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Automatic Sorting of Sawlogs by Grade

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SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

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Abstract

Optical log scanners provide a possibility for sawmills to pre-sort logs automatically by grade. Logs were classified by different grades and sawn timber properties using external log geometry variables such as taper, surface unevenness, sweep and out-of-roundness. Raw data from commercial shadow scanners and laser point 3D-scanners were used. The analyses were based on data from three sawing studies on Norway spruce, a total of 1095 logs from 22 different stands, and one sawing study on Scots pine. Logistic regression was used as the classification method, and model accuracy was assessed using the areas under receiver operating characteristic (ROC) curves. Models for sorting criteria based on knot size, knot type and grain distortion, like visual stress grades, showed a better predicting performance than commodity grade and MSR (stiffness) models. The results generally improved when variables generated from 3D-scanner data were used.

Similar external geometry variables proved useful in the different studies, even if the parameter estimates differed between stands and regions. A recommendation is that mills should verify and develop classification models for their own log supply and sorting criteria. The opportunity for sawmills to use the methods to improve revenue was shown in a glulam case study, where for example high stress grades were requested. The sorting accuracy, and revenue, increased when non-geometry variables such as density and grain angle were added.

Key words: classification, geometry, grade, logistic regression, log, *Picea abies,* saw, scanner, sorting.

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Contents

Appendix

Papers I-V

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

I. Jäppinen, A., and Nylinder, M. 1997. Automatic sorting of spruce *(Picea abies* (L.) Karst.) sawlogs by grade. *Holz als Roh- und Werkstoff 55:301-*305.

II. Jäppinen, A., and Beauregard, R. 2000. Comparing grade classification criteria for automatic sorting of Norway spruce saw logs, *Scandinavian Journal of Forestry Research* 14. *(in press).*

III. Lundgren, C. and Jäppinen, A, 1998, Grading of logs using external geometry features from 3D- and profile log scanners- a comparison. Proceedings- *3rd IWSS and IUFROS 5.04-10,* Skellefteå.

IV. Jäppinen, A., Grade sorting of Norway spruce logs by external geometry data from a 3D-scanner. (Submitted to *Forest Products Journal.)*

V. Jäppinen, A., Pre-sorting Norway spruce saw logs for glued-laminated timber. (Submitted to *Holz als Roh- und Werkstoff.)*

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Introduction

Background

Sawmills strive to maximise profits. The need to find the best strategy increases as the market is globalised and competition from substitutes increases (Anon., 1992; Johansson, 1999). The sawmills can choose to maximise value recovery with or without further processing (Maness, 1993; Cohen, 1992). One suggested strategy has been to add value to the sawn wood and integrate the operation better with suppliers and customers (Lönner, 1985; Beauregard et al., 1997). Strategies like high productivity or more value added production can also be distinguished among Swedish sawmills (Roos et al., 2000). Another focus can be to improve revenue by better consideration of individual log values (Grönlund, 1995). This includes sawing the appropriate products from each log or group of logs, a decision normally executed either by pre-sorting logs in the log yard or by adjusting the cut to each log as they are sawn (Fronius, 1989). Other alternatives can be to select and prepare logs better in the forest (Björklund & Juhlin, 1998) and to keep track of the logs from forest to sawmill (Anon., 1996a). This can also include keeping track of the log from cross cutting and sorting in the log yard to sawing, as is done in German sawmills sawing to individual construction plan orders (Fronius, 1989).

More than 95 % of the larger sawmills in Sweden are pre-sorting the logs by dimension, commonly small end diameter. About half the sawmills also sort a small share of their volume by grade or length. This amounts to about 10 % of the total volume produced in Sweden (Warensjö & Jäppinen, 1997). A grade or length criterion is normally added to the diameter criteria. Fig. 1 shows the number of bins versus sawn volume in Swedish sawmills. Most Swedish sawmills saw both spruce and pine, and pre-sort logs by species.

Pre-sorting increases the productivity in the saw line since no time is required to re-position the saw between logs, at the same time as the need for board sorting decreases somewhat. Pre-sorting does, however, demand a larger log yard with sorting bins and log measurements in the yard. Another advantage with pre-sorting is the ability to plan and decide saw patterns prior to processing. Fronius (1989) lists further advantages and disadvantages of pre-sorting. These factors are, however, viewed differently in different countries, depending on tradition, saw technology, and log supply factors such as log size and quality distribution. Extensive pre-sorting prevails in Europe and Eastern Canada where log sizes are small, while sawmills in other parts of North America pre-sort less.

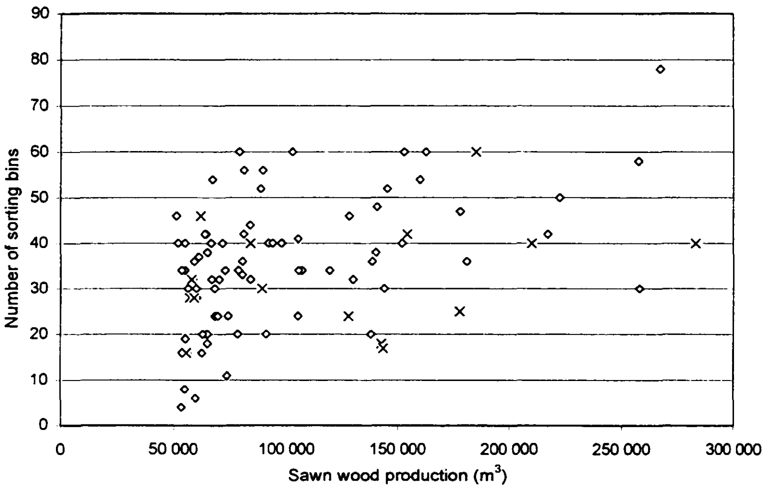

Fig. 1. Number of sorting bins available at all larger softwood sawmills in Sweden, sawing either pine or spruce (x), or both (0) (reconstructed from Warensjö & Jäppinen, 1997).

Most of the sawmills that do pre-sort logs by grade or in other ways adjust their saw patterns to log grade do so by visual inspection of the logs. The majority of the traded saw logs in Sweden are visually graded by the timber measurement associations (Anon., 1995). These grades are rarely utilised for sorting, partly because the national grading rules are too general. The need for specific and flexible sorting is one of the main reasons why automatic log sorting by grade has emerged. Automatic grade sorting is practised at some Swedish sawmills (Grace, 1994).

The applications have so far been limited, and there are many unexplored issues regarding how logs should be pre-sorted by grade. A key issue is knowledge about how to achieve high accuracy and cost efficiency. Scientists and scanner suppliers advocate that sawmills could and should make better use of the automatic scanning systems available (Anon., 1998a).

Objectives and scope

The aim of this thesis is to explore the potential of using external log geometry, as measured by commercially available log scanners, to classify logs before sawing by grades of the sawn wood. The gain of using log features other than geometry has also in part been investigated. Grade can be either a specific property of the sawn wood or a commodity grade, but does not include species, diameter or length. The work mainly concerns Norway spruce *(Picea abies* (L.) Karst.) but some work on Scots pine *(Pinus sylvestris* L.) is also included.

The log properties other than geometry which have been investigated were not readily available from automatic measurements on logs, but may well be in the

future. Other methods were used in this project to assess the gain that could potentially be obtained from the use of these variables.
The automatic sorting of logs by grade can be formulated and illustrated in an Ishikawa graph (Fig. 2). The problem has been divided into five main parts: measurement technology, independent variables, log supply, product requirements and classification models. Each of these may consist of a number of alternatives of which some have been considered during the project and are included in the graph.

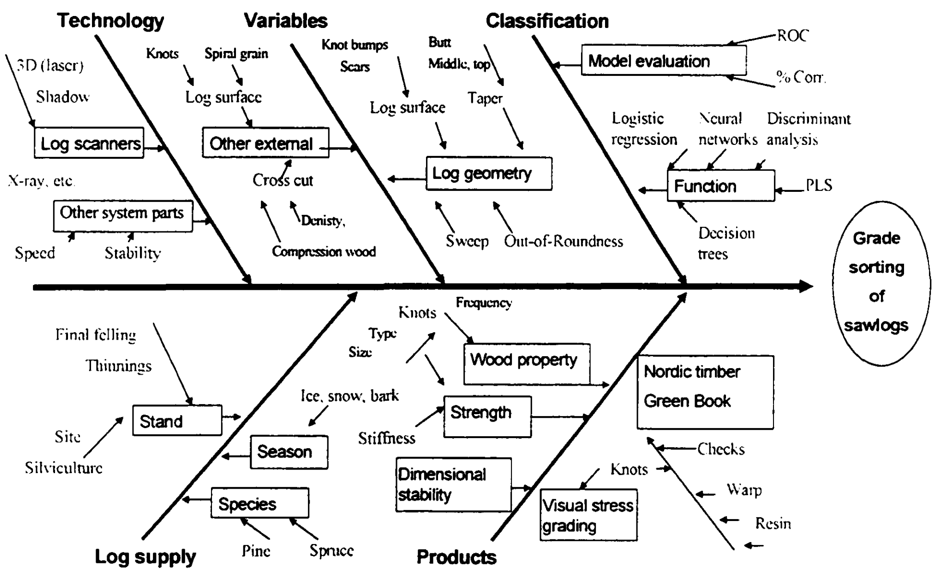

Fig. 2. Some of the factors involved in an automatic log grade classification problem illustrated in an Ishikawa graph.

The terminology used in Fig. 2 is used throughout the work. A few comments should be made on the notation:

- In this context the term log scanner refers to measurement equipment used to capture measurements at multiple positions of the log during length-wise transportation.
- The term variable is used for log or sawn wood properties, used in statistical models to explain or predict grade.
- The classification models use binary response variables, denoted as criteria. The criteria are created using various log or sawn wood grades and properties.
- Nordic timber (Anon., 1994a) and the Green Book (Anon., 1982) are the commodity grading rules used. Machine Stress Rating is sometimes referred to as MSR or as Machine Stress Grading (MSG) which is the same in the scope of this study.

Measurement technology

Log scanners

In Sweden, the dimensions of saw logs are normally measured automatically during length-wise transportation on a sharp chain. A number of technologies are available or potentially available to sawmills, but the thesis has focused on optical log scanners that utilise principles of light absorption and reflection.

Different types of light curtain and shadow scanners dominated during the seventies and eighties (Fronius, 1989). These scanners are referred to as shadow and profile scanners. Scanners that utilise laser light reflection and triangulation principles (Fig. 3) emerged during the last decade, first in North America (Rickford, 1989), and then made their way into Swedish sawmills around 1995. These laser systems generally provide more measurement points (> 20) around the circumference than light curtain systems do (2-6). This provides the ability to generate detailed models of logs and these scanners are thus commonly called 3D-scanners, a term which is used in the thesis.

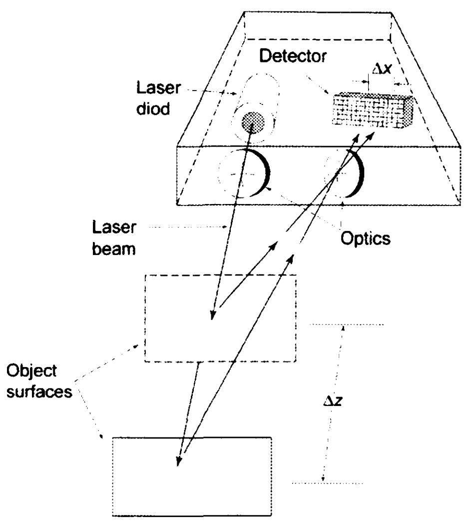

Fig. 3. Principle of laser triangulation, changes in the object's position (Δz) cause a corresponding change on the detector (Δx).

The resolution varies between different types of 3D-scanners, and there are two major commercial systems. One system measures angle and thus distance using a number of individual laser point beams (Fig. 3). The number of beams limits the resolution. The other system uses laser line projection (sheet of light) across the log and a matrix detector, where the detector resolution sets the limit. The laser point method generally provides fewer measurements around the log but more along the log. The length-wise resolution is dependent on the speed of the feed speed. There is a potential to increase the resolution for both systems, and the use of smart sensors has been proposed for e.g. the sheet of light method (Åstrand, 1996).

External log imaging

Any camera, including the detectors in log scanners using the sheet of light principle, can theoretically be used to capture images of log surfaces. Such data have the potential to add important grade information from the log surface (Tian & Murphy, 1997) or log ends (Jonsson, 1992). The principles for analysis of light scattering in wood, the so-called tracheid effect (Åstrand, 1996; Nyström & Hagman, 1999), could also be used to detect knots, grain deviation, or compression wood in logs. The need for systems to handle dirt, bark and other disturbances is more accentuated for logs than for sawn wood, why non-optical systems could be considered an advantage. Among interesting technologies primarily used to measure wood surface properties is the dielectric constant (Steele et al., 1991), and thermography using infra red light (Sadoh & Murata, 1993; Quin et al., 1998). Reflection from light in the near infra red wave lengths (NIR) has also been utilised in measurements on log cross cuts (Spångberg & Thelaus, 1998).

Systems with higher penetration depth have the best potential to get detailed information about internal log properties. Such systems can use elementary particles, electromagnetic waves or mechanical waves (Skatter, 1998). The potential of analysing the transmission of X-rays in logs has been proven for a number of applications (Oja, 1999; Grundberg, 1999). The potential of using polarisation of microwaves was explored by Kaestner (1999). The potential and theory of analysing the velocity of ultra sound have been described by Paschalis (1978). The general potential of these and other similar methods using signal penetration are discussed from a log scanning perspective by Skatter (1998).

Technology adoption in Sweden

More than 90% of the Swedish sawmills producing 10000 m^3 or more per annum had some type of log scanner in 1995 (Warensjö & Jäppinen, 1997). This figure includes both log scanners used at the scaling station for log sorting and scanners used at the mill intake for log turning and log positioning. A number of sawmills have invested in 3D-scanners since 1995. Most log scanners in Sweden are from Rema Control AB, but there are several other Swedish, Finnish, Canadian and American scanners installed. There are also a few mills which have gamma or X-ray scanners supplied by Rema Control AB. Two gamma ray log scanners have been in use at Swedish mills (Sederholm, 1988) and have also been subject to research on detection of internal defects (Hagman, 1993). The potential of a two axis X-ray scanner has been investigated by Grundberg (1999) and Oja (1999), with reference to the industrial prototype system installed at a Swedish sawmill. There are few other commercial systems for automatic detection of defects in logs. Some mills use digital cameras for operator support (Oja et al., 1999b).

Log properties and independent variables

Properties in the stem, log surface or log ends that are correlated with product properties can be used as indirect measures (variables) of end product quality. The variables used in classification rules have often been developed for visual inspection and the capacity of the human brain. The Swedish national log grading rules, for example, were previously based on the perceived grade of the centre boards (Anon., 1987). The current rules are purely based on assessment of log surface variables and include log size and form and knot size and knot type (Anon., 1998b; 1995). There are many different stem and log properties that have been shown to explain important sawn wood properties (Hagman, 1996), and views on which properties that are of highest interest around the world have been presented at an international wood quality workshop (Anon., 1997). A European industry poll in 1998 ranked diameter and species ahead of knot size and type to be of the highest priority for automatic measurement prior to sawing. Diameter and species are not considered as grade properties in this work, but knot size and type are. The preferences and priorities vary between markets and the available technology, and the list below is derived from the perspective used in the thesis. Most of the listed log variables interact, but only those interactions that might be less obvious are mentioned.

Fig. 4. Norway spruce logs reconstructed from external geometry data.

External log geometry

Various dimensional measures of logs can be used to predict grade properties, (Blomqvist & Nylinder, 1988). Fig. 4 shows the geometry of two Norway spruce logs where the shading represents log surface unevenness. The data are from real logs but the proportions are altered. The form of trees and logs can partly be explained by crown dynamics (Hollier et al., 1995; Seifert, 1999), and physical adaptation to environmental factors (Mattheck & Kubler, 1995).

Taper

Taper in different parts of the log indicates height position in the stem and stem form. Most wood properties vary with height in a tree and can thus be estimated indirectly using taper. The taper functions developed by Edgren & Nylinder (1959) and Pettersson (1926) are still used (Moberg, 1999). The taper is modelled through three splined logarithmic functions. The first describes the stem form and taper in the living crown from the top down to 60 % of tree height, the second describes the form from 60 % to the start of the butt flare, and the third describes the butt flare. The start of the butt flare and thus the higher taper is calculated to be at about 15 % of the tree height for mature trees with a form factor of 0.65-0.70. A similar division of the tree in height sections is used by Moberg (1999) to model knot properties in Norway spruce (Fig. 5). This is also the theory behind using taper in sections of logs to predict knot and grade properties (Gislerud, 1974; Blomqvist & Nylinder, 1988). There is, however, a large variation in knot size at a given height, as shown in Fig. 5.

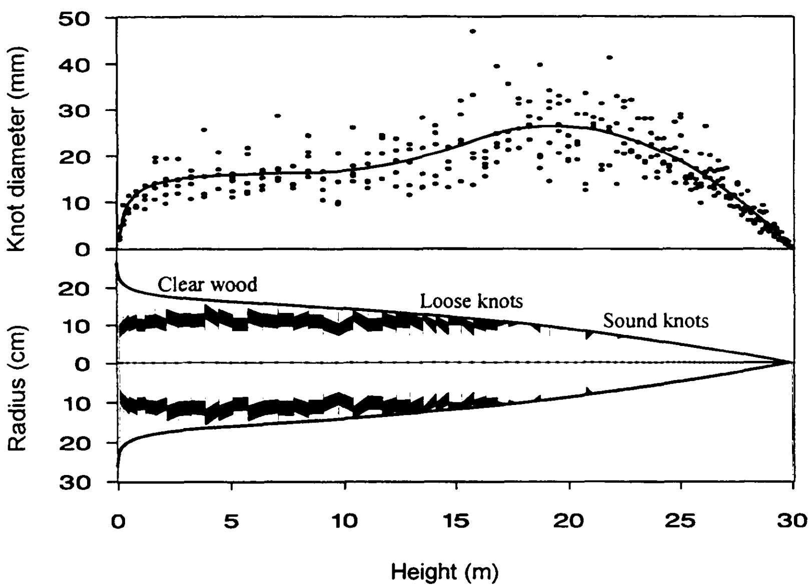

Fig. 5. Knot model for Norway spruce (Moberg 1999).

Large taper and butt swell in the bottom end of logs are distinct indicators of butt logs, which are recognised as generally having certain qualities, like smaller knots. This is reflected in the log grading rules where log type (butt log) is a class variable (Anon., 1998b; 1995). Butt taper has been used to select logs with better sawn wood grade (Grace, 1994). The size and form of butt swell in Norway spruce may indicate rot (Vollbrecht & Agestam, 1995; Ichim, 1973), and be correlated to spiral grain (Klein, 1991). The size of butt swell in Norway spruce is also influenced by site factors like soil, water and wind (Pripic, 1973). Chapman et al. (1998) investigated the butt swell (buttress) formation in 78 species in Uganda, finding support for a theory that it is mechanical adaptation to counter brief critical phases in a tree's development, but that the buttress persists afterwards. The taper in the butt section of a tree (1-6 m) is influenced by thinning and fertilisation (Karlsson, 1999). Taper further up the tree indicates the position and vigour of the living crown and, thus, several wood properties (Houllier et al., 1995). Dominant trees tend to have larger crowns and higher taper than suppressed trees (Larson, 1963). Research has shown dominant trees to have lower density, weaker wood and lower latewood content than intermediate and suppressed trees (Zobel & van Bujitenen, 1989).

Bumpiness or log surface unevenness

Log surface unevenness indicates knots, occluded knots or grain deviation around knots or scars (Fig. 6). The way knots are enclosed follows a general pattern of grain deviation, and the geometry of wood surrounding knots can thus be used to predict presence, size, type and shape of knots. The wood surrounding knots is an important log property in itself since the grain orientation and other wood properties are different from normal clear-wood (Boutelje, 1966), and contain compression wood (Fig. 6a) (Timell, 1986).

Mattheck and Kubler (1995) present a mechanical self-optimising theory of wood formation and stem strength, stating the importance for trees to grow thicker at weak points like branch whorls. The complete surface unevenness patterns around the branch or knot (branch collar and branch tail) develop and change with the branch function. Living branches have to resist high vertical loads and the branch collar therefore has to be strong and large. The stem wood (ring section) beneath the branch also carries part of the vertical load and is therefore larger than above the living branch. When the branch dies, the stem wood section above the branch catches up in a few years time which also reduces stem taper (Shigo, 1989). The spindle shape wood formation around knots results in grain deviation in the longitudinal-tangential cut (Fig. 6c).

The trunk collar gap, which is formed beneath the actual branch on some trees, is under moderate or strong genetic control (Shigo, 1989). After stem damage (e.g. pruning or branch shedding) the tree will produce a lot of wood in the collars until full ring closure. The distribution of branches and associated knot bumps around the stem follows the symmetry of the crown (Seifert, 1999). Fig 6c shows the considerable grain deviation also around smaller loose knots. Studies of wood surrounding knots have mainly been concerned with the occlusion of pruned knot scars.

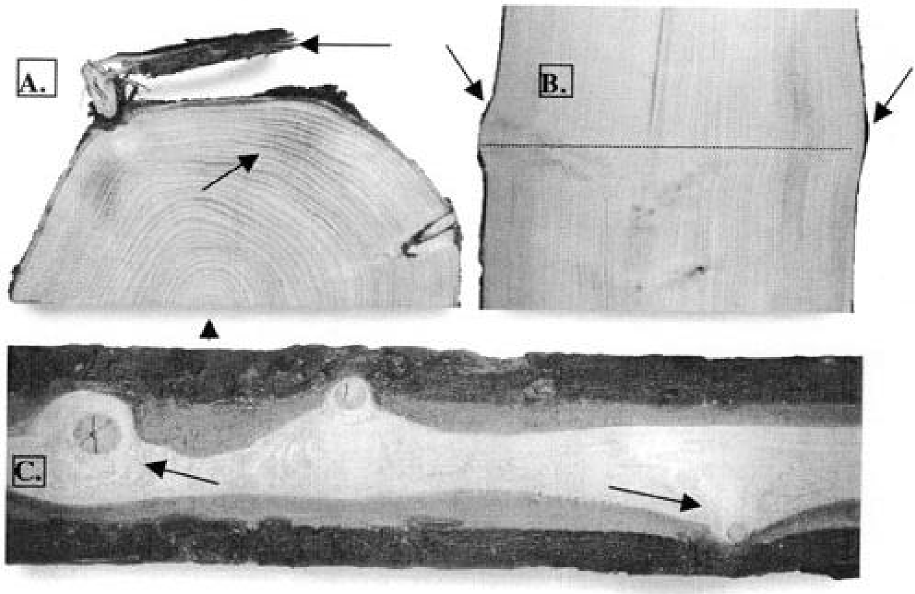

Fig. 6. Pictures of knot bumps from different perspectives, ----- = cross cut A.,
☐ = 20 x 20 mm.

Sweep

Different forms of sweep may indicate uneven crown development, presence of double leaders, spike knots or compression wood. Logs with sweep often contain compression wood (Timell, 1986). The influence of sweep on warp is reduced by curve sawing, even if problems due to compression wood will remain. Taylor and Wagner (1996) suggested that a negative correlation between spiral grain and sweep might exist.

Out-of-roundness

The cross section of a stem is never exactly circular (Matérn, 1956). The degree of log out-of-roundness can be used to calculate pith location and growth ring development within a cross cut (Saint-Andre, 1998). The eccentricity (pith off-set) and ellipticity (maximum/opposite diameter) are correlated. Out-of-roundness is also correlated with compression wood, stem damage, etc. (Shigo, 1989). Fig. 6a shows an example where knot bumps cause out-of-roundness, and where pith off-set is present.

Other log properties

Knots

Knots are widely recognised as important log and wood properties, and are mainly discussed as response variables in this thesis. Knot size and type at the log surface is, however, correlated to knot size and type in the sawn wood (Moberg 1999; Lemieux et al., 1997). Any variables based on direct measurements of knot size and type are of value in log grading or sorting (Samson, 1993; Harless et al., 1991). Other aspects of knots, as predicting or response variables in grading rules, include the size, frequency, relative positions and type such as sound, loose or rotted (Anon., 1995; Anon., 1994a).

Spiral grain

Grain angle on the surface of logs indicate slope of grain in the sawn wood which in turn is correlated with twist and strength of the sawn wood (Harris, 1989).

Bark

Bark, bark type and bark pattern reflect, among other things, tree and log age (Hagman, 1996). The local patterns in the bark can indicate enclosed knots or grain distortion around knots (Tian & Murphy, 1997).

Density

Density is a measure of the amount of cell wall material in the wood and is hence dependent on the ratio between latewood and earlywood, cell wall thickness and cell diameter (Zobel & van Buijtenen, 1989). For Norway spruce, density is generally inversely related to ring width (Olesen, 1977) as growth rate affects the earlywood width while the amount of latewood remains more or less constant. Ring width at the log end can be used as a rough estimate of density and thus stiffness and strength (Boström, 1993), and is included in the log grading rules (Anon., 1998b; 1995).

A number of other log properties are generally considered as defects and undesirable; compression wood, rot, sap stain, resin pockets, etc. Occurrence in log ends of these properties may be used to predict the total amount in the log like e.g. Temnerud (1997) showed for resin pockets

Automatic measurement of log properties

There are plenty of disturbances to be expected when measuring logs at sawmills. Vibrations, dirt, snow, ice and bark damage are some examples. Some mills debark the logs before pre-sorting (Grace, 1993a) to enable accurate under-bark diameter measurements which also changes the conditions for external variable measurement. Harsh debarking can remove knot bumps and butt swell. Dirty log ends can be handled by doing an extra log trim at the mill, mainly practised to prevent saw dulling. Other mills clean the logs by high pressure water spraying for the same reason (Fronius, 1989). One alternative to enable higher accuracy in knot detection is to chip slabs off the log (Fig. 6c.) before measuring knots

(Riihinen, 1993) and deciding the saw pattern of the main centre yield. The degrees of freedom, saw pattern alternatives and volume recovery would however decrease, especially for small logs. The method is more likely to be used after the first saw cut at single band headrigs (Haygreen & Bowyer, 1996).

Surrounding light conditions can also influence signals. These disturbances can normally be filtered by the individual sensors, if not avoided altogether. The next step is to combine data from the sensors to reconstruct the geometry of the log. The disturbances from log movements, bark flares, branches (Fig. 6c.) need to be handled. Given that the measuring accuracy for each data point is not perfect, data need to be processed specifically to maximise the information about different properties. Skatter & Høibo (1998) and Mongeau et al. (1992) show how the number of data points at each cross section can be utilised for diameter measurements, while Lundgren (2000), Saint-André (1998), Blomqvist & Nylinder (1988), Grace (1993a) show ways to calculate dimensional differences along the log. The benefits of a higher resolution for increased volume recovery have been investigated by Skatter (1998) and Oja et al. (1998).

The technology available at saw mills partly decides which log properties that can be measured and used on line. One direction log shadow scanners, can be used to measure geometry features like unevenness, sweep and taper (Grace, 1993a). Scanners with more measurement directions improve the precision and accuracy of these variables and add the potential to measure out-of-roundness (Mongeau et al., 1993). 3D-scanners further improve the potential to measure individual whorl or knot occlusions, sweep and out-of-roundness (Saint-Andre 1998, Lundgren 2000).

Many of the external log properties, are also accessible through the scanners using X-ray or other wave frequencies that penetrate wood and bark. Properties proven valuable as predicting grade variables include density level and variation and the derived log geometry under bark. The potential to extract information about individual defects like knots (Grundberg, 1999) or even resin pockets (Oja & Temnerud, 1999) have also been explored.

Log supply

Given that pre-sorting by grade is done in large batches of similar size logs, logs tend to come from considerable numbers of different stands. This also implies that same-size logs come from different parts of trees and from trees of different ages. Species, genetics, environment and silviculture are all factors affecting wood and stem properties. One aim when defining log variables to be used for log grade classification is that they are stable regardless of log supplies, or that they explain variation between log supplies.

The two major solid wood species in Sweden are Norway spruce and Scots pine, with about half each of the total sawn volume (Warensjö & Jäppinen, 1997). These species are also common in other European countries (Verkasalo et al., 1999) and several studies have included wood properties like tree form, density and knots. Models of knot size and knot type for individual trees are available for both Norway spruce and Scots pine. These models often include stand variables.

The Scots pine tree models by Björklund & Moberg (2000) include individual tree variables, but also stand variables such as age and diameter distribution and site variables like site index and temperature sum. Moberg (1999) used similar variables to model knot properties for Norway spruce.
The number of published grade recovery studies that include both site variables and external geometry variables, like unevenness or taper, is limited. Schutz et al. (1995), however, show that wind is important for the size of knot bumps in pine grown in South Africa.

There are further log supply factors to take into account when estimating log variables in batches of logs, like differences between seasons and delimbing methods. Loose bark will, for example, cause problems when measuring unevenness during spring and summer, while ice and snow will be a problem during winter. Harvester and chain saw delimbing lead to different branch stub forms. Fig. 6a show a broken branch left after harvester-delimbing.

Another important log supply factor is which log properties that have been considered at cross cutting. A model set on a proportion of down grading causes and costs, will depend on that proportion to be valid. Many Swedish sawmills buy logs which are either cross cut based on only length, or according to the national log grading rules were spike knots, sweep, etc. are accounted for.

Product requirements

Different product requirements mean that different wood properties are critical. Grading rules for sawn products is an attempt to organise and rank the importance of different properties, and help sellers and buyers find each other. The main grading rules used for commodity trading of sawn wood in Scandinavia, is the Green Book (Anon., 1982) and its replacement the Nordic timber rules (Anon., 1994a).

The commodity grading rules account for both major markets for sawn timber: structural and joinery. The different requirements on various products within each of these categories are described by Johansson et al. (1993) and Elowson (1984). Different products will be considered depending on the market demand and the properties of the species. Norway spruce timber is mainly used for structural products, partly because of the frequency of resin pockets (Temnerud, 1997) and loose knots (Elowsson, 1984). There is however some interest in using Norway spruce for appearance products and for the past few years there has been a sound knot Norway spruce grade in the Swedish log grading rules (Anon, 1998b; 1995). Some of the structural timber products mainly require strength, others size and form and some both (Johansson et al., 1993). Stress grading of timber is one way to add value and to maximise the performance of sawn wood to its potential. The economic benefits to the industry have been reported by Biernacki et al. (1997).

The use of visually estimated grades leads to problems with the assessment of response variable accuracy. Classification or grading accuracy is important regardless of the method, as highlighted by Grönlund (1995). She tested the association between different board and log grades by means of Somers" coefficient. The association between ordered categorical variables with an underlying bivariate normal distribution (Anon, 1996b), have also been proposed to be tested by means of the polychoric correlation coefficient (Olsson, 1979). Automatic grading is normally based on continuous variables from measurements of properties such as knots or stiffness. The accuracy of the detection of such individual properties varies, but can be more easily quantified, and thus also presents an opportunity for mills to better define their product properties.

Classification models

Sorting logs using several predicting variables requires a system for log classification. Grönlund (1995) lists a number of multivariate statistical models that could be used for log grade classification: cluster analysis; discriminant analysis; logistic discrimination and regression models. Discriminant analysis and logistic regression models are often used for classification of predefined classes, and are provided in standard statistical software packages such as SAS (Anon., 1990) and MINITAB (Anon., 1994b).

The methods used for manual log or sawn wood grading rules are usually decision trees. They are based on a set of rules and threshold values, for example maximum sizes of sound or dead knots. Such a system can also be referred to as a rule based system. Blomqvist & Nylinder (1988) and Grace (1993b) used decision trees and break point values for automatic classification of saw logs using log scanner information. Grace (1994) also tested linear regression to model continuous response values to determine the expected grade of the log.

Discriminant analysis and logistic regression models have been shown to give similar linear functions and classification results for multivariate normally distributed explanatory variables (Press & Wilson, 1978). Halperin et al. (1971) stated that logistic regression is preferable when the normality assumptions do not hold, especially when independent class variables are used. The normality assumption is not valid for butt taper and some other external geometry variables. Logistic regression have been used in a number of different forestry applications, including log grade classification (Ridoutt et al., 1999). The problem of using independent variables with measuring errors in logistic regression models is discussed by Ljung (1998).

Another way to handle measuring errors is through the use of latent variables (Everitt & Dunn, 1991). PLS (partial least-squares) (Wold, 1989) have been tested and proved to be efficient for sawn wood and log grade classification. Hagman (1993; 1996) describes the potential of PLS for complex log and wood classification and Andersson (1997) classified logs by sound knot grades using external geometry data from a 3D-scanner. PLS is considered preferable for its ability to handle noisy and collinear data (Oja et al., 1999a).

Neural networks, or parallel distributed nets, is another option proposed for classification of logs or sawn wood. Schmoldt et al. (1998) showed the potential to classify defects in logs, and Labeda (1995) proposed a combination of neural networks and rule-based systems for classification of individual defects on sawn wood.

Model evaluation

Log pre-sorting is a way for sawmills to select a quantity or volume to be sawn into pre-defined products. The need to select and saw the correct volume for each product does not change when grade requirements are added. It is in other words always important for mills to know the volumes of different grades in a batch of logs. Evaluation of classification accuracy should thus take both volume and grade into account. It is also a problem to accurately decide when a result is significantly better than another, especially for a binary classification case.

Many previous studies on log grading or sorting have reported the results as the proportion of correctly classified logs at one volume cut point, or a small number of different cut points (Blomqvist & Nylinder, 1988; Grace, 1993a; Ridoutt et al., 1999). Other studies included the classification results at many cut points, (Grace, 1994; Hagman, 1993). Different forms of cross validation are proposed to test the validity or significance of classification results (Everitt & Dunn, 1991). Internal validation or cross validation refers to leaving one object, or a segment of objects, out one at a time when generating models, and then testing the models on the omitted object or segment. External validation, the use of a test set of samples left out altogether when generating a model, is argued to be the best validation. This method can however be expensive since there is a need to sample objects that are not used in the calibration of the model (Martens & Naes, 1989).

The number of possible model cut-points and thus combinations of correctly classified events and non-events or false positive or negative classifications can make comparisons between overall results difficult. There are, however, methods and key numbers used to express the performance of a classification model. Hanley & McNeil (1982; 1983) show how the area under the receiver operating characteristic (ROC) curves can be used to calculate confidence limits and make significance tests of classification results. De Long et al. (1988) highlight the problem when comparing correlated ROC-curves. The use of ROC-plots and comparisons of the areas under ROC-curves is established, especially in medical science, as a method of comparing classification methods or models (Zweig & Cambell, 1993).

Commercial applications of log grade sorting

There are a number of cases where automatic log grade sorting was tested or implemented at a commercial operation. Industrial optical scanners have been tested for grade sorting based on different criteria in Scandinavia: log type (Anon., 1996a; Grace 1993b), knot type (Nylinder et al. 1995; Andersson, 1997), knot size (Nylinder et al., 1995), commodity grades (Grace, 1994). Industrial gamma ray scanners have been tested for commodity grade sorting (Hagman, 1993), while a number of criteria have been tested by simulating a specific prototype X-ray scanner (Oja, 1999; Grundberg, 1999). Blackman (1999) refers to grade sorting of *Pinus pinaster* using log geometry, and Aune (1995) describes an industrial X-ray scanner used for log grading tests.

Log sorting economics

The economics of sorting is driven by price differences between different log grades and different sawn products as well as the sorting cost and accuracy. The cost of logs varies between, for example, geographic location and time, which makes general assumptions difficult. Simple calculations may, however, indicate the marginal cost/benefits from grade pre-sorting given different assumptions of price and accuracy levels. Since most Swedish mills have the facilities for pre-sorting, the calculations are less complicated and are similar to calculations for dimension sorting. The scanners are installed to comply with the requirements from the timber measurement association, and to maximise dimension sorting accuracy. This includes the gamma- and X-ray scanners which are installed to allow under bark measurements. The cost of the scanning equipment should, however, also be included when mills calculate the benefits from grade sorting to decide what technology to use.

Only one study on the economics of pre-sorting logs by grade was found (Jonsson & Nylinder, 1990). More studies investigate the economic benefits from knowing the internal properties of logs in detail before log rotation, positioning and sawing, e.g. Steele et al. (1994) on hardwood logs, Grönlund (1992) on Scots pine. Less information is available for Norway spruce, but Verkasalo et al. (1999) found that there is a potential to increase revenue by 20-30 % if knots and compression wood are considered, and if saw patterns aimed at specific products are used. The benefits from sorting increase with more specific product demands, like grade, dimension and drying. Specific demands increase the need to minimise off-grade.

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Material and methods

The focus has been to classify Norway spruce logs by grade criteria, using logistic regression models and external geometry variables from optical log scanners. Other factors and options have also been considered. Table 1 shows how the different papers contribute, given the problem definition in Fig. 2.

Table 1. *List of papers, material and methods.*

Paper	Technology	Variables	Log supply	Grades/ Products	Classification model
I	Shadow scanner	Unevenness, Taper	2x2 stands 2 harvest types Spruce	Green Book	Logistic regression
II	-"-	-"-	4 stands Spruce	Green Book, Nordic timber, Visual stress grade. Knot type	-"-
III	Shadow and 3D-scanner	Unevenness, Taper	10 stands Pine	Nordic timber	-"-
IV	3D-scanner	External geometry and non-geometry variables.	2x7 stands 2 regions Spruce	Stiffness, Log type. Knot size and type, Nordic timber, Visual stress grade	-"-
V	-"-	-"-	-"-	Glulam timber (Stiffness, warp, etc.)	-"-

Scanners used for retrieval of external geometry

Data from commercial optical log scanners have been used throughout the project. The 2-axis profile scanners provided four measurement points around the log. This type of scanner was used as it was available at sawmills at the time of the first sawing studies. Several investments in laser triangulation scanners (3D) has since been made and these scanners were expected to considerably improve the potential to use external geometry, which is why they were included in the project. The laser point triangulation 3D-scanners provide approximately 20 project. The laser point triangulation 3D-scanners provide approximately 20 measuring points around the circumference at the small end on the studied logs, which represents about 20 mm between data points. The scanners had a total of 48 (three batteries of 16) point lasers. The length-wise resolution was about 20 mm in all studies.

Variables

Four main groups of external log geometry variables were used in the project: log surface unevenness, taper, sweep and out-of-roundness.

The first studies using profile scanner data primarily tested unevenness and taper variables, while sweep and out-of-roundness were added in the 3D-scanner studies. In the 3D-scanner studies, a total of more than 30 different external geometry variables were tested. The sensors used were primarily designed to provide raw data for diameter and length variables. The problems with using the same data for other external geometry variables were addressed by analysing repeatability of some independent variables. It was also regarded as interesting to investigate the comparable value of some other variables which have been proven to be important grade predictors (IV). These variables were knot size, log density and grain angle, and it was considered at least theoretically possible to measure them automatically on logs.

A few transformed and combined external geometry variables (IV) were tested while generating classification models. This was done in procedure Genmod in SAS, using the logit link function, and testing 2^{nd} order crossed effects of the main variables (Anon., 1996b).

Log material

The thesis studies primarily Norway spruce (I, II, IV & V), but some work to test and develop systems for 3D-scanners on Scots pine is reported (III). Mainly medium-size logs have been used in the project, because they represent a large share of the total volume given a normal diameter distribution. The thesis altogether covers 1095 Norway spruce logs from 22 stands in three geographical regions. The logs generally came from final fellings, with the first study (I) including two and the last study (IV & V) four thinning stands. The number of replicates of different site and stand factors in each study was aimed at getting representative samples for normal log supplies. The selection of seven stands from two regions with perceived different wood properties (IV), was aimed at determining the importance of adopting models to different log sources for an individual sawmill. The studies were done in winter (III, IV & V) and early spring (I & II).

Targeted product requirements

Norway spruce is mainly used for structural products, and large volumes are sold as commodity grades. The Green Book (I & II) and Nordic timber (II, III & IV) were thus used as standard sorting criteria. The grading rules used by

Scandinavian sawmills has changed during the studies. The Green Book rules are slowly being replaced by the Nordic timber grading rules. Another reason why the Nordic timber grading rules were used in the later studies, was the more clear-cut class borders making them more suitable for research. Even if standard visual grading rules are used, the number of grades and boards from each log creates several alternative log sorting criteria (II). Low grade association between graders and boards is another problem (II), which lead to alternative specifications of properties and sorting criteria being tested (IV).

The 3D-scanner studies also included knot size as response variables, in order to focus efforts on one of the most important sawn wood properties. Knot sizes were measured automatically on line in the study on spruce (IV). Visual stress grading is mainly based on assessment of knot size and grain distortion. This made it a potentially feasible log sorting criteria for external geometry models. Machine stress rating (MSR) or grading (MSG) based on stiffness is another way to classify boards by strength, and was the main sorting criteria in (IV). The association between board classification for the various grading systems was tested (II).

Many large industrial consumers of sawn wood specify their needs in other terms than of general grading rules. The benefits from selecting the most appropriate logs are expected to increase if demands are well specified. The potential increase in revenue from pre-sorting by log grade was tested for such a case (V). The classification criteria was based on specifications for production of glulam beams. The case was chosen mainly due to the varying stress grade requirements, generally requested in odd sawn wood dimensions. Another reason was previous promising results using geometry for visual stress grading.

Classification and evaluation methods

Logistic regression has been used throughout the project. This was based on the assumption that binary response variables, derived mainly from knot properties, were considered appropriate for grade sorting applications. To directly model the probability of a targeted class, and thus include the trade off between finding or missing logs, was also considered an advantage. Other reasons for using logistic regression was that it provided both the selection of significantly contributing variables and definition of the classification model in an integrated operation, based on regression statistics. Some analyses were made to investigate the magnitude of the differences in accuracy that could be expected between statistical models. Standardised parameter estimates are reported in II, IV and V. The reason was to better assess the contribution from each of the different variables. The standardised estimates were obtained by adjusting all variables to zero mean and unit variance before computation.

The main method used to compare model accuracy was based on receiver operating characteristic (ROC) curves (II, III & IV). The area under the ROC-curves ("c") is a measure of the predictive ability of the model, where 1.0 is the maximum value. Standard errors and confidence limits were calculated for the areas (III). The ROC-curves also displayed the trade-off between finding and models (II, III & IV) to indicate the sorting accuracy expected for specific cut points on limited sample sizes and if the models would be used for different log supplies. The possibility to test different logistic regression link functions other than the logit function, or to apply weights were not utilised.

Results

The results are first briefly presented by paper, and then presented in relation to the main investigated factors.

Paper I. Optical log scanners, external geometry variables and logistic regression were feasible means to sort Norway spruce logs to improve a commodity grade mix of sawn timber.

Paper II. The sorting accuracy varied depending on which grading rule or board combination that was used. The problem of low sorting accuracy, a large unexplained variation, and the large number of possible comparisons limited the ability to find significant differences. Even so, the results were considered strong indications that commodity grades, e.g. Nordic timber, are more difficult to predict than visual stress grades.

Paper III. The attempt to evaluate the potential of 3D-laser triangulation scanners showed a significant improvement from profile scanners, when a one-sided test was done.

Paper IV. The results from earlier studies were confirmed, with improvements using 3D-scanner data, and models for log type and knot related (e.g. visual stress grading) sorting criteria being more accurate. External geometry variables could also be used to classify logs by MSR (stiffness), and the sorting accuracy was at about the same level as for the Nordic timber grading rule criteria. Several additional non-geometry variables improved the models. Especially density and grain angle seemed to explain variation in stiffness not well accounted for by the tested external geometry variables.

Paper V. Sorting logs by grade improved glulam timber grade and value recovery, even with a modest sorting accuracy and low price differences between sorts.

Effects from external geometry raw data

Sorting accuracy is dependent on features of the raw data like e.g. measurement resolution and accuracy. The difference in sorting accuracy between a two axis profile scanner and a laser triangulation scanner was 5—10 % (Table 2).

Table 2. *The sorting results ("c") for the visual stress grading and Nordic timber grading criteria (Both centre boards = grade C30 or A).*

Criteria:	Nordic timber			Visual stress grade	
Paper:	II	III	IV	II	IV
2-axis shadow scanner	0.64	0.68		0.83	
Laser point triangulation 3D-scanner		0.76	0.72		0.91

The measuring accuracy of the surface unevenness variables was lower than for taper (III), indicating that further development of the technology and the ability to handle raw data would improve the value of unevenness. This is confirmed if the change in relative strength of unevenness in comparison to taper between shadow and 3D-scanners studies is assessed through the standardised parameter estimates (Table 3).

The simulation of other potential measuring systems showed that the average density, grain angle and knot size measurements would improve MSR (stiffness) and glulam timber grade prediction models.

Important variables

The external geometry variables, primarily developed for Scots pine, proved to work on Norway spruce as well and the parameter estimates seemed stable between the various studies (Table 3). Which of the unevenness and taper variables that contributed most, varied between sorting criteria.

Table 3. *The main external geometry variables, with standardised parameter estimates from logistic regression models* $P_{Event} = e^{\beta(\cdot)} / 1 + e^{\beta(\cdot)}$ *(n.s. = did not stay in the model at* $p < 0.05$*)*

Criteria:	Green Book		Nordic timber		Visual stress grade	
Paper:	I[a)]	II	II	IV	II	IV[c)]
Unevenness	-0.36	-0.54	-0.30	-0.42[b)]	-0.49	-0.60
Top taper	-0.26	-0.26	*n. s.*	*n.s.*	-0.40	-0.45
Butt taper	*n.s.*	*n.s.*	*n.s.*	*n.s.*	0.42	0.65

[a)] Standardised parameter estimates- not presented in Paper I
[b)] The parameter estimate in the model if only one unevenness variable was used.
[c)] The parameter estimates if only these variables were used

The visual stress grade criteria proved the most feasible to sort by external log geometry, and several variables contributed to the models. In the logistic regression the better grade was modelled as the event (probability 1) with the worse grade consequently being the non-event. Unevenness, taper and sweep variables thus had negative parameter estimates, while butt taper had positive parameter estimates. The machine stress grade sorting models relied mainly on taper, unevenness and sweep.

Some of the used variables showed collinearity (Table 4, Paper IV) and several similar variables were sometimes included in the models, as the two unevenness variables in the Nordic timber models (Table 2, Paper IV). The improvement of this model was marginal, in comparison with a model with only one unevenness variable and similar to a model with unevenness and butt taper. No significant correlation between grain angle and sweep or butt taper was found.

Log supply effects

Results from different log samples can be compared in Tables 2 and 3, since different log materials were used in the studies. The results in Table 2 show that the sorting accuracy per criteria is stable between studies, if the assumed improvement from the 3D-scanner is accounted for. There is also a pattern with parameter estimates (Table 3) varying less between the different materials than between the different sorting criteria. Differences between individual stands have not been studied in detail, but it was shown that average unevenness and taper partly could be explained by stand (I). Independent models were also generated for each stand, but with only four stands no systematic difference between, e.g. thinning and final felling could be proven.

The models and sorting accuracy varied between the two regions in (IV) where logs from seven stands in each region were sampled. The external geometry variables like unevenness and taper worked better for the coastal regions on visual stress grades, knot size and Nordic timber grades, while sorting accuracy for the stiffness criteria was better on the material from the western region. The correlation between unevenness and stiffness was a little stronger for the eastern region, especially for butt logs. Log diameter did not explain any significant part of the variation in taper and unevenness (I).

Feasible product requirements

Some product requirements and grades, were classified with higher accuracy ("c") than others (Table 4). General grade sorting criteria like the ones derived from the Green Book and Nordic timber grading rules proved to be difficult, and part of the reason may be found in the distribution of down grading causes (Fig. 3, IV). Many of the down grading causes, such as rot and resin pockets, are not necessarily correlated with log geometry. Pure knot size or visual stress grades were easier (II & IV).

Table 4. *The classification accuracy ("c"), in the different studies*

Paper:	I	II	IV
Green Book	0.67	0.77	
Nordic timber		0.64	0.72
Stiffness (MSR)			0.74
Visual stress grade		0.83	0.91
Knot size (side board)			0.85
Knot type (log grade 2)		0.71	0.85
Log type (butt logs)			0.99

Classification and evaluation

No significant difference between classification methods could be established within this project. The differences in accuracy when selecting logs with the highest or lowest class probabilities are described in the ROC-curves (II, III & IV). The worst skewness was displayed for the visual stress grade in Paper II. Another way to display the trade-off between accuracy and volume is to display the grade proportions at different volume proportions. Fig. 7 is derived from the same results as the ROC-curves in Paper IV.

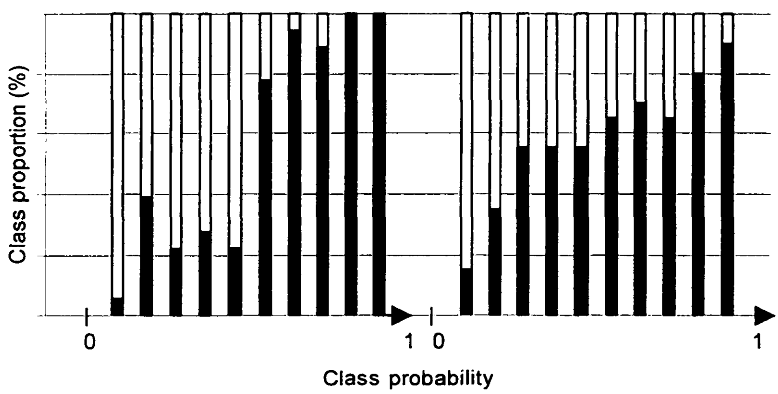

Fig 7. The classification accuracy (☐ = events, ■ = non-events) in each often even log-volume proportions. Stiffness model using all available variables (left) or only external geometry (right) (cf. Fig. 5, Paper IV).

Discussion

The results show the approximate accuracy levels to be expected when sorting Norway spruce saw logs by grade, using external geometry variables. Logistic regression was a feasible grade classification method, and provided the means to compare the classification accuracy and strength of predicting variables between the studies. Especially visual stress grades, but also machine stress grades and visual commodity grades proved to be feasible sorting criteria.

Scanners and raw data

All the studies relied on automatic measurements from commercial equipment, which may limit the ability to explain the results in detail, but strengthens the practical applicability. The studies using 3D-scanner data confirmed the improved potential these scanners provide for sawmills to utilise external geometry variables to define and predict log grade. A one-sided test (III) seemed to have been appropriate when testing for any significant improvement, given the subsequent studies (IV; Lundgren, 2000). No work was done to assess the further improvements that can be expected if 3D-scanners with higher resolution are used. Other modelling approaches and better tuned variables should have the potential to further improve the accuracy. The used 3D-scanner gave a raw data resolution of about 20 x 20 mm. This does not allow for modelling of individual knot bumps, at least not for Norway spruce.

The studies include examples of the measuring accuracy to be expected for the predicting and the response variables. The problem of data accuracy is ubiquitous, but becomes even more important when the aim is to estimate the geometry variation within logs. One problem with the repeatability studies is that one of the most important factors is the bark cover, which will be reduced for each re-run of the logs. The bark factor will be very important to handle, especially during the summer. Grace (1994) studied mainly debarked logs.

The scanner, the sharp chain systems, the feed speed, the filtering of raw data and log condition are all factors that influence the accuracy of the variables. That there is a considerable measuring error for both profile and 3D- log scanners was shown (III). The measurement errors of the independent variables were not specifically dealt with, but Ljung (1998) describes a method to do it in logistic regression models. This approach is likely to be useful since unevenness can be expected to be less stable in comparison to taper, regardless of technology.

External geometry variables

A large number (>30) of variables were tested in (IV & V). There are, however, limited opportunities to compare the contribution from these variables with other studies, where other classification models have been used and where predicting and response variables have been defined differently (e.g. Grace, 1994; Andersson, 1997). Stiffness is often modelled as a continuous response variable. The same principal variables, however, seem to work for Norway spruce as for scanner data (Grace, 1994) and 3D-scanner data (Lundgren, 2000). The general constitution of the models also corresponds between both scanner types. The results support the hypothesis that the association between external geometry variables and internal properties is general, even if there are some anatomical differences between the species. A general opinion in Sweden has been that Norway spruce shows fewer signs of internal qualities on the surface, one reason being the shade resistance allowing living branches further down the stem. Other factors being held against the potential of using external geometry of Norway spruce include better form factor, taller trees and occlusion of knots or scars without formation of taps or distinctive bumps. The occurrence of defects like spike knots is also considered to be higher for Scots pine. This work has not investigated in detail how unevenness variables correlate to knots, but log unevenness has proven valuable also for knot and grade predictions of spruce. Unevenness variables could still be expected to have a better potential for pines, not the least for knot prediction in fast grown species like *Pinus radiata* (Riddout et al., 1999) or *Pinus pinaster*. The correlation found between unevenness and taper (IV) was expected, but nothing was found to support an association between spiral grain and butt taper (Pripic, 1973) or spiral grain and sweep (Taylor & Wagner, 1996). The number of external geometry variables found significant in the models may partly be dependent on the number of logs in each study. That more information from the log geometry can be utilised was also indicated by the PLS models used by Andersson (1997) and Jacobsson (1998). The external geometry variables tested within the frame of the project can also be further developed. Especially variables reflecting specific areas or parts of the logs have not been fully explored. The detection of individual whorls in middle and top logs has been reported to be feasible by Saint-Andre (1998).

Log supply

That differences in log supplies, e.g. between different stands and tree ages, may be important was found in (I). It was, however, regarded as difficult to systematically choose certain types of stands, and at the same time achieve models reflecting the variation within an area supplying a sawmill. The results in from two different regions (IV) indicate that there are some differences that would be worth considering, but the number of stands and logs did not allow any final conclusions. Stiffness and knot size should be modelled as continuous response variables, to enable a better understanding of the influence from different site, stand, stem and log properties. Models generated on half the material in Paper IV tended to be sensitive to stiffness cut points. The difference found between the two regions (IV) still suggests that knot bumps are more pronounced in windy areas, thus supporting the results by Schutz et al. (1991). The ability to use similar sorting models for other log sizes was not tested within the project. The first study included three log dimensions, within the same range of log sizes as in other external geometry studies (Grace, 1994; Blomqvist & Nylinder, 1988; Jacobsson, 1998). Diameter have shown to have a moderate influence on the models within the studied log diameter ranges. The change in targeted products between log dimensions are likely to ensure that models are adapted for different dimension. The number of different saw patterns will for example increase with larger logs, and the sorting criteria of most interest may be the side board grades.

Product requirements

External geometry reflects a number of grades and wood properties, but especially those related to knots. Appearance and structural grades, which are highly knot-dependent have a good potential to be predicted by external geometry variables. This was also confirmed by the results from sorting by knot size and visual stress grade. The precision of the automatic knot size measurements used in Paper IV were lower than expected, but the results are indications along the same lines as in the study on Scots pine (Lundgren, 2000). Knot size is common in grading rules, but is seldom the main problem in final products from Norway spruce. Other knot criteria that have a potential to be predicted by log position and external form include knot frequency (Moberg, 1999) and distance between whorls (Saint-André, 1999). The distance between whorls is of special interest for multi-nodal species, such as Radiata pine (Grace et al. 1998). The expectations on classification of logs according to machine stress grade by external geometry variables were not totally fulfilled. Log unevenness, however, was found to have about the same value as the tested knot measures, which confirmed the influence of grain distortion on stiffness. This, in turn indicates, a further potential to use external geometry together with X-ray, ultra sound or NIR sensors. It is also noted that stiffness is normally not the final product requirement, but used due to the high correlation to strength (Foley, 1997; Biernacki, 1999).

Classification

Logistic regression models were used throughout the project. Some initial analyses with shadow scanner data indicated that decision trees and discriminant analysis models were of almost similar predictive power. PLS was also tested with the 3D variables, but since the improvements were marginal, PLS was not used due to the unclear link between dependent and independent variables. Neural networks were considered, but not used due to similar reasons. The potential improvements from using the very best modelling approach vary with the complexity of the application (Hagman, 1993). The problem of having multiple dimensions in the response variables like in the commodity grades, is not well accounted for in a single logistic regression model. The number of independent variables, which can be considerable in e.g. a multi-sensor approach, will also influence the suitability of different classification methods. The multi-collinearity between log variables can be handled through data-compression models like PLS (Oja, 1999). Which model will be best depends on the aim of the pre-classification. If the technology is fixed and the importance of establishing the contribution from different variables is less important, it is likely that the PLS or Neural Networks would improve the sorting accuracy. The need for more response classes than two is another potential issue, as logistic regression models only work for classes on an ordinal scale. Whether it is the problem logs that should be avoided or the very best logs that should be selected will also influence the choice of modelling approach.

The classification accuracy reported throughout this thesis has been obtained when the aim was to select about half the log volume for a specific use. The ROC-curves do however display that the sorting accuracy generally is higher if only part of the volume is selected.

General reflections

The achieved grade classification using external geometry variables were less than in studies with a simulated two axis X-ray systems. Grundberg & Grönlund (1997) graded Scots pine logs into classes of Nordic timber grades with high accuracy, and Oja (1999) classified Norway spruce logs into machine stress grades. The short-term issue for Swedish sawmills has so far not been whether to choose an optical 3D or an X-ray scanner, even if comparisons have been done on the ability to measure dimensions under bark accurately (Oja et al., 1998). The main issue has been which technique that would be most cost effective together with high resolution 3D scanners.. A combination of an optical 3D and one axis X-ray scanner, has thus been suggested (Oja, 1999). There are also other possible combinations depending on the classification needs (Ridoutt et al., 1999). It should also be noted that in cases where cross cutting is done at the mill (Saint-André, 1998; Fronius, 1989), the potential for investments in measuring technology will improve, as long the throughput is not limiting. There will be a limited need to pre-sort logs by grade, as long as most of the sawn timber is traded as run of mill commodity grades. The last study (V) explored the possibility to select logs for a specific processing need and some of the implications of doing so by pre-sorting logs with external geometry variables. One of the difficulties is to find an appropriate use for the off- grade logs and sawn wood. The economic calculations in (V) showed gains from pre-sorting logs that should cover the costs associated with it. The study also revealed that if logs with generally better knot properties than the average are selected it lowers the commodity grade mix of the remaining logs which is a potential weakness of the system. The remaining log grade mix, and thus economy of the operation, improved if logs with high density and low spiral grain were selected. These properties are not as strongly reflected in the commodity grading rules, even if asked for by many end users (Johansson, 1999). An important issue is for mills to handle short-term versus long-term profitability. The most important long-term issue is to make sure that customers get the right product, which will push for selection of suitable logs.

A main problem for mills before any implementation, not studied in the project, is the interaction between mill personnel and the automatic classification systems described. Automatic sorting will e.g. enable fast responses to changing market demands, but it will require more frequent changes of the price levels in e.g. edger and trimmer optimisers than what is mainly practised today.

Further applications and studies

Another possible application for automatic log grading in Sweden is the grading performed by the timber measurement councils according to national log grading rules (Anon., 1998b, 1995). The ability to predict the sound knot log grade was reported in this thesis, but more work is underway to assess the potential of external geometry variables as general grade predictors. A number of automatically measured external log geometry variables have been shown to be associated with all log grades in the national log grading rules (Anon, 1995; Oja et al., 1999b). The Swedish system with scaling of individual logs will enable collection of detailed external geometry data and log grade as defined by the timber measurement councils. This material will be valuable for further development of geometry variables, and explanation of regional differences. The general principle of calculating grade probability with external geometry variables used in these studies is also likely to be of value at cross cutting. The short log system, with cross cutting of logs in the forest by harvesters, requires use of robust technologies. Geometry variables like the ones from the profile scanners can be calculated from measurements available in harvesters (Uusitalo, 1999). I recommend that the potential of such variables to improve knot size models (Moberg, 1999) and log cross cutting algorithms (Björklund & Juhlin, 1998) is further evaluated. The recently built stem banks (Jaeger et al., 1999; Grundberg et al., 1995; Björklund et al., 1999; Verkasalo et al., 1999) are good starting points since they can provide both external and internal information on stem and wood properties. This would improve our knowledge of the relationship between individual knots and knot bumps, as well as the variation within and between trees and stands. The methods and results from this and other studies on log geometry can be utilised throughout the conversion chain. Using similar data and optimisation methods for cross cutting, log sorting and sawing provides the potential to improve value recovery (Maness & Adams, 1991; Usenius, 1999). Assessing the influence of wind on grain distortion around knots is another important issue to clarify. I recommend that this is studied on materials where the genetic influence is limited, e.g. clones, preferably together with studies on spiral grain and resin pockets which also are properties influenced by genetics and wind (Harris, 1989; Temnerud, 1997). The common practice in Sweden is to saw maximum cant and centre board dimensions from each log. This has limited the potential of log sorting by grade, but several recent studies have shown benefits from choosing other saw patterns. Øyen et al. (1999) describe the potential to maximise the yield of sound knot timber, and Woxblom (2000) to reduce warp through adjustment of saw pattern to log properties. This could lead to more log grade sorting. Further sawing adjustment to log geometry, e.g. feed speed and diameter classes, might be a way of improving sawing accuracy and volume recovery.

Knot bumps and grain distortion are important stem properties (Foley, 1997) which should be recognised along with knot or branch size in forest mensuration. New technology for pre harvest mensuration (Grace et al., 1998) will allow for variables like branch sizes, stem surface unevenness, taper and sweep to be measured. These variables could be as important as some of the knot size measurements in focus today. Recognising grain distortion reflected in knot bumps as an important stem variable will encourage further research into which factors that influence its formation.

Final reflections

Standard technology and methods to start to sort logs by grade automatically is available for virtually all sawmills in Sweden, and in other industrially developed countries. All the factors in the proposed system can be improved, even if the gains from any single factor will be limited. To get the full potential of external geometry sorting, sawmills should find assortments with different demands on knot-related properties. The sawmills may consider other sorting criteria, like MSR, if the requested volume is limited.

The constitution of the models and the prediction results from different regions and sorting criteria, emphasise that sawmills should define their own models, even if the principles are general. It should also be recognised that the number of logs sampled needs to be high to get reliable results, especially for models with low sorting accuracy, e.g. the Nordic timber criteria. This calls for efficient sawing study routines or simulations.

Sawmills are advised to devote greater attention to product quality, even if the methods to realise the full economic potential of grade sorting can be further developed. To produce truly well-suited solid wood products for specific uses is demanding, and will require the handling of many different grades. My advice to mills is to make sure they have routines and knowledge in place when available technology and algorithms allow, and market competition demand, comprehensive sorting by grade.

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This work explores the potential value recovery associated with better knowledge about log geometry. I personally acknowledged the value of strong branch collars much earlier, thanks to the great view solitary spruce trees provided from the top. I also benefited from spruce geometry during my short international career as a logger, when I first entered the forest industry. Getting paid by piled log volume meant that our revenue was maximised if the geometries of the spruces denoted "Betty Boops" were utilised to their full potential. We knew that there was a quality issue involved, but given the hard work we put in and the tough business environment, we left it to be handled by someone else. I obviously jumped at the chance, when I was offered to study Spruce geometry in depth ten years later.

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