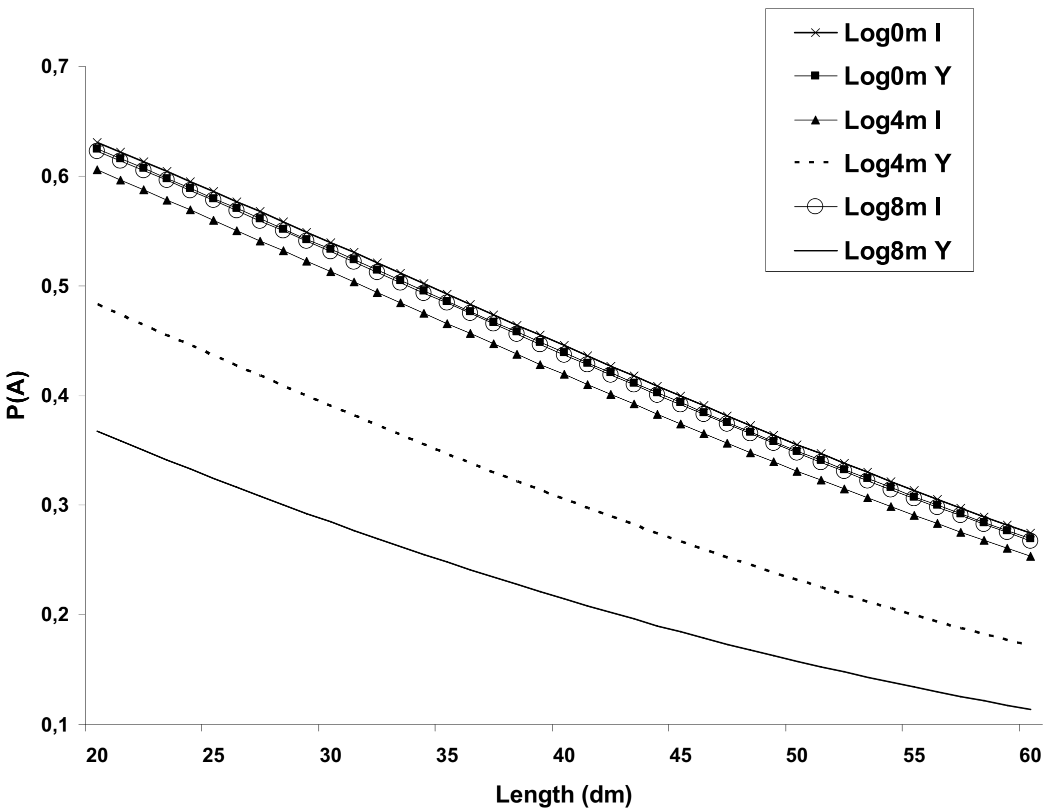

Figure 3. Probability for grade A in the NT-boards model. I indicates inner boards and Y other boards

Grading after INSTA 142 (IN)

IN-log model

Log type (p-value < 0.0001) and the interaction effect of length and log type (p-value = 0.0003) were found to be significant together with the length (p-value < 0.0001). The log model for IN-grading is stated in equation 3 and parameter estimates are given in Table 3.

$$P(Y \leq k) = \frac{e^{\alpha_k + \alpha_L + (\beta_L + \beta_0) \times length}}{1 + e^{\alpha_k + \alpha_L + (\beta_L + \beta_0) \times length}}, \text{ k=T3, T2, T1} \qquad (3)$$

Table 3: Parameter estimates for the IN-log model where α_k is dependent on the grade, α_L and β_L on the log type

Parameter		**Estimates**	**Odds ratios**
α_k	α_{T3}	-1.6751	
	α_{T2}	0.1560	
	α_{T1}	3.0773	
	β_0	-0.0373	
α_L	α_{Log0m}	2.7697	
	α_{Log4m}	0.6875	
	α_{Log8m}	0.0000	
β_L	β_{Log0m}	-0.0317	0.933
	β_{Log4m}	-0.0049	0.959
	β_{Log8m}	0.0000	0.963

Figure 4 shows the models together with the actual frequency of the IN-grades for the different logs.

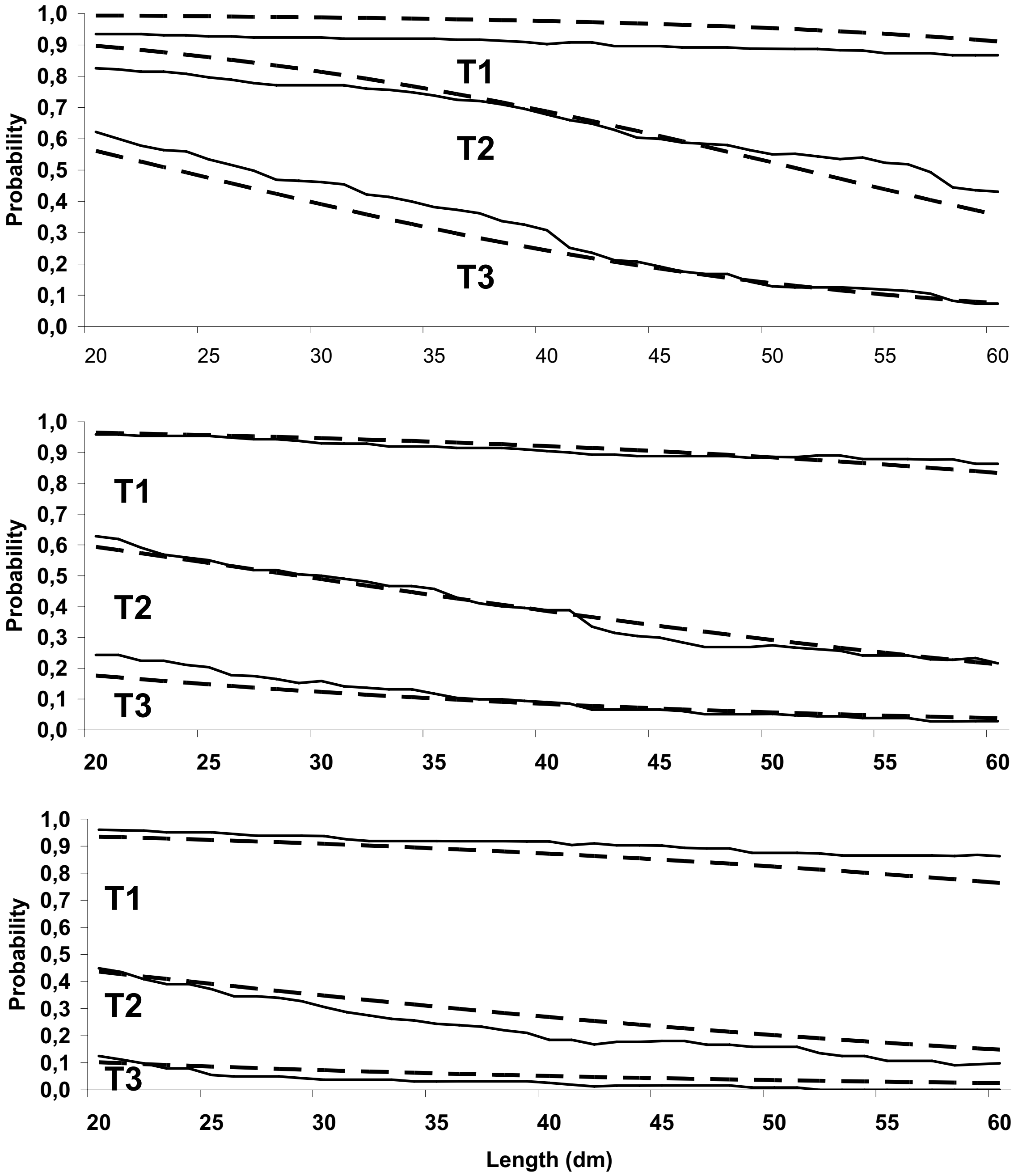

Figure 4. Log models for IN-grades (dotted lines) together with the frequency of IN-grades (solid lines). From the top, Log0m, Log4m and Log8m.

IN-board model

For the board model, the length (p-value < 0.0001), the log type (p-value < 0.0001), the interaction effect of length and log type (p-value = 0.0052) and the interaction effect of length and board type (p-value = 0.0004) were significant. Neither board (p-value = 0.50), nor the interaction effect of board and log (p-value = 0.22) were found to be significant.

The board model for IN-grading is stated in equation 4 and parameter estimates are given in Table 4.

$$P(Y \leq k) = \frac{e^{\alpha_k + \alpha_L + (\beta_{LB} + \beta_0) \times length}}{1 + e^{\alpha_k + \alpha_L + (\beta_{LB} + \beta_0) \times length}}, \text{ k=T3, T2, T1} \quad (4)$$

Table 4: Parameter estimates for the IN-board model where α_k is dependent on the grade, α_L on the log type, and β_{LB} on the board x log combination

Parameter		**Estimates**	**Odds ratios**
α_k	α_{T3}	-1.6098	
	α_{T2}	0.2362	
	α_{T1}	3.1884	
	β_0	-0.0527	
α_L	α_{Log0m}	2.7383	
	α_{Log4m}	0.6657	
	α_{Log8m}	0.0000	
β_{LB}	$\beta_{Log0m\ I}$	-0.0098	0.9394
	$\beta_{Log0m\ Y}$	-0.0245	0.9257
	$\beta_{Log4m\ I}$	0.0139	0.9619
	$\beta_{Log4m\ Y}$	-0.0008	0.9479
	$\beta_{Log8m\ I}$	0.0147	0.9627
	$\beta_{Log8m\ Y}$	0.0000	0.9487

Figure 5 shows the probability for grade T3 in the different log and board combinations.

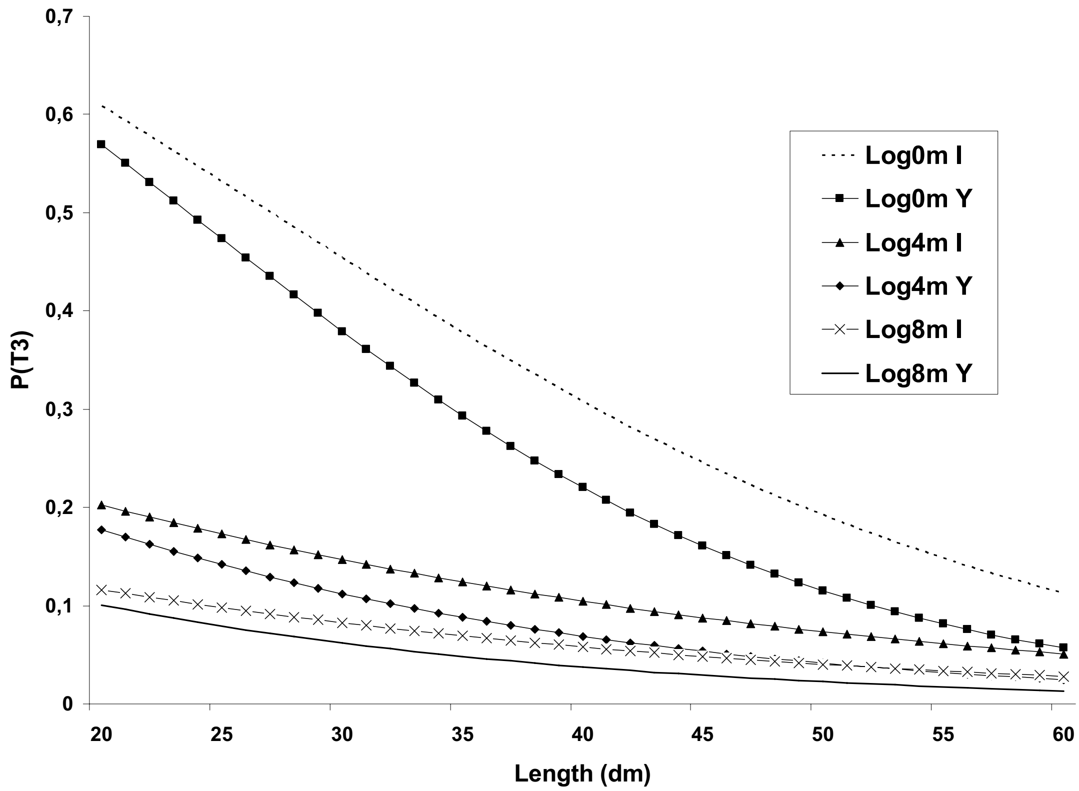

Figure 5. Probability for grade T3 in the IN-board model. I indicates inner boards and Y other boards

Discussion

The effect of length on grade yield is larger in IN-grading than in NT-grading since IN is more prone to downgrading by increasing knot size because these rules have no distinction between sound and dead knots. In a previous study of this material , when each meter along the stem was graded independently, Øvrum et al. (2008) found larger longitudinal variation in IN-grades than in NT-grades. This explains the stronger length effect in IN-grading.

The smaller decrease in length effect upwards in the tree in NT-grading compared to IN-grading is most likely because the variation in grade due to knots may be evaluated as approximately uniformly distributed throughout the trees (Øvrum et al. 2008) for NT-grading. NT-rules are stricter on dead knots, which will be the most frequent downgrading feature at the bottom of the trees. As the sound knot frequency increases towards the crown base, the knot size will also increase giving more downgrading for sound knots. In the crown region the knot size will decrease towards the top end which will correspond to the decreasing timber size. Downgrading for other properties than knots could be viewed as uniformly distributed both vertically and horizontally for both grading rules (Øvrum et al. 2008), and will emphasize a constant length effect in trees. It is necessary to note that the variation in this material was limited because it was sampled from an area where spruce timber is known to have quite good quality. Trees with poorer quality may have a larger longitudinal variation in knot size (Vestøl and Høibø 2001), and this may influence the differences in length effect between butt logs and other logs. The NT-board model showed that the length effect was constant throughout the trees, while the log model suggested decreasing length effect upwards in the trees. This discrepancy may be explained by general lower grades higher in the tree, and also that the difference in grade between board types is very strong in log8m. Figure 5 shows that in IN-grading the length effect is most pronounced in butt logs, and somewhat larger in middle logs compared to top logs. This is most likely due to the strong increase in knot size in lower parts of the stem (Moberg 2001; Vestøl and Høibø 2001). The smaller length effect in IN-grading for inner boards compared to boards farther from the pith is probably due to the larger knot size in general in outer boards, since the knot size increases from the pith towards the bark as long as the knots are still sound.

In NT-grading a decrease in grade yield was found in logs extracted higher up in the trees, which also Rikala (2003) found in his studies of Norway spruce. Blomqvist and Nylinder (1988) did not find any difference in grade between logs of Norway spruce, only more homogenous grade in butt logs when grading after “Grøna boken” (Anonymous 1976). Høibø (1991) on the other hand, found an increasing trend in grade yield higher up in trees when grading Norway spruce according to the “ØS-rules”(Anonymous 1981). However, he only extracted two boards from each log, which were thicker boards than in this study, namely 75 mm thick, leading to increased downgrading for dry knots in butt logs than in this study, where the boards were 38 mm and 50 mm thick.

The type of board gave a strong effect in NT-grading in middle and top logs resulting in higher grade yield of inner boards in these logs. For butt logs, the effect can be disregarded in practice. This may be attributed to the inner boards having very few dead knots which NT-rules grades very strictly, and the size of these are larger as the distance from stump increases.

In IN-grading, the pattern was quite clear with significantly higher grade yield in butt logs than in middle logs, which had higher yield than top logs. This was also shown for visual strength grading of Norway spruce by Høibø (1991) and Rikala (2003). The board type did not have a significant effect for grade yield in IN-grading, which is probably because the effect of larger knots in outer boards is counterbalanced by more frequent downgrading due to edge knots in inner boards.

Application of the models

One possible application of the models is to evaluate the cost of reduced grade yield due to increased length under different price assumptions, parallel to the theory of size effect in structural timber (Rouger and Barrett 1995). If one assumes that the value of the total volume of sawn timber is constant, this implies that the decrease in grade yield with increasing log length must be balanced by increasing the value of longer logs (eq. 5.1).

$$P_{L1} \times Y_{L1} = P_{L2} \times Y_{L2} \qquad (5.1)$$

where:
P denotes average price,

Y denotes yield, and is given by the frequency of the different grades at the actual length, and the relative ranking between the different grades, the price gap,

L1 denotes the length (baseline length) to which a new length L2 is compared.

The size of the length effect may be expressed as the relative price (RP) compared to the baseline length (eq. 5.2). RP will depend on the price gap between the grades of sawn timber, and whether the price gap is to be constant or dependent on length.

$$RP = \frac{P_{L2}}{P_{L1}} = \frac{Y_{L1}}{Y_{L2}} \qquad (5.2)$$

From this, it is possible to derive RP with different assumptions about price gaps between the grades by using the various models. In Figure 6, RP is shown for the NT-log model (eq.

1) on butt logs (Log0m) with different assumptions. L1 is set to 45 dm representing the average log length in Norway. *Pricegap 10 %* means that there is a constant ten percent difference in value between the NT grades by saying the price of grade A, B, C and D is 1, 0.9, 0.8 and 0.7 respectively. In *Pricegap 25 %,* the grades are set to 1, 0.75, 0.5 and 0.25 respectively. In *Market,* the current market prices in Norway are used and they are 1, 0.875, 0.625 and 0.4375 respectively. In *A=0,7 X Rest,* the price of the grades B, C and D is set to 0,7 X grade A at the length 45 dm. This means that for this particular assumption, the RP is the difference in value for grade A alone, treating the price of grades B, C and D independent of length.

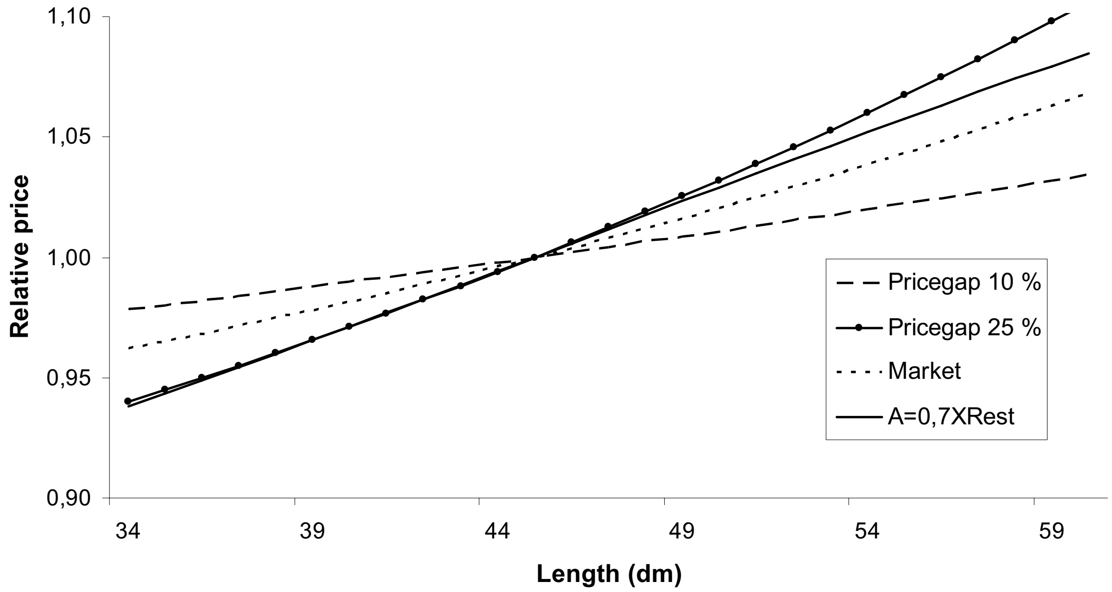

Figure 6. RP with different assumptions about the price gap between grades for Log0m in the NT-log model

In Figure 7, the RP is shown for the different logs in the IN-log model (eq. 3) keeping the price gap constant on all the boards by ranking grade T3, T2, T1 and T0 as 1, 0.9, 0.85 and 0.5 respectively. This reflects the current market prices of the grades, and the increasing frequency of T0 in logs higher up in the tree counterweighs the stronger length effect in the logs closer to the stump resulting in an almost equal RP-development in the logs.

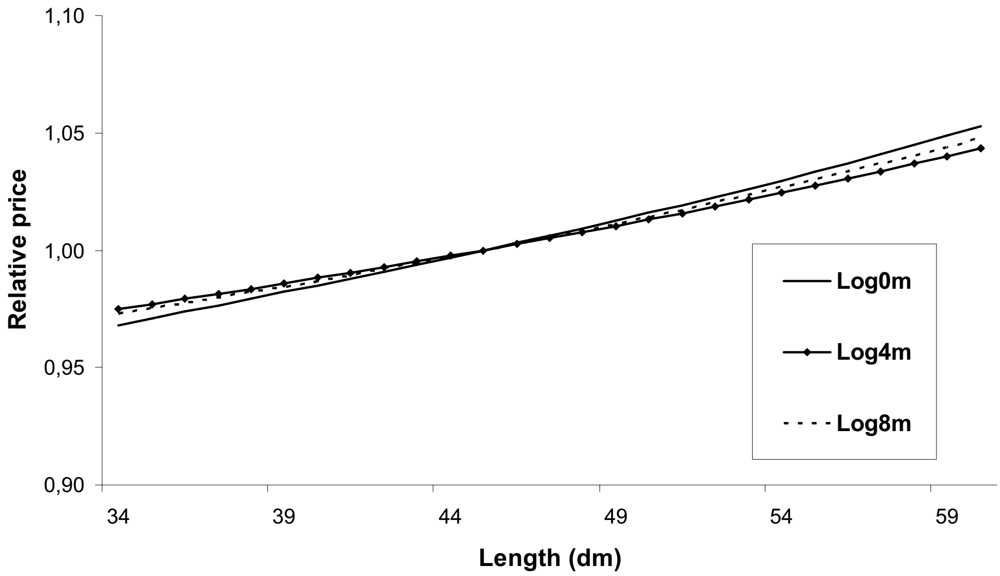

Figure 7. RP for the logs in the IN-log model

The size of RP will depend on the assumptions about the price gap, but shows that from current market prices an increase in the log length from 45 dm to 60 dm will decrease the value of the sawn timber in stock by about 6 %. In addition, a decrease in yield of timber in longer logs will amplify this effect, while a higher efficiency in the production process will diminish it.

Conclusions

Length had a significant effect on grade yield, and the cost of increasing the length of timber can be substantial if the price gap between sawn timber grades is considerable. The length effect was stronger in IN-grading compared to NT-grading. The length effect was most pronounced in butt logs, and somewhat greater in middle logs compared to top logs. Also a smaller length effect in inner boards compared to boards farther from the pith was found for IN-grading, but not for NT-grading. Current market prices in both grading rules gave a decrease in value of the sawn timber in stock by about 6 % with an increase in the log length from 45 dm to 60 dm. Since the samples were collected from a limited area, further studies are recommended using samples from a wider range of sites in order to test the general applicability of the findings.

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Paper III

Grade yield of sawn timber in Norway spruce (*Picea abies* (L.) Karst.) as affected by forest quality, tree size and cross-cutting length

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Abstract

The grade yield of sawn timber is affected by many different factors related to variations in wood properties, how logs are cross-cut from stems, the sawing pattern and how timber is graded. A change towards a classification of logs based only on length and top diameter has in the later years been the trend in Norway, making the variation in grade yield even more unpredictable. The aim of this study was to investigate the effects of forest quality, tree size, cross-cutting length and the interactions between these on grade yield.

The study comprised boards from 160 Norway spruce (*Picea abies* (L.) Karst.) trees which were cross-cut in fixed lengths of 20 dm, 40 dm or 60 dm respectively. The trees were sampled from six sites which were selected based on general forest quality to obtain a representative variation of the procurement area for a sawmill. The boards were graded according to appearance by Nordic Timber, strength was graded by INSTA 142, and machine strength was graded by a Dynagrade.

Cross-cutting length gave the strongest effect on grade yield for the visual grading rules. The overall results suggest that poorer sites should be cross-cut in shorter logs, especially if visually strength graded timber is the main product for the sawmill. Even though the tree size was significant, it did not affect the grade yield very strongly, but larger trees were found to be more sensitive to increased cross-cutting length. Overall, medium-sized trees gave the highest grade yield for both the visual grading rules. The difference in grade yield between sites of different forest quality was greatest in machine grading, and it was the only significant effect for this grading. For the visual grading the effect of forest quality was significant, but not very strong.

Introduction

The grade yield of sawn timber is of great importance to a sawmill's profitability. It is affected by variations in wood properties, how logs are cross-cut from stems, the sawing pattern and how timber is graded. When the Norwegian grading rules for saw logs were developed in the late 1960s, the aim was that saw logs graded as "prima" should yield sawn timber grade third and fourth according to the "ØS-rules"(Anonymous 1981). Saw logs graded as "second" should yield boards of grade fifth, but if one board was grade sixth, the other should be of third or fourth (Müller 1984). The system was based on a two board centre yield sawn with 1/3 vane, giving thicknesses ranging from 50 mm to 100 mm. Since it is not common to produce boards thicker than 63 mm anymore, four or even more boards are nowadays produced from the centre yield from larger logs. The grading rules for both saw logs and sawn timber have been modified several times since the 1960s, without paying much attention to the relationship between log grade and yield of sawn timber grade. This has weakened the ability to predict grade yield from certain log grades (Haugen 1996), and today the Norwegian sawmilling industry often buy logs with no distinction between "prima" and "second". Also by taking quality into account when cross-cutting the stems usually yields shorter log lengths, which is commercially undesirable. Moreover, the sawmills still buying "prima" and "second" do not separate the grades on the log yard.

Different log models for grade yield of Norway spruce have been presented (Brännström et al. 2007; Edlund et al. 2006; Jäppinen 2000; Oja et al. 2001), but even if such systems establish relationships between log variables and different sawn timber properties, the cross-cutting is usually carried out prior to these optimizing processes, and some economic yield is lost. An optimal system would involve cross-cutting the stems according to the required wood properties and dimensions (i.e. thickness, width and length) of the final product. In order to function properly, good models for predicting the properties of the wood and skilful handling throughout the whole conversion chain are needed. The relationship between price and quality is also important. Therefore, such systems will only be worth considering if the quality within the stem and stand varies considerably, and the range in prices between qualities is large enough.

Appearance grading and strength grading by visual inspection are based on the worst part of each piece determining the grade, making longitudinal variation in wood characteristics yield lower grades if the timber length increases (Øvrum and Vestøl 2008). Using only one grade of saw logs will entail a change in priorities to length at the expense of quality. This will probably make grade yield more dependent on the longitudinal variation in wood properties. Thus more knowledge about the relationship between grade yield and log length, and how this relationship varies between trees in stands and between different forest types, is needed.

The rotation age is normally higher at sites with low fertility, and hence these sites have a higher risk of damages. Increasing altitude entails lower average temperatures and a larger snow load, which again implies a higher probability of mechanical damages. Further more, the branching will be less uniform when the crown ages, giving a higher frequency of dead branches within the living crown. Frogner (1997) showed that this resulted in low fertility sites producing very little sound knot timber. All these factors, in addition to the larger taper in trees grown on low fertility sites, imply that trees from poorer sites, i.e. sites with low fertility and/or from higher elevations, should be cross-cut in shorter logs to obtain a decent grade yield.

Dominant trees in stands will have large crowns, which again will yield more sound knot timber. The knot size will, however, increase (Vestøl and Høibø 2000, 2001; Øyen 1999), and the net effect of tree size on grade yield will depend on the grading rules in use, although a stronger effect of length would be expected in more dominant trees. In strength grading the smallest trees would be anticipated to give the best grade yield mainly due to smaller knots (Høibø 1991), but also more narrow annual ring widths, giving a higher density. More random defects such as mechanical damages, compression wood and resin pockets might not be influenced by relative tree size within the stand.

Models for several grading features exist (Øvrum et al. 2008), but the most important feature by far for Norway spruce is knots, and several models are developed to model variation in knot diameter and sound knot length within the tree bole. Moberg (2001, 2006) explained most of the variation in knot properties by stand variables, while Vestøl and Høibø (2001) found tree variables to be the most important. Also, Mäkinen et al. (2003) found that stem properties sufficiently predicted branch characteristics, although stand level variables slightly improved the model performance. Even if a model is capable of describing the systematic variations in different stem properties such as knots, there are still random defects like ramicorn branches, resin pockets, compression wood and top breakage present, making the grade yield more unpredictable. Knots and other down-grading features are also assessed differently depending on where in the cross-section they appear, making the grade yield even more unpredictable.

The aim of this study is to investigate the effects of forest quality, tree size, cross-cutting length and the interactions between these on grade yield in sawn timber.

Material and methods

The stands were selected based on the occurrence of splay knots and crook caused by top breakage, and categorized as poor, medium or good. Top breakage is a significant challenge in Norwegian forestry, and it is usually caused by snow load, often in interaction with temperature changes and wind. Since snow load depends on altitude, the selection of sites also represents variation in other variables that vary with altitude, i.e. site fertility and taper. All stands were located within a circumference of 10 km. The reason for this approach was to reflect the variation within the procurement area of a medium-sized sawmill in Norway. The altitude ranged from 350 meters to 770 meters above sea level, with site indices ranging from G11 to G20 in the H40 system (Tveite 1977). The silvicultural history of the stands was not known except that all stands were naturally regenerated mature stands of Norway spruce which were about to be clear cut.

Within each stand, an area containing typically 150-200 trees was selected and all trees were cross-measured at breast height. In order to be able to extract normal dimensions of sawn timber from at least one log, the diameter at breast height had to be at least 16 cm over bark. Trees with breast height diameter exceeding 16 cm over bark were assigned to one of three groups of tree sizes based on diameter at breast height. This in order to get the total range of trees available for saw logs represented in the study. The groups contained an equal number of trees, and were defined as large, medium and small trees. Within each group nine trees were randomly selected, resulting in 27 sampled trees from each stand. From all the selected trees an increment core was taken at stump level, and if rot was detected the tree was replaced by a new tree from the group. Since the logs should be possible to saw in standard sawing machines, forked trees and trees with excessive sweep were omitted. Forestry data and different features of the sampled trees are presented in Table 1.

Trees were assigned to be cross-cut in fixed lengths of 20 dm, 40 dm or 60 dm, resulting in three replicates of each tree size and cross-cutting length within each stand. This gives a factorial design of the experiment (Montgomery 2001). The hierarchy is shown in Figure 1.

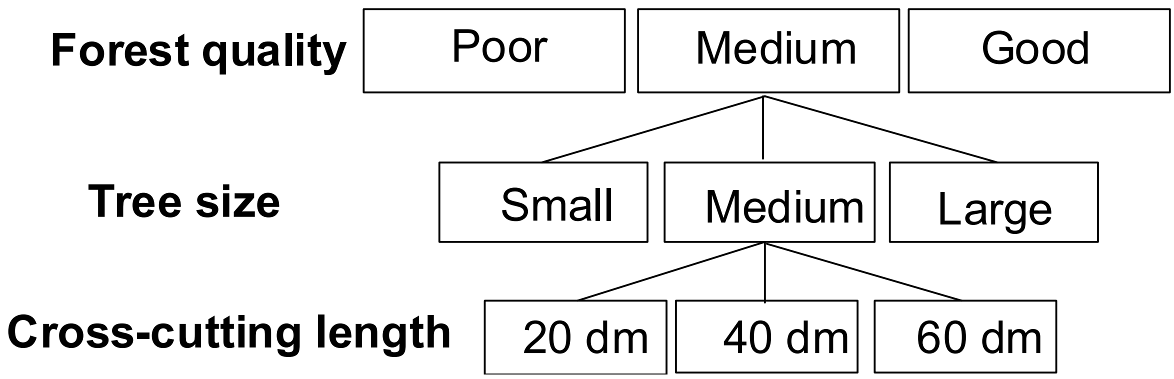

Figure 1. The hierarchy of the experimental design

In total 162 trees were logged but since two trees were lost during hauling and transportation, the study comprises 160 trees in total. The trees were cross-cut into 529 logs, all satisfying the lower dimension limit of saw logs in Norway, namely 13 cm in top diameter over bark.

Table 1. Means and standard deviations (in brackets) of the features recorded on trees from each stand.

Site	Site index H_{40} [m]	Altitude [m]	Forest quality	Age [yrs.]	DBH [mm]	H [cm]
1 (Grimsrud)	G17	450	Medium	99 (16)	282 (80)	2012 (411)
2 (Runnen)	G14	470	Good	117 (9)	260 (53)	2137 (236)
3 (Kortungen)	G14	620	Medium	106 (30)	241 (54)	1918 (248)
4 (Svera)	G11	630	Poor	100 (27)	249 (60)	1625 (243)
5 (Olavrud)	G20	350	Good	102 (16)	289 (71)	2523 (303)
6 (Lushaugen)	G11	770	Poor	119 (15)	273 (73)	1555 (308)
Total				107 (21)	266 (67)	1961 (439)

The logs were sawn according to Nordic practice (Anonymous 1994), with heart splitting giving either 2, 4 or 6 ex-log in the centre yield depending on the small-end diameter of the log processed (Figure 2).

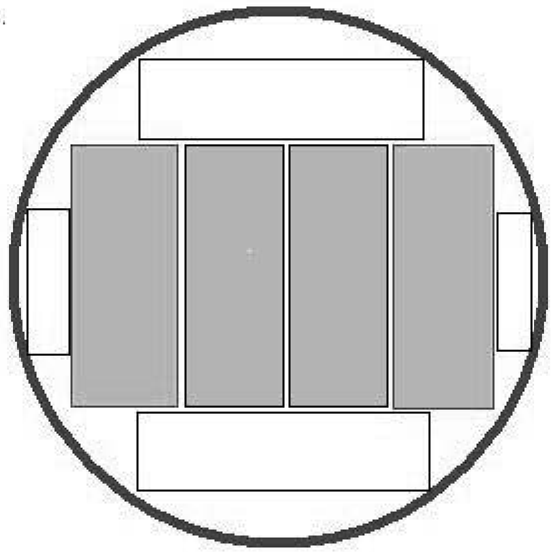

Figure 2. Sawing pattern with boards from centre yield in grey, and side yield in white

Board dimensions were commercial dimensions determined by the sawing pattern giving the maximum volume yield from each log. The volume yield of sawn timber for 20 dm, 40 dm and 60 dm cross-cutting length were 49.2 %, 48.1 % and 48.7 % respectively. Table 2 gives the dimension combinations for the centre and side yields.

Table 2. Dimensions of the boards in the centre- and side yields respectively

Centre yield	Thicknesses [mm]	38, 44, 50, 63, 75
	Widths [mm]	100, 125, 150, 175, 200, 225
Side yield	Thicknesses [mm]	19, 25, 38, 50
	Widths [mm]	100, 125, 150, 175, 200, 225

A total of 2141 boards was extracted from the logs, and all the boards were graded according to Nordic Timber, which utilizes four grades; A, B, C and D with A as the best, and D as "reject". It is possible to divide grade A into four different subclasses A1-A4. Only A3 and A4 were graded in this study, since A1 and A2 are mainly used for Scots pine as raw material for furniture, mouldings, windows and other almost knot-free products.

Boards thicker than 32 mm, a total of 1416 boards, were also strength graded by visual inspection according to INSTA 142 (1997), the Nordic visual strength grading rules. These rules specify four grades, and in the standard EN 1912 (2005) each grade is assigned to strength classes defined in EN 338 (2003). The grades used in this study (strength class in brackets) were T3 (C30), T2 (C24), T1 (C18) and reject.

A sub-sample consisting only of the boards of 40 dm and 60 dm length and thicker than 32 mm, 572 boards in total, was also strength graded by a Dynagrade (Boström 1997), which is the most common machine for strength grading in Norway. In addition, the visual override requirements of EN 519 (1995) were applied. These boards were dried by yard seasoning for two years resulting in a moisture content of about 18 % at the time of grading. Dynagrade measures the resonance frequencies originating from a strike by a metal hammer to the end of the board. Together with the length measured by a laser, the machine calculates the dynamic modulus of elasticity (E_{dyn}), and the board can be assigned to a strength class based on borders for the different strength classes that are set after the requirements in EN 519 (1995).

Statistical modeling

Grades from the different grading rules were treated as categorical responses, with a multinomial distribution and inherent ranking, i.e. ordinals. As such, ordinal logit models were made where *Y* (grade in this case) takes on one of *k*+1 possible values denoted by 1, 2, ..., *k*, *k*+1 (Agresti 2002). This is expressed as:

$$p_i = P(Y_i \le k | x)$$

The tested effects were cross-cutting length (20 dm, 40 dm or 60 dm), forest quality (Good, Medium or Poor), tree size (Small, Medium or Large) and the interaction between these effects. They were all considered as categories. The full model tested was:

$$\log it(p_i) = \ln\left(\frac{p_i}{1-p_i}\right) = \alpha + \beta_{length}x_1 + \beta_{tree-size}x_2 + \beta_{FQ}x_3 + \beta_{lengthXFQ}x_4 + \beta_{lengthXtree-size}x_5 + \beta_{tree-sizeXFQ}x_6$$

where α is the intercept for the different grades

all the *x*s are dummy variables taking the values 0 or 1

length = 20 dm, 40 dm or 60 dm

tree size = Small, Medium or Large

forest quality (FQ) = Good, Medium or Poor

Each board was weighted by its proportion of the total volume of the boards in order to have a total weight equal to the number of boards in each analysis. Based on results from a previous study (Øvrum et al. 2008) boards were assumed to be independent. The effects yielding a p-value<0.05 in a type 3 test were considered significant and included in the model. Odds ratios are presented to show various effects, where “odds ratio” is defined as ratio of the odds of an event occurring in one group to the odds of it occurring in another group (Agresti 2002), in this case the odds of one group having a better grade than the group it is compared to. The analysis was performed using the procedure GENMOD in the software SAS (SAS 1999).

RESULTS

Appearance grading according to Nordic Timber (NT)

The observed NT-grading yield for the different crosscutting lengths, tree sizes and sites is shown in Figure 3.

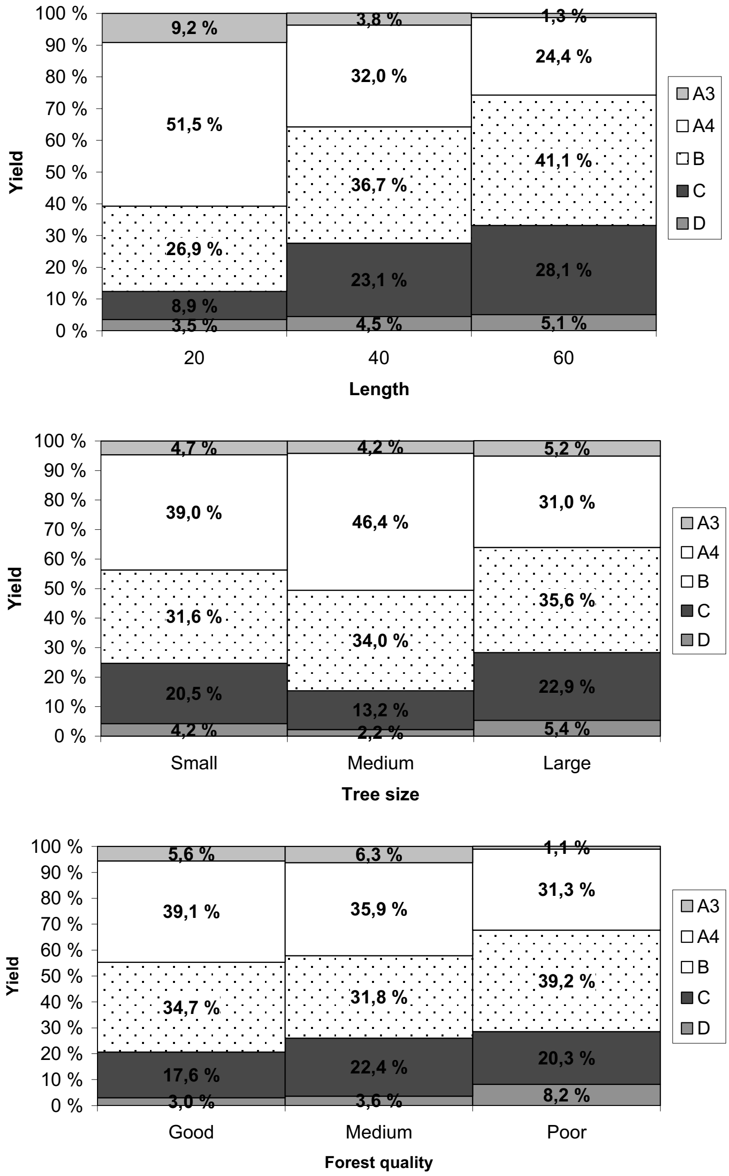

Figure 3. Grade yield in Nordic Timber in the different cross-cutting lengths, tree sizes and sites

Different features lead to down-grading, and Figure 4 shows the frequency of down-grading in NT-grading.

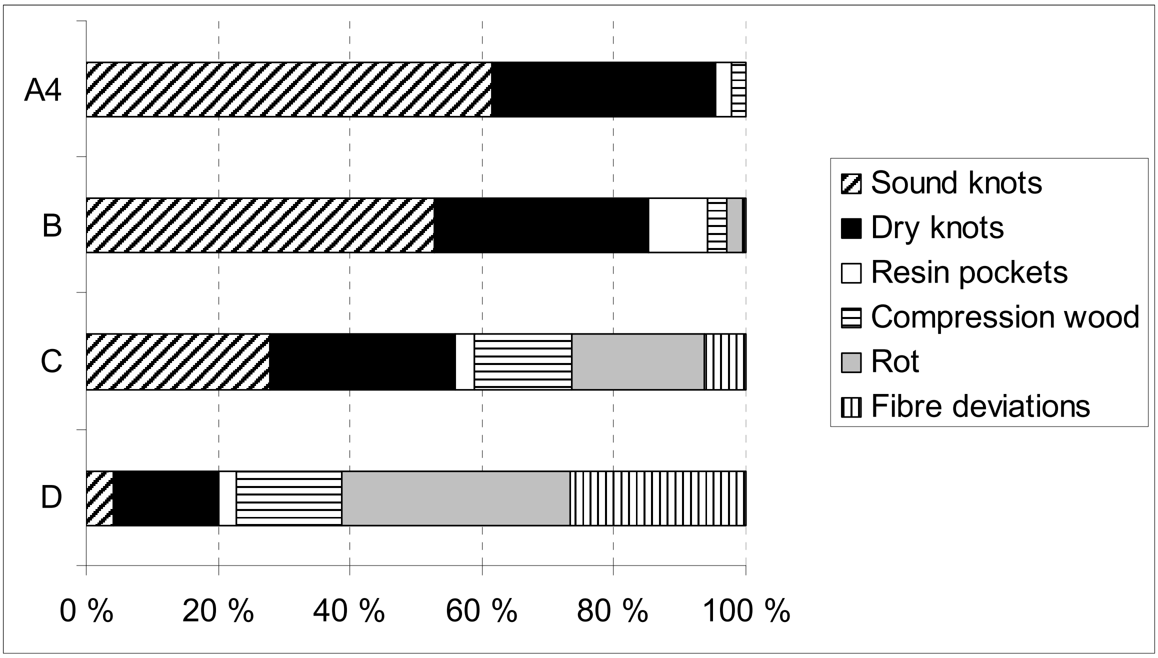

Figure 4. Frequency of down-grading features in Nordic Timber in the different grades

Knots, and in particular sound knots, are the most frequent down-grading factor in the highest grades, but it looses its importance in the lower grades. The portion of boards down-graded due to other features than knots was clearly largest for the small trees with 38.3 % vs. 22.8 % and 18.9 % for large and medium-sized trees respectively. The down-grading for other features than knots was most frequent in butt logs. No difference in the frequency of down-grading features were found between the different forest qualities.

All the tested main effects and the interaction between cross-cutting length and tree size were significant. The interactions between cross-cutting length and forest quality (p=0.19), and between forest quality and tree size (p=0.74), were not significant, and were removed from the model before parameters were re-estimated. Parameter estimates and p-values are shown in Table 3.

Table 3. Parameter estimates and statistics for the effects in Nordic Timber grading

Parameter		DF	Estimate	Standard error	Wald Chi-square	p-value (type 3)
$\hat{\alpha}$	A3	1	-4.2582	-0.2397		
	A4	1	-1.4401	0.2164		
	B	1	0.2616	0.214		
	C	1	2.3129	0.2325		
$\hat{\beta}_{length}$	20	1	1.3715	0.2853		
	40	1	0.5999	0.3037	127.01.	<0.0001
	60	0	0	0		
$\hat{\beta}_{tree-size}$	Large	1	-0.4116	0.2159		
	Medium	1	0.9019	0.234	43.63	<0.0001
	Small	0	0	0		
$\hat{\beta}_{FQ}$	Good	1	0.573	0.104		
	Medium	1	0.4406	0.1107	30.90	<0.0001
	Poor	0	0	0		
$\hat{\beta}_{lengthXtree-size}$	20 X Large	1	0.3982	0.3096		
	20 X Medium	1	-0.5804	0.3354		
	20 X Small	0	0	0		
	40 X Large	1	0.1254	0.3297		
	40 X Medium	1	-1.0423	0.353	34.34	<0.0001
	40 X Small	0	0	0		
	60 X Large	0	0	0		
	60 X Medium	0	0	0		
	60 X Small	0	0	0		

Increasing length gave lower grade yield, and the odd ratios for the different lengths were 2.76 (20 vs. 40 dm), 3.71 (20 vs. 60 dm) and 1.34 (40 vs. 60 dm) respectively.

Medium-sized trees gave the highest yield followed by small and then large trees. The odds ratios were 1.82 (medium vs. large), 1.43 (medium vs. small) and 1.27 (small vs. large) respectively.

Decreasing forest quality gave decreasing grade yield, and the odds ratios were 1.77 (good vs. poor), 1.14 (good vs. medium) and 1.55 (medium vs. poor) respectively.

The percentages of grade A (A3+A4) for the different combinations of cross-cutting length, tree sizes and forest qualities are shown in Figure 5.

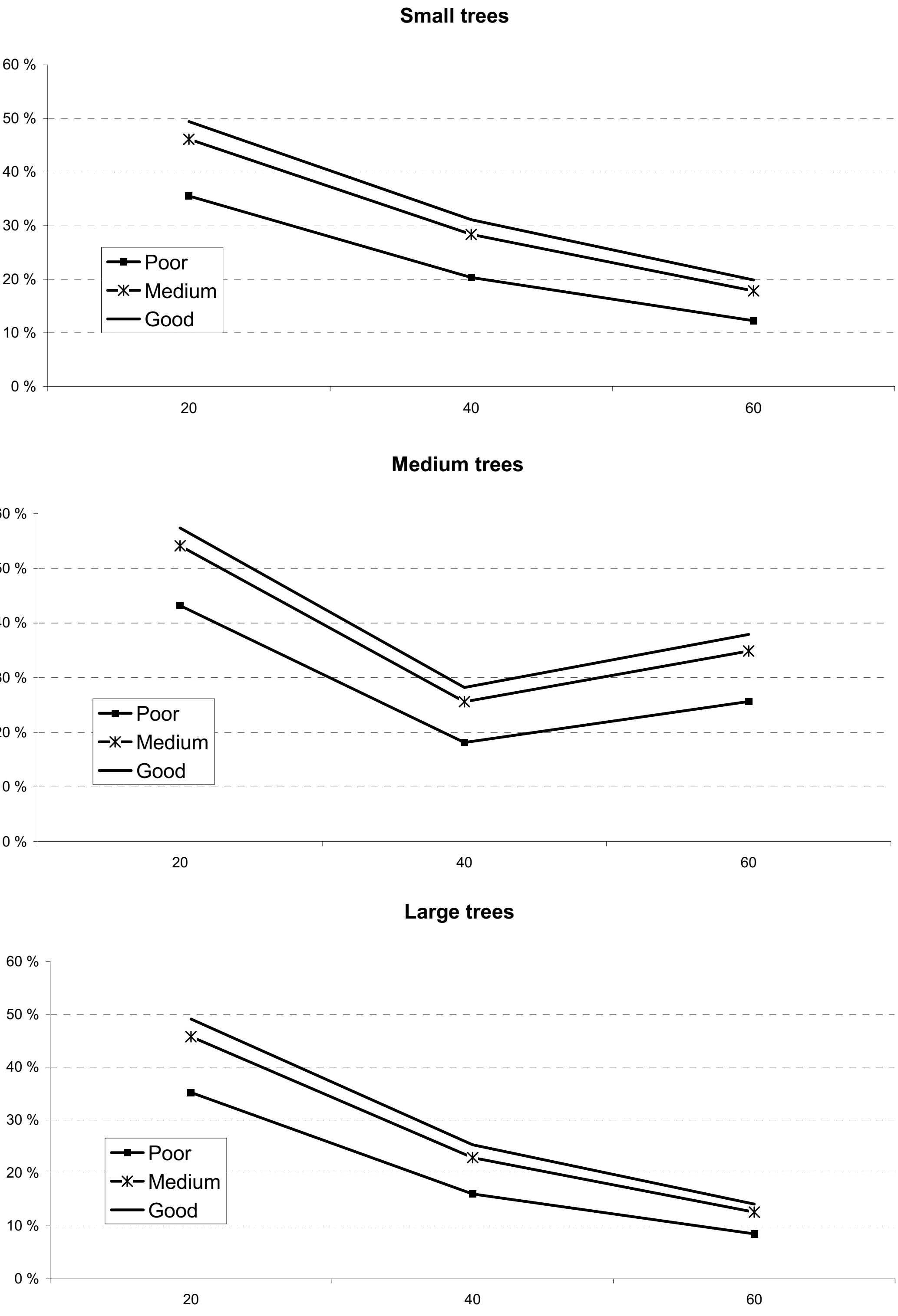

Figure 5. The predicted percentages of grade A in Nordic Timber for the different combinations of cross-cutting length, tree sizes and forest qualities

Visual strength grading according to INSTA 142 (IN)

The observed IN-grading yield for the different cross-cutting lengths, tree sizes and sites is shown in Figure 6.

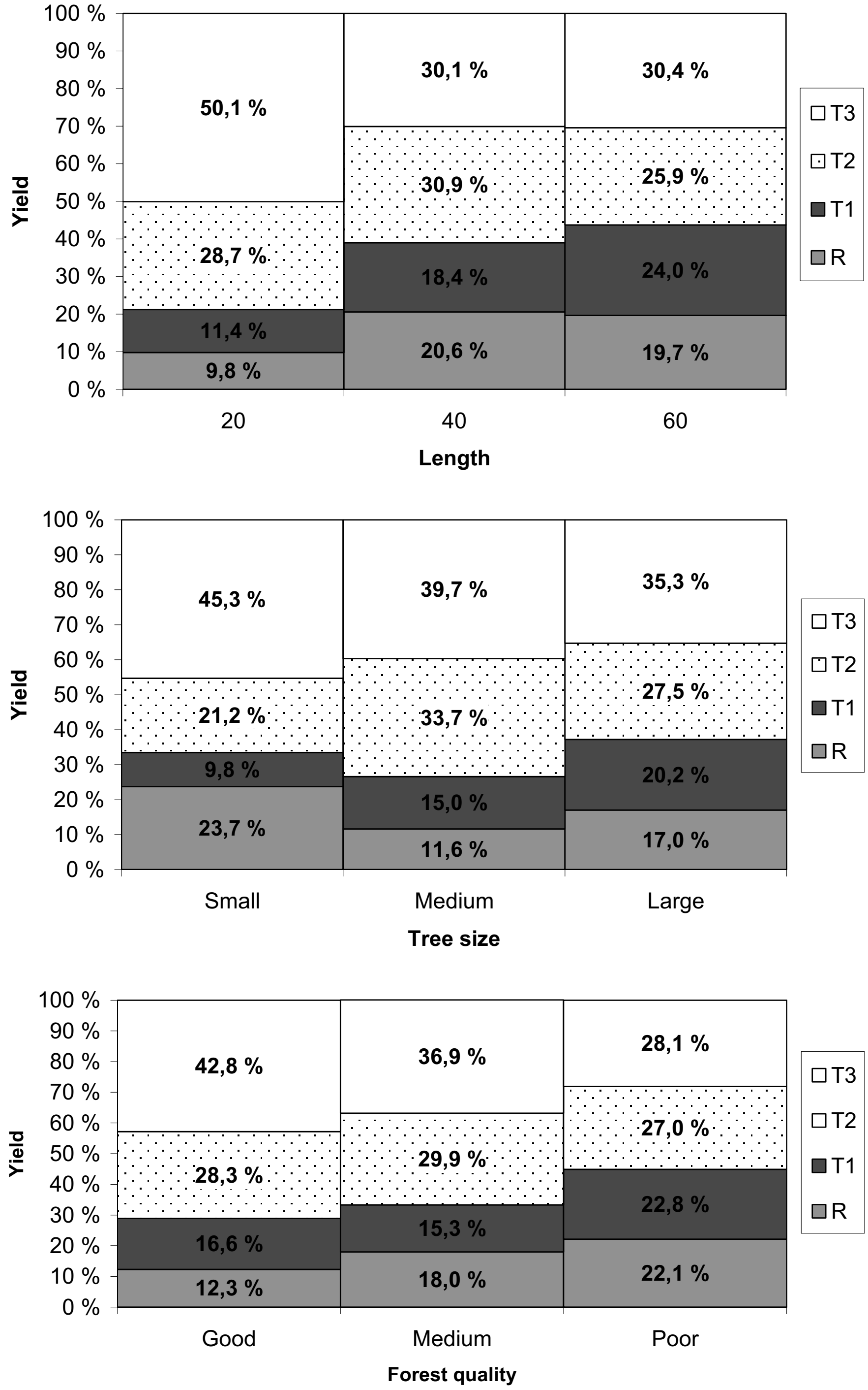

Figure 6. Grade yield in INSTA 142 in the different cross-cutting lengths, tree sizes and sites

Different features lead to down-grading, and Figure 7 shows the frequency of down-grading in IN-grading.

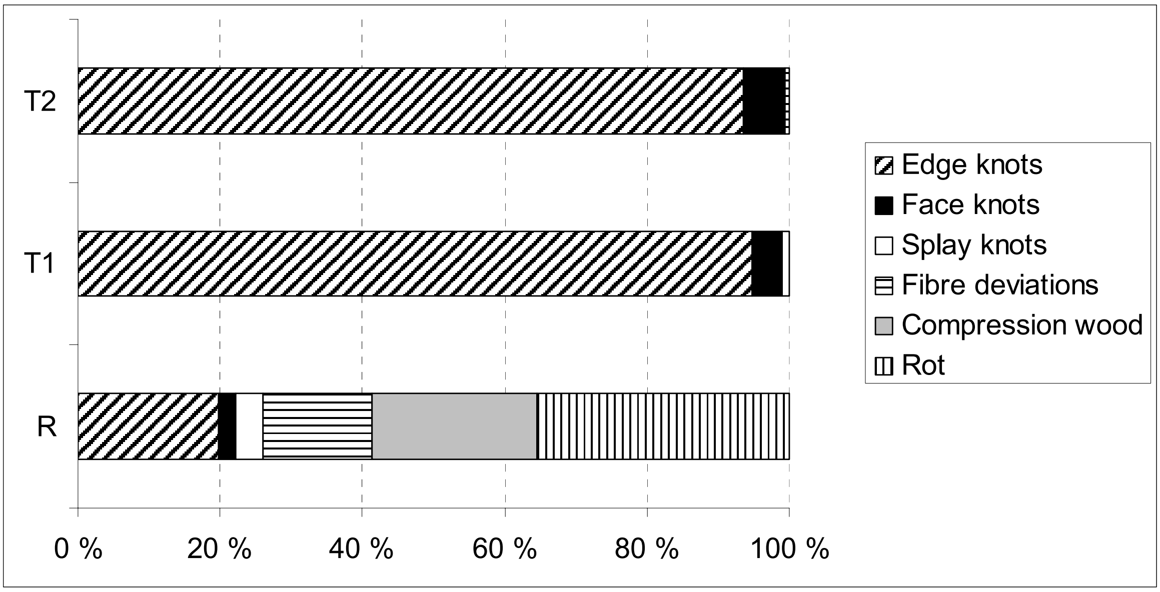

Figure 7. Frequency of down-grading features in INSTA 142 in the different grades

Edge knots are utterly dominant as down-grading feature except for down-grading to reject. Similar to the results obtained using NT-grading the portion of boards down-graded due to other features than knots was clearly largest in the small trees, with 43.3 % vs. 19.7 % and 19.4 % in large and medium-sized trees respectively. The tendency of higher frequency of down-grading due to other features than knots in butt logs was stronger than in NT-grading. Between the different forest qualities no difference in the frequency of down-grading features were found.

All the tested main effects and interaction effects were significant contributors to the fit, except for the interaction effect between tree size and forest quality (p-value=0.25). This effect was removed from the model before the parameters of the significant effects were re-estimated. Parameter estimates and p-values are shown in Table 4.

Table 4. Parameter estimates and statistics for the effects in INSTA 142 grading

Parameter		DF	Estimate	Standard error	Wald Chi-Square	p-value (type 3)
$\hat{\alpha}$	T3	1	-1.9675	0.3153		
	T2	1	-0.6863	0.3122		
	T1	1	0.357	0.3112		
$\hat{\beta}_{length}$	20	1	1.9553	0.4258		
	40	1	1.0742	0.4534	50.99	<0.0001
	60	0	0	0		
$\hat{\beta}_{tree-size}$	Large	1	-0.0736	0.2935		
	Medium	1	0.7496	0.315	7.79	0.0204
	Small	0	0	0		
$\hat{\beta}_{FQ}$	Good	1	1.2566	0.22		
	Medium	1	0.9428	0.2271	30.60	<0.0001
	Poor	0	0	0		
$\hat{\beta}_{lengthXtree-size}$	20 X Large	1	0.0484	0.3941		
	20 X Medium	1	-0.4937	0.4257		
	20 X Small	0	0	0		
	40 X Large	1	-0.4766	0.4324		
	40 X Medium	1	-1.512	0.4619	18.70	0.0009
	40 X Small	0	0	0		
	60 X Large	0	0	0		
	60 X Medium	0	0	0		
	60 X Small	0	0	0		
$\hat{\beta}_{lengthXFQ}$	20 X Good	1	-1.2846	0.3042		
	20 X Medium	1	-1.0571	0.3219		
	20 X Poor	0	0	0		
	40 X Good	1	-0.366	0.318		
	40 X Medium	1	-0.3616	0.3349	19.92	0.0005
	40 X Poor	0	0	0		
	60 X Good	0	0	0		
	60 X Medium	0	0	0		
	60 X Poor	0	0	0		

Increasing length gave lower grade yield, and the odd ratios for the different lengths were 2.36 (20 vs. 40 dm), 2.79 (20 vs. 60 dm) and 1.18 (40 vs. 60 dm) respectively.

Medium-sized trees gave the highest yield, followed by small and then large trees. The odds ratios were 1.08 (medium vs. small) 1.35 (medium vs. large) and 1.24 (small vs. large) respectively.

Decreasing forest quality corresponded to decreasing grade yield, and the odds ratios were 2.03 (good vs. poor), 1.27 (good vs. medium) and 1.60 (medium vs. poor) respectively.

The percentages of T3 for the different combinations of cross-cutting length, tree sizes and forest qualities are shown in Figure 8.

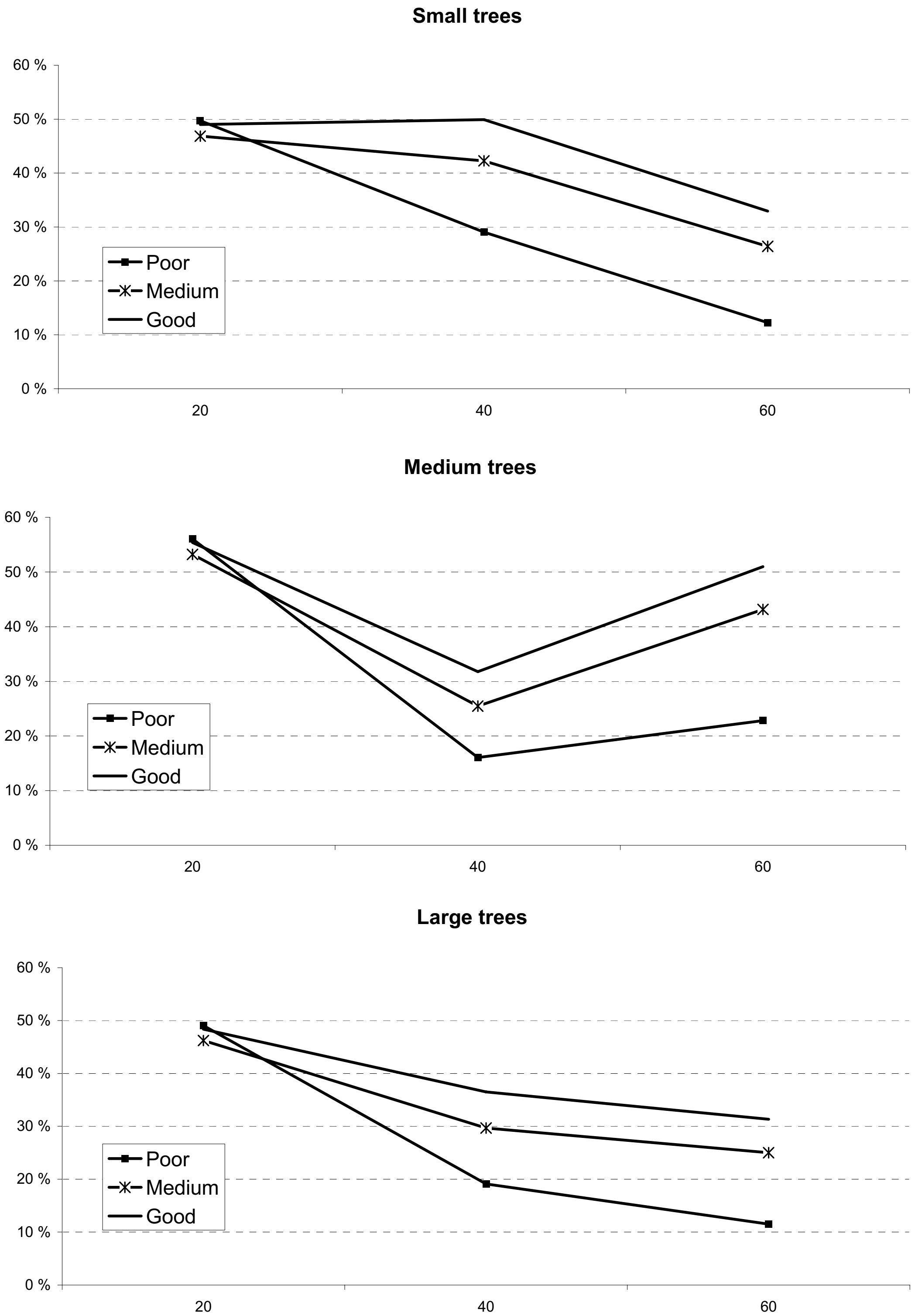

Figure 8. The predicted percentages of T3 in INSTA 142 for the different combinations of cross-cutting length, tree sizes and forest qualities

Machine grading with visual override (MGV)

The observed MGV-grading yield for the different cross-cutting lengths, tree sizes and forest qualities is shown in Figure 9.

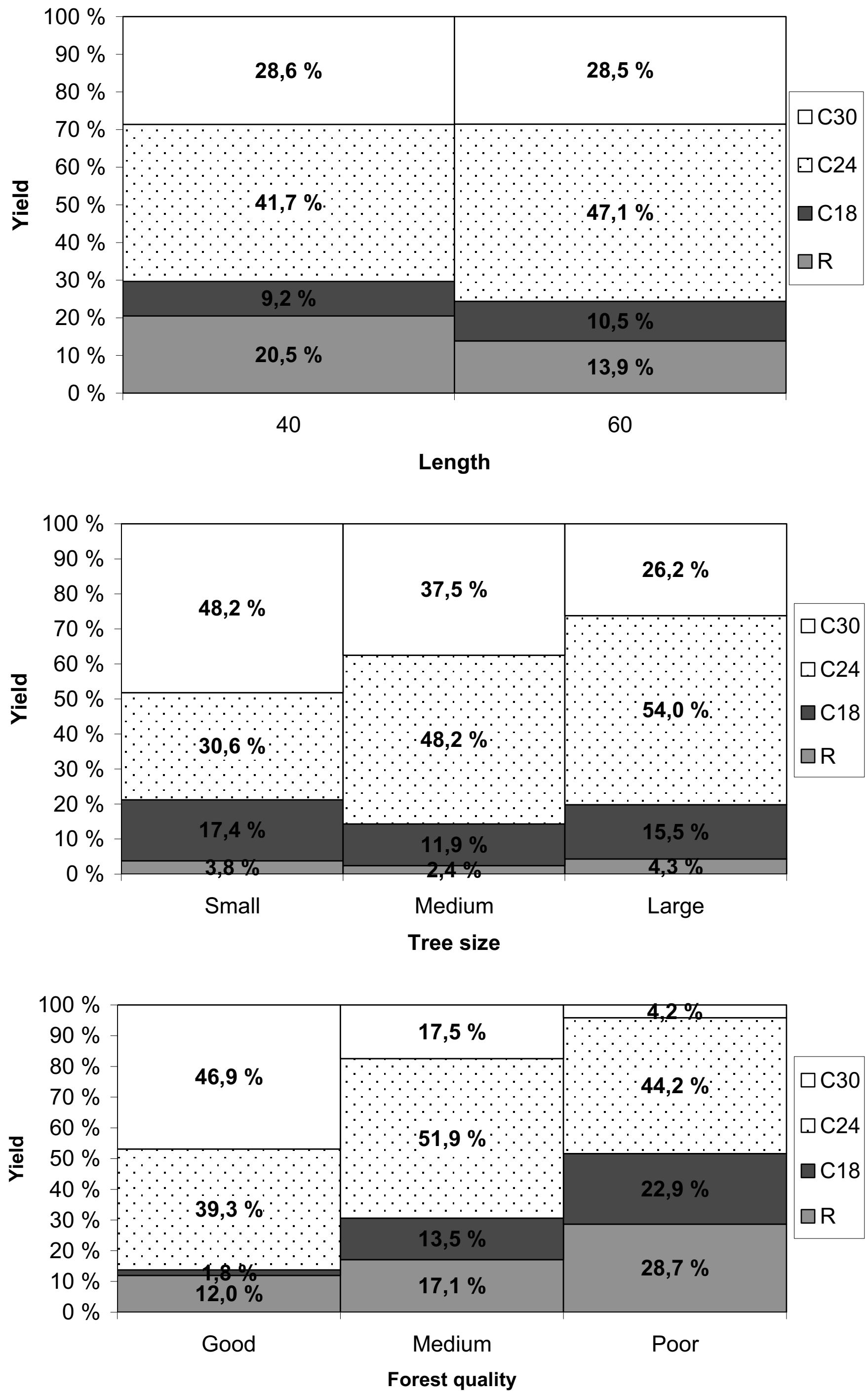

Figure 9. Grade yield in machine strength grading the different cross-cutting lengths, tree sizes and sites

Neither length (p-value=0.09) nor tree size (p-value=0.06) were found to be significant effects for grade yield in machine grading, leaving only forest quality. Parameter estimates are shown in Table 5.

Table 5. Parameter estimate and statistics for the effects in machine strength grading

Parameter		DF	Estimate	Standard error	Wald Chi-Square	p-value (type 3)
	C30	1	-2.2714	0.2012		
$\hat{\alpha}$	C24	1	-0.0211	0.1697		
	C18	1	0.6188	0.1745		
	Good	1	2.0653	0.2237		
$\hat{\beta}_{FQ}$	Medium	1	0.8159	0.2145	100.69	<0.0001
	Poor	0	0	0		

Decreasing forest quality corresponded to decreasing grade yield, and the odds ratios were 7.89 (good vs. poor), 3.49 (good vs. medium) and 2.26 (medium vs. poor) respectively.

Discussion

The odds ratios show that for the visual grading rules, cross-cutting length had the strongest effect on grade yield, while tree size and forest quality were judged equally important for grade yield. The strong effect of length was anticipated due to the extreme variation in lengths in this study.

The decrease in grade yield was stronger from 20 dm to 40 dm than from 40 dm to 60 dm. 20 dm is shorter than the normal lengths of Norway spruce logs and represent an extreme way of cross-cutting. The effect of increasing from 40 dm to 60 dm, however, is within the range of normal log lengths. The anticipated stronger effect of length on grade yield in large trees were found, but only for IN-grading. This can be explained by the higher dependency on knot size in strength grading. For medium-sized trees the grade yield actually increased when the length increased from 40 dm to 60 dm in both NT- and IN-grading. This contradicts our hypothesis and may be caused by several factors. The trees which were cross-cut in 40 dm lengths have more logs from higher up in the stem represented, and these generally yield lower grades (Øvrum and Vestøl 2008). However, the trees cross-cut in 20 dm lengths have even more logs from higher up in the stem represented, but they show a much better grade yield. Also, the smallest trees could be assumed to encounter the effect of increased grade yield with increasing length first, since such trees will often have only one log extractable when cross-cutting in 60 dm lengths. The butt logs of the smallest trees generally had lower quality, however, due to the aforementioned higher frequency of down-grading for other factors than knots, i.e. rot, compression wood and fibre deviations. This will diminish the effect of overrepresentation of butt logs for the longer lengths in the smallest trees, and may as such explain the fact that it is medium-sized trees that show this increased grade yield by increasing length from 40 dm to 60 dm. It should also be mentioned that in this study, all variables were treated as categories which will have the form of threshold values, making the resolution of the scales quite coarse. Combined with few observations in each group, this will make the chance of effects coincidentally working together to make unexplainable statistical inferences possible. It should also be emphasized that the grade yield clearly decreases with increasing length for both the small and the large trees, and for all tree sizes when cross-cutting is increased from 20 dm to 40 dm lengths. The lesser effect of forest quality on shorter cross-cutting lengths, which is significant in IN-grading and a trend in NT-grading, is in line with the assumption that at sites with low forest quality trees should be cross-cut in shorter lengths. The effect of decreasing grade yield with increasing cross-cutting length was stronger for NT-grading than for IN-grading, which contradicts the results of Øvrum and Vestøl (2008). However, their material only included saw log quality logs. In addition, five grades were used for NT-grading in this study, making the scale of NT- and IN-grading not directly comparable since only four grades were used in IN-grading. For machine grading including visual override, no effect of cross-cutting length was found. This might be attributed to the fact that the Dynagrade identifies the global E_{dyn} (Boström 1997), and as such do not point out the weakest point in the boards. In addition, 20 dm cross-cutting length was not tested in machine grading since the minimum length of pieces gradable in a Dynagrade is 24 dm (Boström 1997), making the length range investigated a bit narrow.

The fact that medium-sized trees gave the best grade yield for both NT- and IN-grading is somewhat in disagreement with Høibø (1991), who found a decreasing trend of grade yield for all grading rules by increasing DBH. However, his conclusions were based on measuring DBH at different points in a tree's life. He found that the effect of DBH on grade yield decreased as the trees got older, and the age at final felling in his study was a mere 51 years. Furthermore, the site fertility was very high, and the stands were intensively managed in his study, making a direct comparison somewhat biased. Since knots are the most frequent down-grading factor (see Figure 4 and Figure 7) the combination of not too big and the fairly high occurrence of sound knots is the most probable reason for the medium-sized trees giving the highest grade yield in NT-grading. For IN-grading, however, the smallest trees were thought to give the best grade yield because of the smaller knot size, and they did so for the cross-cutting length of 40 dm, but not for 20 dm and 60 dm. As Figure 6 shows, small trees yielded most boards in the highest grade (T3), but they also had the largest reject portion. The higher frequency of down-grading to reject because of rot, compression wood and fibre deviations in small trees is the reason, and it overcompensates the effect of smaller knots in the smallest trees. The machine grading gave highest grade yield in small trees, which could be attributed to smaller knots and more narrow annual rings causing higher density in such trees. When the visual override was included, however, no significant difference was found between the diameter classes for machine grading.

The effect of forest quality was as presumed but with an insignificant odds ratio between good and medium forest quality for NT- and IN-grading. In the actual work with the sampling of the sites it should be mentioned that it turned out to be easier to define the ”poor” sites than to find the delimitation between ”good” and ”medium”, and this is probably reflected in the results. The effect of forest quality was clearly most important in the machine grading, where it was the only significant effect. The reason for this very strong forest quality effect must be attributed to factors not assessable by visual strength grading, most probably density and fibre deviations. Also, the Dynagrade assigns a continuous E_{dyn} to each board, which in turn assigns them to a strength class. It is well known that the modulus of elasticity provides a better accuracy in the grading process than does the visual grading rules (Johansson 2003), and as such might explain the effect of forest quality in machine grading. To examine whether this corresponds to an actual difference in strength properties between the sites would require real testing of the strength properties in the boards.

The effect of defining site quality before cross-cutting seems more important for machine strength grading, and less important if visual grading is performed. The possibility of tracking logs back to their origin is not commercially possible at the moment, but has been investigated by (Uusijärvi 2000), and through the LINESET project (Uusijärvi 2003). This work is currently being developed further through the project Indisputable Key (Anonymous 2006), which aims at enabling tracking back to the raw material by using existing equipment and developing new systems for obtaining data back in the value chain. This will increase the potential for implementation of forest data in the sawmilling process.

Conclusions

Cross-cutting length had the strongest effect on grade yield when the visual grading rules were applied, and the overall results suggest that poorer sites should be cross-cut in shorter logs, especially if visually strength graded timber is the main product for the sawmill. The effect of tree size was significant, but did not affect the grade yield very strongly. The largest trees were most sensitive to increased length in the IN-grading, but this effect was not found in NT-grading. Overall, medium-sized trees gave the highest grade yield for both the visual grading rules. The difference in grade yield between sites of different forest quality was greatest when machine grading was performed, and the only significant effect for this grading, while for the visual grading the effect was significant, but not very strong.

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Paper IV

Modeling the effects of timber length, stand- and tree properties on grade yield of Norway spruce (*Picea abies* (L.) Karst.) timber

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Abstract

Since grade assessed by visual inspection is determined by the worst part of a board, grade yield will decrease if the average length of timber increases. This effect of length varies due to longitudinal variation in the grading features and their appearance on the sawn surface, as given by the cross-cutting and the sawing pattern. In this study models identifying the length effect's dependence on site, stand, tree and log level characteristics have been developed.

The study comprised boards from 160 Norway spruce trees (*Picea abies* (L.) Karst.) which were cross-cut in fixed lengths of 20 dm, 40 dm or 60 dm respectively. The trees were sampled from six sites which were selected based on general forest quality to obtain a representative variation of the procurement area for a sawmill. The boards were visually graded according to appearance by Nordic Timber (NT) and strength was graded by INSTA 142 (IN).

The negative effect of increasing length on grade yield was strongest at stump level and decreased upwards in the trees. Trees with large relative diameter at breast height within a stand had the strongest effect of length. Grade yield decreased upwards in the stem. Inner boards gave better grade yield than other boards, an effect which increased towards the top end in the NT-grading. Increasing tree height had a positive effect on grade yield other variables held constant, while the mean diameter at breast height of the stand affected the grade yield negatively. In addition to length, position of the board within the tree was the most important factor influencing grade yield. The variation in grade yield within stands was greater than between stands for the grading rules used in this study. The models predicting grade probabilities seemed to fit within a 10 % margin.

Introduction

Common to many visual grading rules is the assessment of grade based on the worst part of each piece. Since the features vary along a piece of timber, grade yield will decrease if the average length of timber increases. Orvèr (1973) described this effect in a study of Scots pine (*Pinus sylvestris* L.). The Nordic timber market demands longer timber, and the sawmills transfer this demand to the forestry through the price system for saw logs. This demand is not only affecting the length distribution of logs and sawn timber, but also the grade yield.

A general description of the distribution of grades in trees of Norway spruce, based on Nordic Timber (Anonymous 1994b) and INSTA 142 (1997), was presented by Øvrum et al. (2008b). They found that the expected grade of sawn timber decreased towards the top end. This was attributed to increased knot size compared to board size higher up in the trees. Øvrum and Vestøl (2008) simulated boards from the same material to find the effect of length on timber grade and how this effect varied according to the position of the board in the stem, both longitudinally and transversely. The logs started at 0 m, 4 m or 8 m from stump level. The boards were defined as “inner boards”, boards adjacent to the pith, and “other boards” for the rest. They found a decreasing length effect upwards in trees for both appearance- and visual strength grading. This was explained by the stronger variation in knot properties in the lower part of the trees compared to the more uniform vertical knot pattern further up in the trees. In visual strength grading a smaller length effect for inner boards compared to boards farther from the pith was found, and this was explained by the higher sensitivity to knot size in outer boards. Their study was based on dominant trees from high quality stands, and they suggested a new study to be carried out in order to investigate how forest parameters and tree parameters might influence the length effect. This was carried out by Øvrum et al. (2008a), in which samples representing variation both between sites and within stands were analysed. Their study showed that both forest quality and tree size influence the grade yield. The length effect was found to be stronger in poorer stands due to more down-grading for other features than knots. The largest trees had the strongest length effect, and this was explained by a larger variation in knot properties in such trees (Vestøl 1998).

The results presented in Øvrum et al. (2008a) showed that categorizing sites into quality classes is not necessarily a straightforward and objective matter. After investigating the effect of such coarse variables on grade yield, it is desirable to develop more general models based on objective site, tree and log characteristics. The aim of this study is, as such, better to describe the effect of length in interaction with stand and tree variables. In addition, the prediction accuracy of the new models is to be compared with the models of Øvrum and Vestøl (2008).

Material and methods

The stands were selected based on the occurrence of splay knots and crook caused by top breakage, and categorized as poor, medium or good. Top breakage is a significant challenge in Norwegian forestry, and it is usually caused by snow load, often in interaction with temperature changes and wind. Since snow load depends on altitude, the selection of sites also entails variation in other variables that vary with altitude, i.e. site fertility and taper. All stands were located within a circumference of 10 km. The reason behind this approach was to reflect the variation within the procurement area of a medium-sized sawmill in Norway. The altitude ranged from 350 meters to 770 meters above sea level, with site indices ranging from G11 to G20 in the H40 system (Tveite 1977). The silvicultural histories of the stands were not known except that all stands were naturally regenerated mature stands of Norway spruce which were about to be clear cut.

Within each stand an area containing typically 150-200 trees was selected, and all trees were cross-measured at breast height. In order to be able to extract normal dimensions of sawn timber from at least one log, the diameter at breast height had to be at least 16 cm over bark. Trees with breast height diameter exceeding 16 cm over bark were assigned to one of three groups of tree sizes based on diameter at breast height. This in order to have the total range of trees available for saw logs represented in the study. The groups contained an equal number of trees, and the trees were defined as large, medium and small trees. Within each group nine trees were randomly selected, resulting in 27 sampled trees from each stand. An increment core was taken at stump level from all the selected trees and if rot was detected the tree was replaced by a new tree from the group. Since it should be possible to saw the logs in standard sawing machines, forked trees and trees with excessive sweep were omitted. Forestry data and different features of the sampled trees are presented in Table 1, the definitions are stated in Table 3. Trees were assigned to be cross-cut in fixed lengths of 20 dm, 40 dm or 60 dm, resulting in three replicates of each tree size and cross-cutting length within each stand.

In total 162 trees were logged but since two trees were lost during hauling and transportation, the study comprises 160 trees in total. The trees were cross-cut into 529 logs. All logs were graded by a professional grader from the Timber Grading Association (Norsk Virkesmåling) according to the standard log grading system used in Norway, assigning saw logs to one of two different classes, Prima or Sekunda (Anonymous 1994a), and the rest as reject, i.e. pulp and energy wood. The yield of the saw log grades are shown in Table 1, as P (prima), S (Sekunda) and R (Reject).

Table 1. Mean values (standard deviation) in the stands for the different features recorded on the trees and logs

Site	Site index H_{40} [m]	Altitude [m]	Forest quality	Saw log classification [%]	Age [yrs.]	DBH [cm]	H [dm]	HC360 [dm]	HC180 [dm]	HLB [dm]	HDB [dm]
1 (Grimsrud)	G17	450	Medium	P: 48.6 S: 17.6 R: 33.7	99 (16)	28.2 (8.0)	201.2 (41.1)	115.3 (35.5)	81.0 (24.3)	42.5 (16.8)	9.4 (7.9)
2 (Runnen)	G14	470	Good	P: 68.6 S: 15.8 R: 15.6	117 (9)	26.0 (5.3)	213.7 (23.6)	140.1 (26.8)	104.7 (28.7)	51.9 (13.9)	16.8 (10.0)
3 (Kortungen)	G14	620	Medium	P: 61.3 S: 9.7 R: 29.0	106 (30)	24.1 (5.4)	191.8 (24.8)	128.3 (38.5)	99.3 (29.9)	61.2 (24.4)	9.3 (5.8)
4 (Svera)	G11	630	Poor	P: 32.8 S: 30.0 R: 37.2	100 (27)	24.9 (6.0)	162.5 (24.3)	997 (32.5)	59.5 (27.9)	30.9 (23.3)	6.3 (4.3)
5 (Olavrud)	G20	350	Good	P: 76.4 S: 7.1 R: 16.5	102 (16)	28.9 (7.1)	252.3 (30.3)	167.0 (35.9)	134.8 (34.0)	73.7 (31.3)	14.2 (6.9)
6 (Lushaugen)	G11	770	Poor	P: 50.6 S: 25.4 R: 24.0	119 (15)	27.3 (7.3)	155.5 (30.8)	83.1 (45.3)	50.7 (19.5)	25.1 (10.0)	8.6 (5.8)
Total				P: 60.0 S: 15.6 R: 24.4	107 (21)	26.6 (6.7)	196.1 (43.9)	122.1 (45.0)	88.2 (39.6)	47.2 (26.7)	10.7 (7.8)

The sawing was done according to Nordic practice as defined by Anonymous (1994b), with heart splitting giving either 2, 4 or 6 ex-log in the centre yield depending on the diameter of the log processed (Figure 1).

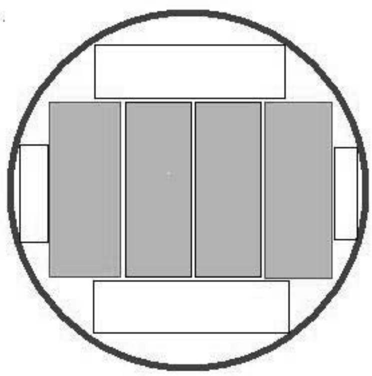


Figure 1. Sawing pattern with boards from centre yield in grey and side yield in white

Board dimensions were commercial dimensions decided by the sawing pattern producing the maximum sawing yield from each log. Table 2 gives the dimension combination for the centre and side yield.

Table 2. Nominal dimensions of the boards in the centre and side yield respectively

Centre yield	Thicknesses [mm]	38, 44, 50, 63, 75
	Widths [mm]	100, 125, 150, 175, 200, 225
Side yield	Thicknesses [mm]	19, 25, 38, 50
	Widths [mm]	100, 125, 150, 175, 200, 225

The study was based on the logs satisfying the lowest quality for saw logs in Norway (Anonymous 1994a) and which started no longer than 120 dm from stump level. This yielded 397 logs, out of which 1667 boards were extracted. All the boards were graded according to Nordic Timber (Anonymous 1994b), which utilizes four grades A, B, C and D with A as the best and D as "reject". It is possible to divide grade A into four different subclasses, A1 to A4, but this was not done in this study since it is usually done only for Scots pine as raw material for furniture, mouldings, windows and other almost knot free products.

The planks, i.e. boards with thicknesses above 32 mm, 1118 planks in total, were also strength graded according to INSTA 142 (1997), which is the system of Nordic visual strength grading rules. These rules specify four grades, and in the standard EN 1912 (2005), each grade is assigned to strength classes defined in EN 338 (2003). The grades used in this study (strength class in brackets) were T3 (C30), T2 (C24), T1 (C18) and reject.

Statistical modeling

Grade yield

Since the aim of this study was to model grade yield, the response was the different grades in the different grading rules. These grades must be considered as categories with inherent ranking. The predictors to be tested were both continuous and discrete, and as such logistic regression analysis was chosen similar to the approach used by Øvrum and Vestøl (2008). A multinomial distribution was chosen treating the response levels, i.e. grades, as ordinals. The new model was expanded based and the findings by Øvrum et al. (2008a), and several variables measured on logs, trees and sites were tested to find an overall model for grade yield. In an ordinal multinomial logistic regression *Y* (grade in this case) takes on one of k+1 possible values, denoted by 1, 2, ... k, k+1 in a parallel lines regression model based on the cumulative probabilities of the response categories, also known as the proportional odds model (Agresti 2002). The model can be expressed as:

$$P(Y \leq k) = \frac{e^{\alpha_{grade}+\alpha_{board}+\beta_{site}x_1+\beta_{tree}x_2+\beta_{\log}x_3}}{1+e^{\alpha_{grade}+\alpha_{board}+\beta_{site}x_1+\beta_{tree}x_2+\beta_{\log}x_3}} \qquad \text{k= grade 1, grade 2, grade 3, grade 4} \qquad (1)$$

where:

α_{grade} is the intercept dependent on grade

α_{board} is the intercept dependent on board type

β_{site} is the effect of site variables

β_{tree} is the effect of tree variables

β_{log} is the effect of log variables

The tested variables are presented and defined in Table 3.

Table 3. Notation and definition of the tested variables

	Variable	**Type**	**Definition**
Site variables	Age	Continuous	Stand age
	SI	Continuous	Site index [m]
	Alt.	Continuous	Altitude
	DBH_{site}	Continuous	Mean DBH for site [dm]
	$HC360_{site}$	Continuous	Mean HC360 for site [dm]
	$HC180_{site}$	Continuous	Mean HC180 for site [dm]
	HLB_{site}	Continuous	Mean HLB for site [dm]
Tree variables	DBH	Continuous	Diameter at breast height over bark [cm]
	H	Continuous	Tree height [dm]
	H/DBH	Continuous	
	HC360	Continuous	Distance from stump to the point where all branches in the whorl is alive [dm]
	HC180	Continuous	Distance from stump to the point where 50 % of the branches in the whorl is alive [dm]
	HLB	Continuous	Distance from stump to the lowest living branch [dm]
	DHB_{rel}	Continuous	DBH/DBH_{site}
	Length	Continuous	Cross-cutting length [dm]
Log variables	LD	Continuous	Log diameter at top end [cm]
	Taper	Continuous	Log taper [mm/m]
	LP	Continuous	Log position in the stem [dm from stump]
Board variables	Board	Discrete	Inner board [I] or other board [Y]
Interactions			Length x DBH
			Length x DBH_{site}
			Length x DHB_{rel}
			Length x H
			Length x LP
			Length x IorY
			LP x IorY

Each board were weighted by:

$$\text{volume of board/mean board volume} \qquad (2)$$

The analyses were performed in the procedure LOGISTIC in the software SAS (SAS 1999), which is a procedure specially developed for logistic regression. First, a stepwise multiple regression analysis was performed with all the above predictors included to screen for the best suited predictors. Both the level for entry p_E and removal p_R was set to 0.4 as recommended by Hosmer and Lemeshow (2000) to ensure that all variables were properly judged in the iteration process. In the final model only predictors with a significance level of 0.05 in type 3 tests were included. The most parsimonious model was chosen, meaning that for models with an almost identical fit, the model with the fewest and the most robust variables was chosen.

Measures of association were assessed by the proportion of concordant and discordant pairs (all boards were compared with each other). Two boards are concordant if the board ranking higher on X (predicted grade) also ranks higher on Y (observed grade). A pair is discordant if the board ranking higher on X ranks lower on Y. A pair is tied if the subjects have the same classification on X and/or Y (Agresti 2002). Also, the gamma value as defined by Goodman and Kruskal (1954) is presented, given as:

$$\gamma = \frac{\text{proportion of concordant pairs - the proportion of discordant pairs}}{\text{proportion of concordant pairs + the proportion of discordant pairs}} \qquad (3)$$

To show the trends and relations within and between the variables, odds ratios are presented in various forms. In principle, “odds ratio” is defined as the “odds for success” (Agresti 2002). In this paper the odds ratio for continuous variables is the odds of retaining the grade by increasing the variable with an increment of one. This means that an odds ratio of 0.9 is interpreted as a 10 % chance of a decrease in grade by increasing the variable with an increment of 1. Oppositely, an odds ratio of 1.1 is interpreted as a 10 % chance of increase in grade by increasing the variable with an increment of 1. The odds ratio for categorical variables is the odds of getting a higher grade in one category compared to another category of the variable.

The models of Øvrum and Vestøl (2008) were tested on the boards which satisfied the constraints of Øvrum and Vestøl (2008). This comprised 687 boards in total. The yield predicted by Øvrum and Vestøl (2008) was compared to the observed grade yield and the yield predicted by the new models developed in this study. The compared yields were computed by multiplying the probability of the different grades for every board with the board volume, and then sum the total volume of each grade and divide it by the total sum of board volume. Another approach is to compare observed grade in each board to the predicted grade by constructing a classification table. However, such comparisons do not work properly if some response levels have low probabilities, often defined as lower than 0.2 (Hosmer and Lemeshow 2000). This is the case for this study, where the two lowest grades in NT- and the lowest grade in IN-grading are well below 0.2. As an example, the predicted grade of NT based on the board model of Øvrum and Vestøl (2008) was only A or B, which makes classification by the model inappropriate.

RESULTS

Appearance grading according to Nordic Timber (NT)

The parameter estimates for the NT-grade model are shown in Table 4.

Table 4. Parameter estimates for the significant predictors (p <0.05) in the Nordic Timber model

Parameter		**DF**	**Estimate**	**Standard error**	**Wald Chi-Square**	**p-value (type 3)**
	A	1	2.0259	0.8312	5.9405	0.0148
Grade	B	1	4.0382	0.8368	23.2893	<0.0001
	C	1	7.0905	0.8712	66.2316	<0.0001
H		1	0.0112	0.0016	50.9553	<0.0001
LP		1	-0.0120	0.0034	12.3502	0.0004
Board(I)		1	0.4480	0.0685	42.7764	<0.0001
Board(Y)			-0.4480			
DBH_{site}		1	-0.1107	0.0345	10.2910	0.0013
Length*LP		1	0.0002	0.0001	9.1753	0.0025
Length*DBH_{rel}		1	-0.0386	0.0031	155.8736	<0.0001
LP*Board(I)		1	0.0052	0.0014	13.0460	0.0003
LP*Board(Y)			-0.0052			

Out of a total of 848 708 possible board pairs 73.9 % were concordant while 25.5 % were discordant, leaving 0.5 % of the pairs tied. This yielded a gamma value of 0.486, indicating that the proportion of concordant pairs is 0.486 higher than the proportion of discordant pairs as outlined by Agresti (2002).

Some of the effects could be suspected to be correlated, and a correlation matrix between the most obviously correlated variables are shown in Table 5.

Table 5. Correlation between some variables in the model

	H	DBH_{site}
DBH_{site}	0.521	
DBH_{rel}	0.387	-0.029

The odds ratios for the significant predictors not included in any interactions were 1.011 for tree height and 0,895 for DBH_{site}.

Odds ratios for the predictors included in interaction terms depend on the predictors they interact with. The odds ratio for length depended on log position and DBH_{rel}. This relationship is shown in Figure 2.

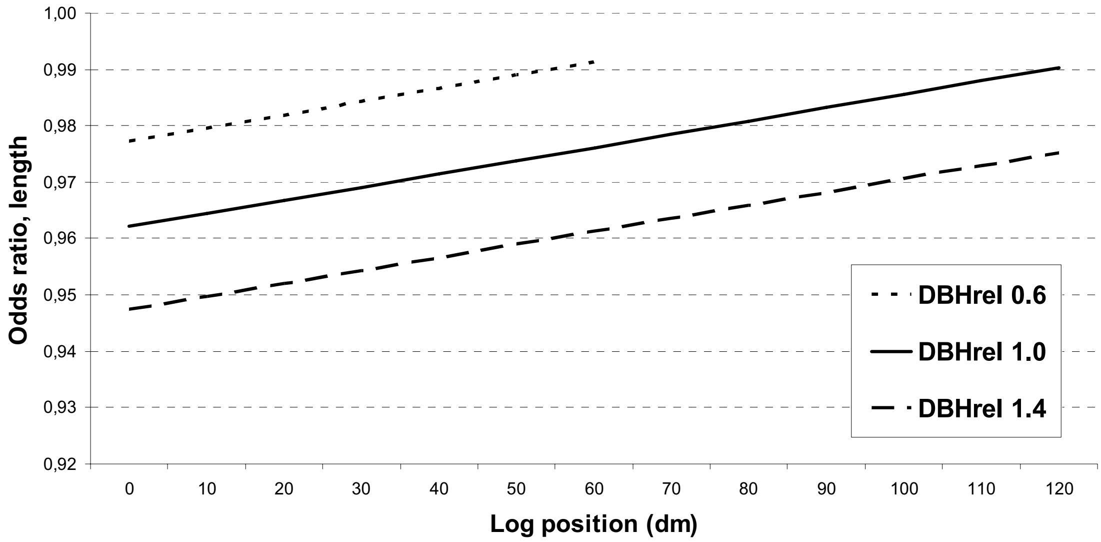


Figure 2. Odds ratio for the length effect in Nordic Timber as affected by log position and relative DBH

Figure 2 shows that the effect of length on grade yield decreases with the distance from stump and increases with increasing DBH_{rel}. The corresponding odds ratio for log position's dependency on length is shown in Figure 3.

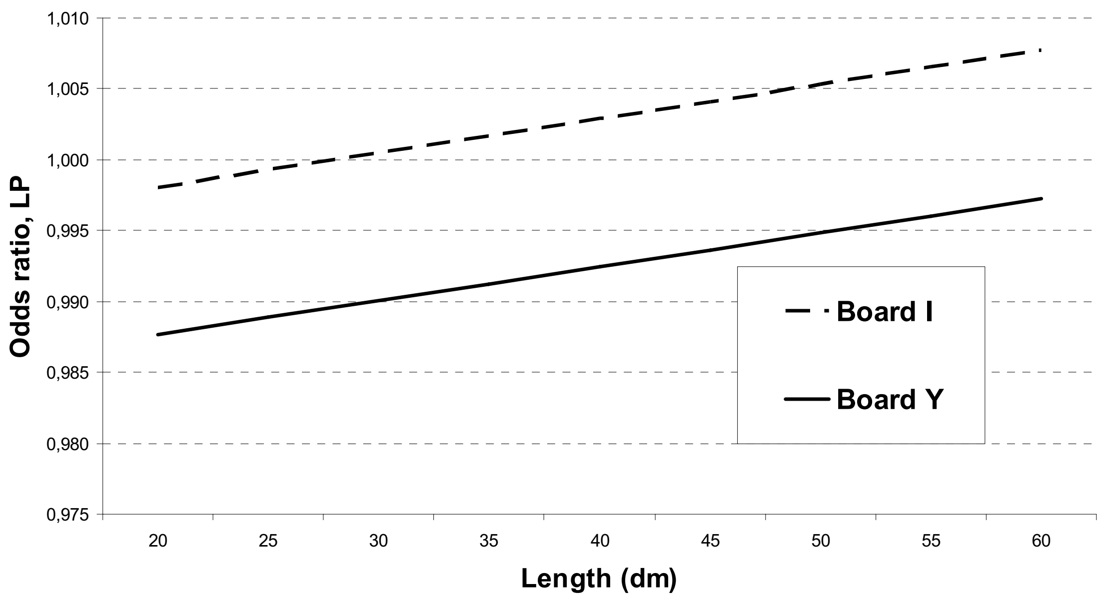


Figure 3. Odds ratio for the log position in Nordic Timber as affected by length and board type

Odds ratio for log position increased with increasing length (Figure 3). Together with Figure 2 this indicates that the grade yield is less sensitive to length increase when the distance from stump increases.

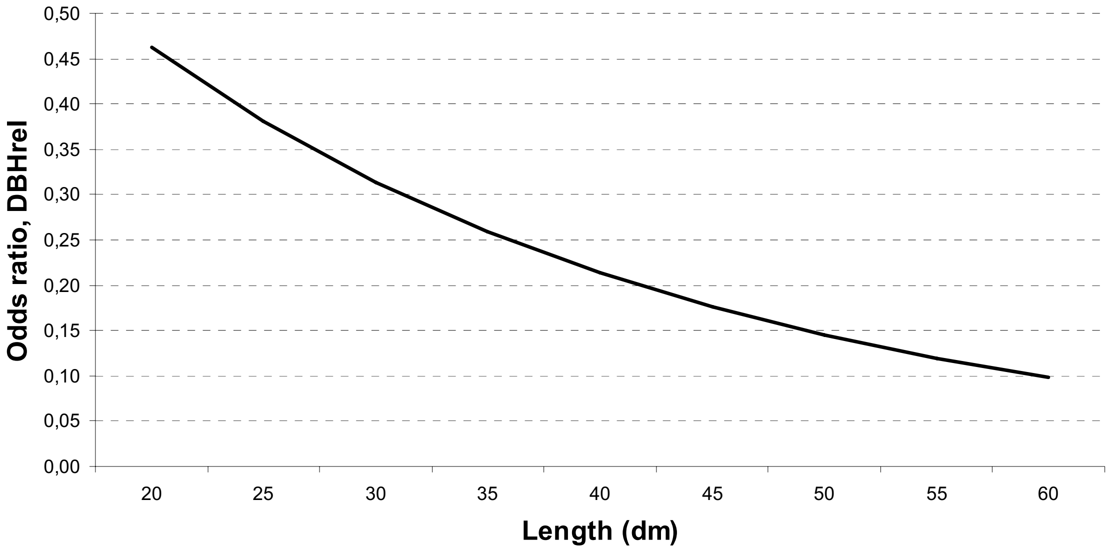


Figure 4. Odds ratio for relative DBH in Nordic Timber as affected by length

The odds ratio for relative DBH decreased with increasing length (Figure 4). This indicates a stronger decrease in grade yield with increasing tree size.

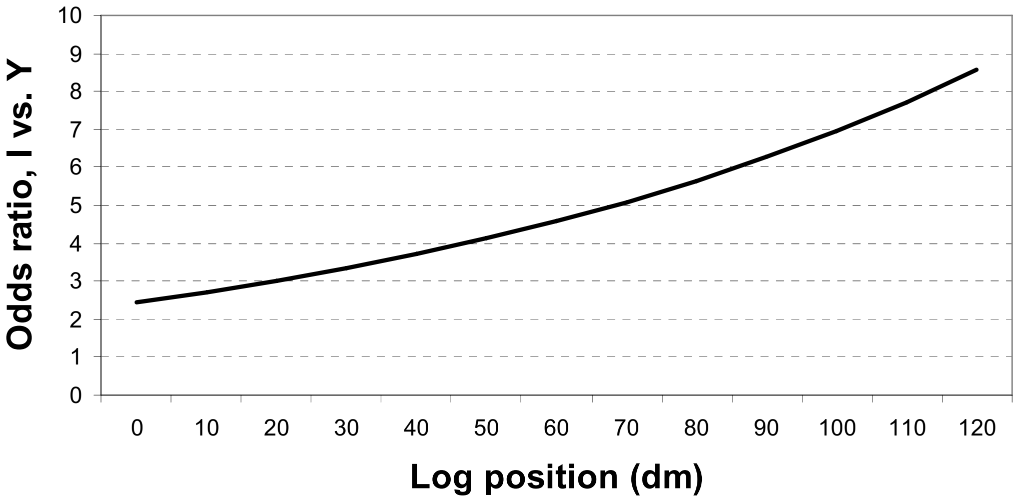


Figure 5. Odds ratio for board type (I vs. Y) in Nordic Timber as affected by log position

The better grade yield for inner boards compared to other boards (Odds ratio, I vs. Y) increases with distance from stump (Figure 5).

Visual strength grading according to INSTA 142 (IN)

The parameter estimates for the IN-grade model are shown in Table 6.

Table 6. Parameter estimates for the significant predictors (p <0.05) in the INSTA 142 model

Parameter		DF	Estimate	Standard error	Wald Chi-Square	p-value (type 3)
Grade	T3	1	2.4352	0.9923	6.0227	
	T2	1	4.0036	0.9973	16.1163	
	T1	1	5.3084	1.0033	27.9959	
Length		1	-0.0272	0.0095	8.2357	0.0041
H		1	0.0170	0.0020	76.1337	<0.0001
LP		1	-0.0320	0.0041	59.8744	<0.0001
Board (I)		1	0.4505	0.0741	36.9867	<0.0001
Board (Y)			-0.4505			
DBH_{site}		1	-0.1546	0.0418	13.7017	0.0002
Length*LP		1	0.0003	0.0001	9.0946	0.0026
Length*DBH_{rel}		1	-0.0193	0.0069	7.7900	0.0053

Out of a total of 424.491 possible pairs 69.5 % were concordant while 30.0 % were discordant, leaving 0.4 % of the pairs tied. This yielded a gamma value of 0.397, indicating that the proportion of concordant pairs is 0.397 higher than the proportion of discordant pairs as outlined by (Agresti 2002).

The odds ratios for the significant predictors not included in any interactions were 1.017 for tree height, 0.857 for DBH_{site} and 2.462 for inner boards versus other boards.

The odds ratio for length depended on log position and DBH_{rel} (Figure 6).

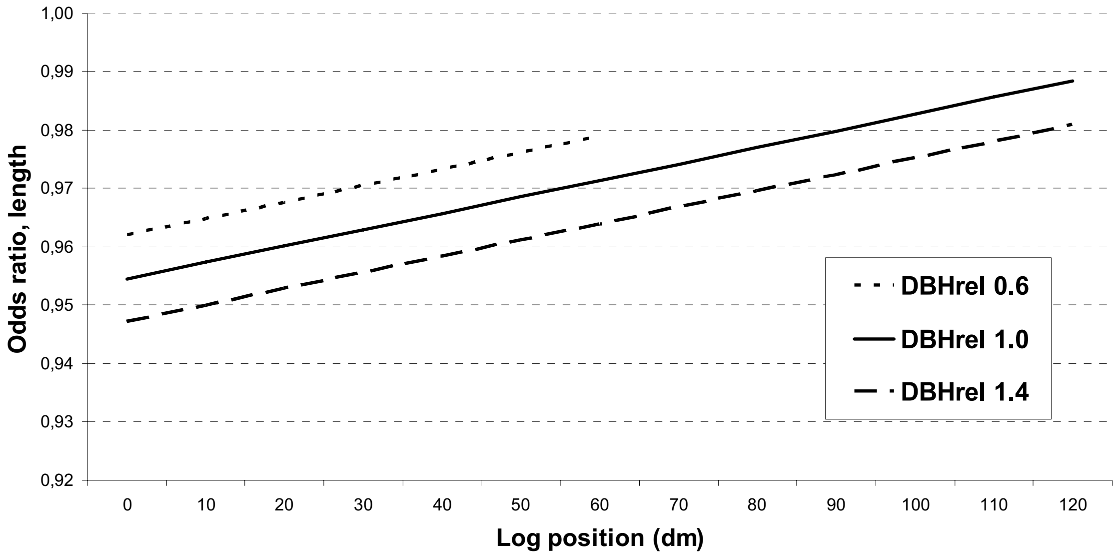


Figure 6. Odds ratio for the length effect in INSTA 142 as affected by log position and relative DBH

The effect of length on grade yield decreased with distance from stump and decreasing DBH_{rel}. The corresponding odds ratio for the log position's dependency on length is shown in Figure 7.

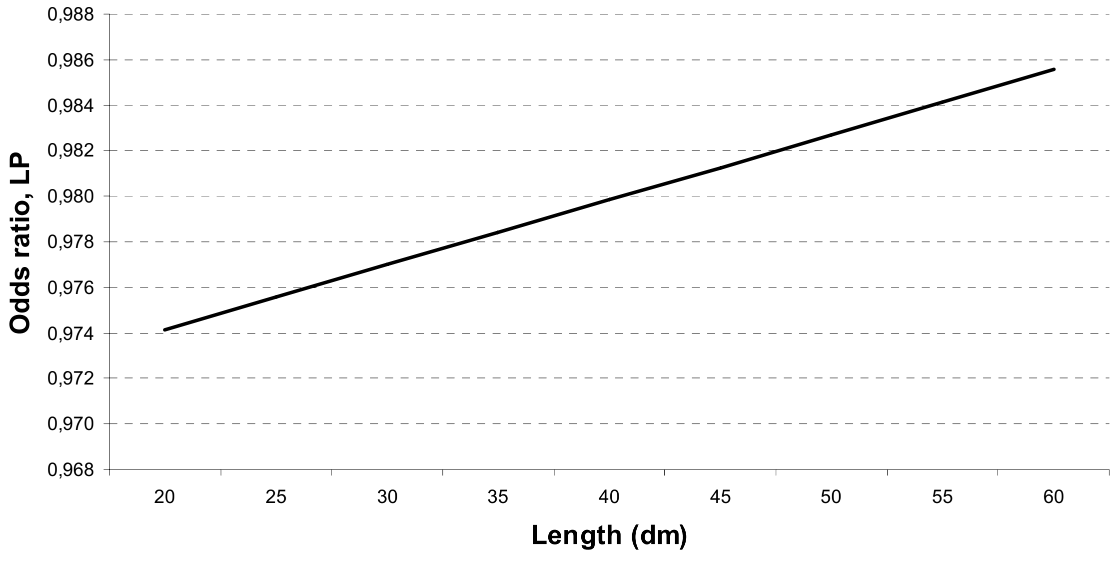


Figure 7. Odds ratio for the log position in INSTA 142 as affected by length

The odds ratio for log position increased with increasing length (Figure 7). Together with Figure 6 this indicates that the grade yield is less sensitive to length increase when the distance from stump increases.

Figure 6 indicates that the odds ratio for relative DBH depends on length. The continuous relationship is shown in Figure 8.

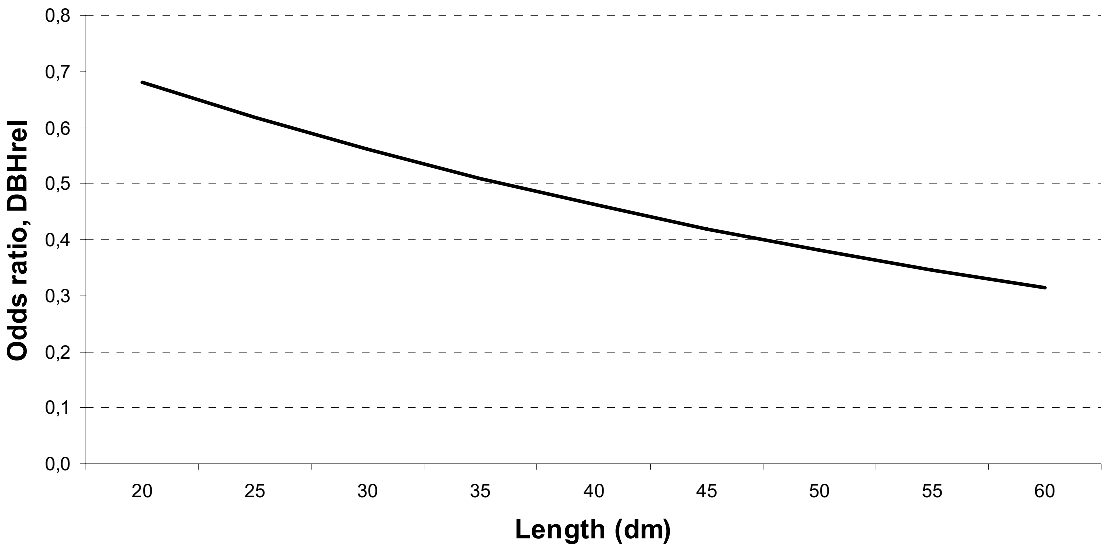
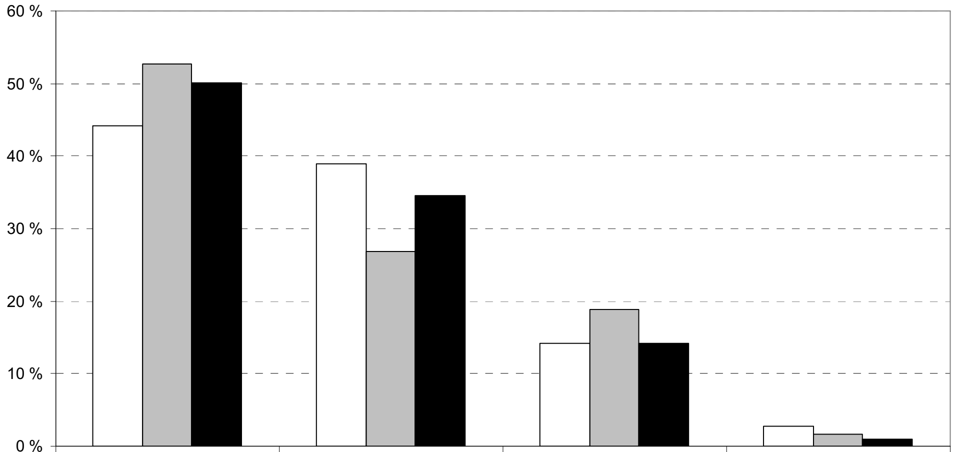


Figure 8. Odds ratio for relative DBH in INSTA 142 as affected by length

The odds ratio for relative DBH decreased with increasing length (Figure 8). This indicates a stronger decrease in grade yield with increasing tree size.

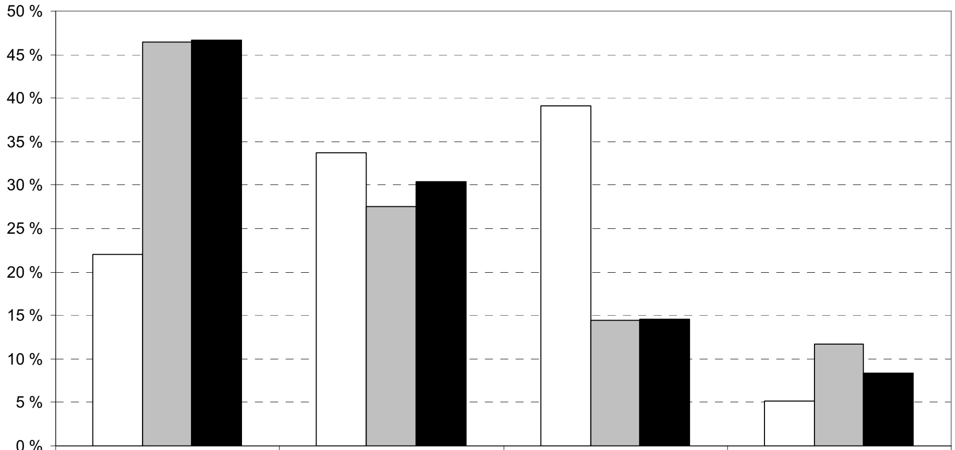
Comparison and testing of the models

In Figure 9 and Figure 10 the predicted yield by the models of Øvrum and Vestøl (2008) and the models developed in this study (new model) are shown together with the observed grade yield.



	A	B	C	D
□ Øvrum and Vestøl (2008)	44,1 %	39,0 %	14,2 %	2,7 %
■ Observed	52,7 %	26,8 %	18,9 %	1,6 %
■ New model	50,1 %	34,6 %	14,2 %	1,0 %

Figure 9. Predicted and observed Nordic Timber grade yield for the boards satisfying the requirements of Øvrum and Vestøl (2008)



	T3	T2	T1	T0
□ Øvrum and Vestøl (2008)	22,1 %	33,7 %	39,1 %	5,2 %
■ Observed	46,4 %	27,5 %	14,4 %	11,7 %
■ New model	46,6 %	30,4 %	14,6 %	8,3 %

Figure 10. Predicted and observed INSTA 142 grade yield for the boards satisfying the requirements of Øvrum and Vestøl (2008)

To see how the models perform for different categories of forest qualities, tree sizes and cross-cutting lengths based on the findings of Øvrum et al. (2008a), the grade yield was computed for the various combinations. The results are shown in Table 7 for NT-grading and Table 8 for IN-grading.

Table 7. Predicted and observed grade yield in Nordic Timber for the different forest qualities, tree sizes and cross-cutting lengths, and the mean deviation between the yield in the different grades in absolute value (Abs. dif)

Category	Model	Grade yield [%]				Abs dif [%]
		A	B	C	D	
Length 20 dm	Øvrum and Vestøl (2008)	59.6	31.3	7.7	1.3	5.8
	Observed	70.7	21.8	5.7	1.7	
	New model	64.7	27.6	7.3	0.4	3.7
Length 40 dm	Øvrum and Vestøl (2008)	42.5	41.1	13.8	2.5	6.7
	Observed	48.9	29.7	20.7	0.7	
	New model	52.1	35.5	11.7	0.7	4.5
Length 60 dm	Øvrum and Vestøl (2008)	35.3	40.3	20.2	4.2	6.4
	Observed	35.8	28.8	32.5	2.9	
	New model	29.1	42.0	26.7	2.2	6.6
Forest quality Poor	Øvrum and Vestøl (2008)	47.5	37.4	12.7	2.4	5.3
	Observed	44.8	29.6	22.7	2.9	
	New model	39.8	37.7	20.7	1.7	4.1
Forest quality Medium	Øvrum and Vestøl (2008)	38.3	42.1	16.4	3.2	9.9
	Observed	54.3	23.9	20.2	1.7	
	New model	50.5	35.1	13.6	0.9	5.6
Forest quality Good	Øvrum and Vestøl (2008)	40.7	40.8	15.5	3.0	7.8
	Observed	55.6	27.3	16.1	0.9	
	New model	55.1	32.7	11.4	0.7	2.7
Tree size Small	Øvrum and Vestøl (2008)	52.5	35.4	10.2	1.8	6.6
	Observed	49.7	25.1	20.5	4.7	
	New model	57.0	32.2	10.2	0.6	7.2
Tree size Medium	Øvrum and Vestøl (2008)	42.9	38.9	15.2	3.0	8.8
	Observed	60.5	24.2	13.8	1.5	
	New model	54.9	33.4	11.1	0.7	4.6
Tree size Large	Øvrum and Vestøl (2008)	42.6	39.7	14.8	2.9	6.6
	Observed	48.6	28.7	21.6	0.1	
	New model	46.0	35.8	16.9	1.3	3.9

The new model predicted grade yield better in all the groups, except the small trees.

Table 8. Predicted and observed grade yield in INSTA 142 for the different forest qualities, tree sizes and cross-cutting lengths, and the mean deviation between the yield in the different grades in absolute value (Abs. dif)

Category	Model	Grade yield [%]				Abs dif [%]
		T3	T2	T1	T0	
Length 20 dm	Øvrum and Vestøl (2008)	36.6	34.9	26.0	2.5	13.9
	Observed	60.7	22.9	10.2	6.1	
	New model	59.3	25.9	9.9	4.9	1.5
Length 40 dm	Øvrum and Vestøl (2008)	18.3	35.2	40.9	5.5	12.4
	Observed	37.0	35.2	16.1	11.7	
	New model	45.4	31.9	14.8	7.9	4.2
Length 60 dm	Øvrum and Vestøl (2008)	9.6	29.8	52.7	7.9	21.9
	Observed	42.6	21.6	17.0	18.7	
	New model	32.8	33.8	20.2	13.2	7.7
Forest quality Poor	Øvrum and Vestøl (2008)	24.6	31.0	38.1	6.3	10.6
	Observed	35.4	27.6	20.4	16.6	
	New model	35.8	32.2	19.2	12.7	2.5
Forest quality Medium	Øvrum and Vestøl (2008)	17.7	32.0	43.8	6.5	16.1
	Observed	45.9	33.6	11.7	8.8	
	New model	45.5	31.2	15.0	8.4	1.6
Forest quality Good	Øvrum and Vestøl (2008)	20.6	33.4	40.5	5.5	18.6
	Observed	52.3	23.6	13.1	11.0	
	New model	52.9	29.0	12.0	6.1	3.0
Tree size Small	Øvrum and Vestøl (2008)	23.5	34.7	37.4	4.3	23.5
	Observed	52.2	17.0	8.2	22.6	
	New model	46.0	31.0	14.7	8.3	10.2
Tree size Medium	Øvrum and Vestøl (2008)	20.5	31.1	41.4	7.0	14.7
	Observed	44.4	33.7	12.0	9.8	
	New model	47.5	30.9	14.1	7.5	2.6
Tree size Large	Øvrum and Vestøl (2008)	21.6	33.3	39.7	5.4	15.0
	Observed	46.4	25.9	17.1	10.6	
	New model	46.3	30.0	14.9	8.8	2.1

The model of Øvrum and Vestøl (2008) predicted the new material poorly for IN-grading, and the improvement was substantial with the new model. The small trees had the largest deviation between predicted and observed grade yield as in NT-grading.

Discussion

As expected, the length was the variable most strongly associated with grade yield. The larger length effect in bigger trees is probably due to larger crowns and knots and a steeper knot diameter profile in the lower part for these trees compared to intermediate and suppressed trees (Abetz and Unfried 1983; Colin and Houllier 1991; Moberg 2001, 2006; Vestøl and Høibø 2001). The decreasing length effect upwards in the trees is parallel to the findings for IN-grading of Øvrum and Vestøl (2008). In the present study a reduced length effect upwards in the trees was found for NT-grading as well, a trend present in Øvrum and Vestøl (2008) too, but not claimed to be statistically significant. The lesser length effect higher up in the trees is probably due to the more homogenous vertical knot pattern in these stem parts compared to the noticeable increasing knot size from the butt end towards the crown base, and the higher occurrence of dead knots (Øyen 1999) and other down-grading features in the lower stem parts. The length effect was slightly stronger for IN-grading than for NT-grading, which was expected since strength grading is more prone to down-grading due to knot size. The length effect was similar to what Øvrum and Vestøl (2008) found, implying that the level of cost of increasing length found in Øvrum and Vestøl (2008) was reasonable.

The decrease in grade yield for logs extracted higher up in the trees is in line with the investigations of Øvrum and Vestøl (2008) and Rikala (2003) on Norway spruce. Blomqvist and Nylinder (1988) did not find any difference in grade for logs of Norway spruce, only more homogenous grades in butt logs when grading after "Grøna boken" (Anonymous 1976). Høibø (1991), on the other hand, found an increasing trend in grade yield higher up in trees when grading Norway spruce according to the "ØS-rules"(Anonymous 1981). However, he only extracted two boards from each log, which were thicker than those extracted in this study, thus leading to more dry knots down-grading for the butt logs as compared to this study. The deviance in results indicates that the last decades' changes in sawing pattern influence the grade yield. The grade yield is a result of the bole quality, mainly the knot characteristics inside the bole, cross-cutting pattern and sawing pattern, which decide where in the cross-section each log is split.

The higher grade yield in inner boards compared to other boards corresponds to Øvrum and Vestøl (2008). The stronger difference between boards towards the top end for NT-grading can be attributed to the smaller board sizes in other boards (boards outside the inner boards), which cause much down-grading for sound knot size. Also, side boards are represented in NT-grading (see Figure 1), but not in IN-grading. Side boards generally had lower grades, a well-known effect with Norway spruce.

The better grade yield in smaller trees can be explained by means of the smaller knot size in such trees, but may seem, at first glance, to be contradicted by the positive effect of tree height. However, the interpretation should be that, given a relative DBH, increasing tree height is positive for grade yield, since slender trees have better quality due to a smaller knot proportion (Gislerud 1974) and smaller knot diameter. An expression of slenderness of trees will be H/DBH, and this variable was tested, but gave a poorer fit than including both tree height and relative DBH. The decreasing grade yield with increasing mean DBH can be explained through similar reasoning.

Tree variables, i.e. tree height and $DBH_{rel,}$ seem to be more important than site variables, implying a higher variation within stands than between stands, indicating the same relationship as for knot size (Vestøl and Høibø 2001) and fibre properties (Molteberg 2006) in Norway spruce. However, position of the board within the tree, both longitudinally and in the cross section, was the most important factor for grade yield, except for length, where inner boards in butt logs obtained the highest grade yield.

The new models developed in this study fit the data much better than the models of Øvrum and Vestøl (2008). Especially for IN-grade, the model fit was substantially improved. This was expected since the material of Øvrum and Vestøl (2008) was based on a limited data set from a quality point of view. The material in this study has a much wider range in tree and site qualities. This will make the models developed in this study able to predict a wider range of sites and tree types, and be good enough to assess size and trends of grade yield within a 10 % margin as long as they are used within the range of the data set, but to ensure this a validation should be performed. In further studies on this topic a larger variation in tree and stand ages should be emphasized, in addition to including sites with higher fertility, i.e. site indices of G23 and G26.

Conclusions

Increasing length influence grade yield in Norway spruce negatively. This effect is strongest at stump level, and decreases upwards in trees. Trees having a large relative diameter at breast height compared to the stand mean will have the strongest length effect. Grade yield decreases upwards in the stem, and inner boards give better grade yield than other boards, an effect which is increasing towards the top end in NT-grading. Increasing tree height had a positive effect on grade yield, while the mean diameter at breast height of the stand affected the grade yield negatively. In addition to length, position of a board within a tree is the most important factor for grade yield, and the variation in grade yield within stands is greater than between stands for the grading rules used in this study. The models for predicting grade probabilities seem to fit within a 10 % margin.

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