Abstract

Edlund, J. Methods for Automatic Grading of Saw Logs. Doctoral dissertation
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The aim of log grading for pricing is to apply an economic value based on volume and log grade. However, unlike many other commodities logs are hard to characterize into different grades. The reasons are: internal properties are hard to decide from the external appearance, the wood properties are often heterogeneous and there are a variety of different grading criterias. In Sweden, as in many other countries, the log grading is based on visual assessment of log characteristics, which can be considered intricate, time consuming and monotonous. Moreover, factors like increasing labour cost, structural changes among sawmills and the introduction of new technology, are all changing the possibilities and demands for the sawmills. New technology is important in order for the sawmill industry to remain competitive and therefore the log grading system for pricing needs to become more flexible and adaptable to the new technology.

This thesis investigates two different methods using automatic measuring techniques to grade logs for pricing. In the first method a 3D log scanner is used to estimate log shape and this information is used to grade the log. The accuracy when using 3D log scanning to grade logs, according to the grades in the current Swedish national grading system, was comparable with but somewhat lower than manual grading of logs. Scanner data were used to estimate curvature type and compression wood content. Models based on log scanner data could discriminate between curvature types if the curvature was severe and bow height larger than 0.8 %. The models predicting compression wood were significant even though models using log end information were better. Analysis of whole stems showed that compression wood content was most pronounced near ground level and that stems with basal sweep more often had large amounts of severe compression wood. The second technique used acoustics and the results indicate that the technique has potential for grading logs by the stiffness of the sawn timber. The stiffness criterion was more important for spruce saw logs since spruce lumber is more often used for construction purposes.

Using 3D scanning, acoustic methods and other techniques would probably reduce costs and make log grading for pricing more efficient. To enable this, the log grading system needs to be simplified and adapted to the new automatic technologies. Based on the findings in this thesis, a base for a new grading system for pine and spruce is proposed.

Key words: saw, log, grade, geometry, acoustic, scanner, sorting, classification

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Appendix

Papers I-IV

This thesis is based on the following papers/studies, which will be referred to by their corresponding Roman numerals

I: Edlund, J. 2004. Automatic grading of softwood saw logs for pricing using external geometry. *Scand. J. For. Res.* 19(Suppl. 5): 38-47, 2004

II: Edlund, J. & Warensjö, M. Repeatability in automatic sorting of curved Norway spruce saw logs. *Silva Fennica XX* (Accepted after revision)

III: Edlund, J. & Warensjö, M. Modelling compression wood in Norway spruce saw logs using log shape and log end information

IV: Edlund, J. & Lindström, H. Modulus of elasticity of Norway spruce saw logs versus structural grade in sawn lumber

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Introduction

Background

The aim of log grading for pricing is to apply an economic value based on correct quantities and grades for log deliveries. This implies that logs are commodities whose properties can be standardized into different grades acceptable to buyers and sellers. However, logs may be hard to characterize into different grades, partly because it is difficult to predict internal properties from the external features of the logs and partly because of the heterogeneous properties and the varying uses of logs.

In earlier days, a skilled, experienced woodworker could go to the forest and select the tree that he thought was the best for e.g. making a cabin, building a boat or making a rake. This system of selecting the right tree for the right purpose was useful given that he had a lot of time. In today's sawmill industry the increasing cost of labour has reduced the time to evaluate each log to approximately two seconds, which is why more efficient methods of estimating the value and the grade of the log are required.

The structural change of the Swedish sawmill industries has been studied in repeated surveys and a move towards market-oriented production has been observed (Staland et al., 2002). Thus, end-users of today have more specific demands on the sawn timber, which in turn should result in more specific demands from sawmills on the logs. Therefore, there is a need for the log grading system to become more flexible so that the demands can be implemented in the grading.

Several technologies have emerged over the last decades that can be used to measure relevant log properties quickly and accurately. These techniques are mostly used for process control but the use of these techniques for grading could enable a faster and improved pricing system where log sellers receive better compensation for high-grade timber.

A problem with using automatic grading methods for pricing is to guarantee the grading accuracy for buyers and sellers (Grönlund, 1995). The demand for accuracy of grading for pricing is stricter than for grading for production purposes since an incorrect grading leads to incorrect compensation. Methods for grading for pricing are therefore a sensitive issue.

In conclusion: increasing cost of labour, sawmill structural change and new technology, change both the possibilities for- and the demands on sawmills. New technology is needed for the sawmill industry to become competitive and as a consequence the log grading system for pricing needs to become more flexible and adaptable to technology.

Objectives and scope

The main objective of this thesis was to explore how two log measuring technologies can be used to make log grading for pricing more effective and how the grading system could be adapted to these technologies. Throughout the thesis, the rules of the Swedish national log grading system were used as a reference grading system. The work concerned both pine and spruce saw logs, but some studies were only performed on spruce.

In a pilot study, the properties of the log grades were investigated in order to assess which properties were important: i.e. the board grade distribution by log grade and the causes of downgrading in the different log grades. Two automatic methods used together covered some of the more important properties for log grading. The first automatic method used external geometry retrieved from 3D log scanners to grade the log. The scanner data was used to sort logs according to the national grading system of Sweden and thereby log type and knot structure was considered. Log shape data was also used to estimate curvature and compression wood content. The log scanning method was considered because it is a widely used technique at sawmills in Sweden and therefore a system using this method could be easily implemented. The second method using acoustics measures the modulus of elasticity, which is closely correlated with board strength. This method was considered because it is simple and can easily be implemented for log grading at sawmills. However, the implementation of an on-line acoustic measuring technique needs to be investigated further.

Log and lumber properties to consider in grading systems

Properties in the stem, on the surface and on the log ends that are correlated to wood properties desired by the end user can be used as measures of the log grade. Depending on the product and user, what variables that are considered most important differ. The variables in the Swedish national grading system were chosen because the human eye can see them, the brain can comprehend them and because they are measurable. These properties are however not necessarily the most important from an end user and thus grading perspective and the properties measured by new technology not measurable by manual methods should be considered instead. Below are the most important variables concerning log and lumber grading listed and are also briefly explained. These variables are directly or indirectly considered during ordinary log grading and are also considered in this thesis.

Taper and log position

The taper from butt to top can be used to describe the stem form of a tree. The taper is concave and often large close to the ground, small in the middle and larger and convex at the top (Larsson, 1963). The taper is related to the relative length of the living crown and by that to the knot properties in the stem. Taper can be calculated using the functions of Edgren & Nylinder (1949). Models for predicting knot structure in different zones of the tree have been developed and use site characteristics, silvicultural treatments and data from the individual tree such e.g. tree height and live crown length (Vestol et al., 1996; Björklund, 1997; Moberg, 1999). However, when the tree is cut into logs and transported to the sawmill, the site and tree information is often lost. By measuring the diameters along the log and calculating the taper the information of log position and thus knot properties can be retrieved. Large taper in the butt end of a log indicates a butt log with overgrown small knots; no or little taper indicates a middle log with small dead knots; and large top taper indicates a top log with large sound knots (Jäppinen, 2000). Additional information on knot properties can be obtained by measuring the bumpiness of the log (Blomqvist & Nylinder, 1988a; Blomqvist & Nylinder, 1988b). A recently occluded knot, a large dead or sound knot often leaves a bump even if the log is carefully delimbed.

Knots

Knots are important properties of the final product and are therefore an important feature in grading instructions for both log and lumber (FSS, 1994; VMR, 1999). Different knot types are: sound knots, dead knots, bark-ringed knots and spike knots. The reason that sawn timber with large knots or large number of knots is graded to low quality is primarily because knots affect strength and stiffness of the sawn wood. This effect is not caused by the wood in the knot but by that the wood surrounding the knot having irregular grain angles (Desch, 1981). The number, distribution and type of knot also affects the aesthetic appearance of wood (Broman & Grönlund, 1996).

Spiral grain and warp

Johansson et al. (1994) studied the complaints made by sawn timber users, and determined that warp, in particular twist, was the biggest problem. The study also showed that the grading rules for sawn timber did not sufficiently consider warp. Measurable properties that are correlated with warp are spiral grain, which is correlated with twist, and compression wood, which is correlated with bow and crook (Forsberg, 1999; Nyström, 2002; Warensjö, 2003). The Swedish log grading system does not really consider spiral grain angle as it is difficult to estimate manually and measuring technology for this purpose has not been available until recently.

Density and annual ring width

Basic density is the weight of the dry cell wall material in the wood related to its green volume. In softwoods this is dependent on the share of the denser latewood related to low-density earlywood. Across the annual of a stem, the amount of latewood is more or less constant, whereas the amount of low-density earlywood varies with varying ring width. Wood with high density is preferred since it is positively correlated with strength and hardness. The disadvantages with high-density species are however that the wood swells more than low-density species. Beard (1993) and Perstorper (1995) showed however that warp in softwood lumber does not increase with higher density. The raw density, i.e. the raw weight in relation to volume, can easily be measured industrially using log weight and volume, but to measure basic density the wood has to be dried before weighing.

Indirect measure of basic density is the annual ring width between 2- 8 cm from pith, which considered in log grading. This measure is also indicator of knot structure in the log since slow growth during the first years inhibits the knot size (Orvér, 1970).

Compression wood and log curvature

Compression wood is formed as a response to asymmetric load as the tree tries to maintain an upright position (Timell, 1986). In softwoods, compression wood is normally formed on the lower side of a leaning stem resulting in a crooked stem. The tree starts to produce tracheids with thicker cell walls and high micro-fibril angle in order to bend the stem towards an optimal upright position. Because of the high micro-fibril angle the compression wood shrinks more in a longitudinal direction than normal wood (Ibid.). This difference can lead to warp, particularly crook and bow in sawn timber when compression wood and normal wood is unevenly distributed in a piece of sawn wood. Additionally, compression wood is harder and more brittle than normal wood and is thus difficult to handle when nailing and planing, and because of poor strength properties it is unsuitable for construction purposes (Timell, 1986). Compression wood is often found in stems and logs with pronounced curvature (Öhman, 2001; Warensjö, 2003). Straight trees can also contain compression wood (Low, 1964) but this is often less serious because the compression wood is more evenly distributed and milder and therefore less susceptible to warping. In sawn wood from logs with pronounced curvature, cross grain in combination with severe compression wood creates severe distortion (Warensjö, 2003). Cross sections from curved trees with compression wood tend to be elliptical with eccentric piths (Larsson, 1965; Robertson, 1991). Compared to straight logs, logs with curvature cause problems in the sawing process, as they yield less if not cut with curved sawing equipment (Lier, 1977; Sederholm, 1978). If curve sawing should give the same yield as sawing straight logs the curvature has to be smooth and in one plane (Ibid).

Juvenile wood and microfibril angle

The 10-20 annual rings closest to the pith from the butt to the top of a stem are called juvenile wood. Compared to mature wood juvenile wood has several properties that are less favourable. Zobel & Spraque (1998) found that juvenile wood in softwood had lower: density, tracheid dimension and cellulose content, all which negatively affect the strength properties of the wood. Strength and stiffness in juvenile wood is also negatively affected by the high microfibril angle (Cave & Walker, 1994), which is the angle between the cellulose fibrils and the fibre axis. The transition from pith and out for many properties characterizing juvenile is more dependent on ring number from pith than distance from pith (Olesen, 1977). Therefore the share of high-stiffness lumber increases with narrowing annual rings width close to pith.

Rot and stain

A common reason for downgrading logs is rot, which is caused by fungus. Inventories have shown that as much as 15-20% of Norway spruce in south and middle Sweden is afflicted with rot (Bengtsson, 1976). Pine is also affected but to a lesser extent. For the end user, sawn timber with severe rot is unsuitable for any purpose. Even when only a slight colour change or softening is detected, strength properties are reduced (Desch, 1981). Although rot does not normally affect all wood in the stem, it is often most extensive near the pith closest to the ground and is extended a couple of metres up in the stem (Stenlid, 1987).

Sap stain is also a fungus that is a major cause of downgrading. It differs from rot by not feeding on the wood. The fungus feeds on the fluids in the wood and grows in the pores, which affects the permeability and aesthetic appearance of the wood but not the strength (Desch, 1981).

Bark and log dimension

One important goal with measuring of logs prior to sawing is to achieve a correct determination of log volume and dimension. An accurate estimate of log dimension under bark makes it easier to optimize the volume recovery during sawing and a correct volume under bark makes the price correct to the sellers. The accuracy is highly dependent on the accuracy of the log scanner, which in most cases measures above bark why the dimension needs to be corrected for bark. Specific functions (Zacco, 1974) are used for a given bark type and region but the input for bark type and bark loss has to be set manually by the grader for every log. Additionally, the shape and colour of the bark gives an indication of species and age (Hagman, 1996) and patterns in the bark can indicate occluded knots and spike knots (Tian & Murphy, 1997).

Other properties

Resin pockets were a variable in the log-grading standard until 1996. After that it was excluded because the occurrence of resin pockets in log ends was not considered enough correlated with the occurrence in the log, and resin pockets was therefore not suitable for the manual visual grading system of today (Temnerud, 1997). Resin pockets are however a variable in lumber grading (FSS, 1994), and considered by many as a major problem when planing and painting.

Other more uncommon properties that can cause downgrading are water stain, resinous wood, bole scar, and different types of cracks (Nylinder et al., 2000). Logs that have insect damage and logs that are not properly prepared for sawing are not considered as saw logs and are therefore rejected (VMR, 1999).

Grading of saw logs

Grading for pricing vs. grading for process control

The reason for grading saw logs is to estimate its quality. Quality could be defined as “the ability to satisfy needs” (ISO 9001). From a sawmill production perspective this would mean how much a log differs from a homogenous ideal cylinder. For the end users of wood the definition of quality would differ greatly depending on the specific use. In this thesis the grading system used and examined is supposed to reflect the different quality aspects for all actors along the forest-sawmills- market chain and foremost the end user. Since wood is a material with a wide variety of uses and a biological material with great natural variability concerning its properties, there will always be a need to grade and sort the wood along the forest-sawmill-market chain. Lönner (1985) emphasized the importance of adding value to the sawn wood through further processing and integration of the operations with suppliers and customers. This integration requires a good flow of information, which should include a relevant and flexible grading system.

Two main purposes of log grading can be differentiated: grading for process control and grading for pricing. There are differences between the two. Grading for pricing must be fair and correct, which implies that grading rules should be objective and the grading should be performed objectively. A log supplier must be certain that logs will be evaluated similarly independent of the person or machine that carries out the grading. A fair, uniform, and transparent log grading system promotes a fair competition between sawmills for raw material and enables the companies to trade or switch logs. In order for the grading system to be justified, the grading should reflect the preferences of the sawmills and the demand of the end users. If the cost to perform the grading does not meet the needs of the sawmills and sellers of logs, it will be ineffective and a cheaper more simplified method would be preferred. Such a situation would not encourage long- term efforts by forest managers to provide forest industries with suitable raw material and could therefore in a long run have a negative effect on the market share of wood material.

Grading for process control is somewhat different from grading for pricing, since it is an internal procedure of the sawmill. Thus, the need for transparency and uniformity is dependent on the demands of the individual sawmill. Accuracy in grading for process control differs since it is more flexible and depending on short-term production factors, which mean that parameters can be added or removed. Information can be gathered from wherever the conditions are right e.g. from harvesters, compartment descriptions or log measuring stations. Data from grading for pricing can also be used.

The Swedish log grading organization

The Swedish log grading system was developed in the late 1900th century from a common interest by log buyers to coordinate their log supply. This resulted in the founding of a range of log measuring associations all over Sweden that acted independently from each other. The rules and regulations were standardized between associations in the 1920's in order to further facilitate the round wood market. Until 1935, only buyers controlled the organizations and a growing discontent among sellers led to a new act that enabled buyers and sellers to have an equal influence. In 1943, the timber measurement law was passed and made the National Board of Forestry the supervising institution for log measuring for pricing (www.svo.se/fakta/stat/ska2/, 3-Aug-2004). A modified version of this law is still valid and the National Board of Forestry authorizes the log-measuring associations to perform impartial and fair log measuring for pricing. The log measuring organisations are geographically divided into VMF Syd (south), VMF Qbera (middle) and VMF Nord (north) and are all gathered under the Timber Measurement Council (http://www.virkesmatning.se/vmr/, 3-Aug-2004), which is set up to work for fair, practical and, as far as possible, nationally uniform timber measuring.

The Timber Measurement Council issues instructions, which are followed by the timber measuring associations. In order to make the measuring impartial the associations have their own personnel at the sawmill who perform the grading and then sort the logs according to the sawmill's wishes. Approved and regularly tested log scanners measure the dimensions of the logs.

In 2003, the log measuring associations measured 89.9-million m^3 (under bark) of timber. Of this volume 36.2 million m^3 was saw logs, 68 % of which were measured using the current log grading system (http://www.virkesmatning.se/vmr/, 3-Aug-2004). The remaining volume was measured with the same grading system but in a more rationalised manner using samples techniques (Orvér, 2002).

The Swedish log grading system

Until 1994, the log grading system comprised the classes I-VI, (classes I-IV often being combined into one class US) (VMR, 1987). To assess a log according to this system, the log grader looked for defects on the log surface and log ends e.g. compression wood content and bole scar, and estimated knot properties of the main yield if the log was sawn. The main criticism of the system was that the means of evaluating the graders log grade was to saw the log, which made the assessment of grading accuracy difficult.

At the department of Forest Products, SLU, Uppsala several studies focussed on a new grading system based on objectively measured parameters and classes that were optimised from the total value of the yield of the log (Orvér, 1970a; Orvér, 1970b; Jakobsson, 1976; Weslien, 1983a; Weslien, 1983b; Flinkman, 1985). Besides considering defects on the log surface and log ends, the value of the log was calculated by functions with the following parameters: log type; number of annual growth rings between two and four cm from pith; size of largest sound knot; and size of largest dead knot. This system was never put into practice, but the studies led to deeper understanding of how objectively measurable variables on the log surface could be used to estimate the grade of a log. In 1988, the timber measurement council appointed a committee to develop a new system "that would satisfy the markets and timber measurements demand for accurate and fair measuring and pricing". The new system should have the following criteria:

1. The grades should be developed with the concern for the final products.
2. The grading system should be objective, transparent, and easy to use and explain.
3. It should able to grade logs with high accuracy according to the system.
4. The grading should be able to be evaluated with objectively measurable factors.
5. It should be possible to continuously develop the system and adapt it to new measuring techniques and new market demands.

This resulted in the existing system VMR 1-99 (VMR, 1999) in which the grades of the log are assessed through the use of variables detectible on the log mantle surface and on the log ends (Table 1). Important variables are knot size, annual ring width, curvature, defects visible on the log surface and on log ends. Logs that do not fulfil the criteria for being sawn are cull and cull are not considered as a grade. However, cull logs are important since they need to be sorted out and are therefore considered in this thesis, i.e. if they are downgraded because of their poor wood properties and not on dimension criteria.

Table 1: *The Swedish saw log measuring system, log grades according to lumber end user requirements*

Pine		**Spruce**	
Grade	**End use of lumber**	**Grade**	**End use of lumber**
1	High-grade joinery lumber	1	High-grade joinery lumber
2	Sound knot lumber	2	Sound knot lumber
3	Joinery lumber	3	Structural lumber
4	Building lumber	4	Low-grade building lumber and lumber for packaging
5	Low-grade lumber e.g. for packaging		

Normally, the log grader has about two seconds to estimate the grade of a log, during which the grader also has to decide the species, amount of bark and bark type. Many sawmills have merged grades in order to make grading easier. In 2002, the log-grading organisation measured 27 973 million m^3 solid volume or 145 million logs, the measuring cost per cubic metre was 5.61 (http://www.svo.se, http://www.vmfsyd.se/, http://www.vmfnord.se/, http://www.vmfqbera.se, 3-Aug-2004). The same year the mean price for saw logs was 386 SEK/m^3 for pine and 379 SEK/m^3 for spruce (volume by top measurement under bark) (www.svo.se/fakta/stat/ska2/, 3-Aug-2004).

There are four different ways to sell timber to industries in Sweden and all consider both wood properties and quantity: delivery timber, cutting commission, stumpage purchase and delivery stumpage purchase. Grading for stumpage purchase and delivery stumpage purchase is done in the forest. In this thesis, only grading by the measuring associations at the mill was considered. This comprised the delivery timber and cutting commission methods.

Log grading outside Sweden

In Norway there is one log-measuring association, Norsk virkesmålning (NVM) (http://www.tommermaling.no, 20-Jul-2004), where both buyers and sellers of timber are represented. Eighty-three percent of saw logs are measured as delivery timber and three main log grades under the sawn timber assortment comprise the log grading routines. Defects that cause downgrading in these classes are e.g. sound and dry knots, curvature and compression wood. The Norwegian system is thus much like the Swedish system.

The Finnish system is different from the Swedish system since private companies, owned by the large forest industries, perform log grading. However, log grading is regulated by the Ministry of Agriculture and Forestry. Eighty percent of the logs are measured using delivery stumpage purchase where the harvester measures the volume. There is, however, an increasing share of log wise measurement. The grading regulations are different for the companies measuring the logs.

In USA, Canada and in most European countries, log grading is performed and controlled by the forest companies. In Germany, volume assessment and grading is performed at roadside. However, many consider the system expensive and have joined in a system called “Verksvermessung”, where the saw logs are graded at the mills. Wood sellers are encouraged to trust that the companies perform impartial log grading (http://www.werkeingangsvermessung.de/, 15-Sep-2003).

Measuring techniques

Manual methods

In Sweden, log grading is predominantly manual and performed at the sawmills. The logs are transported on conveyers using either length feed or transverse feed where mirrors or cameras are used to evaluate the log end and the side not facing the grader. With transverse feed, the log is rolled lengthwise so that all sides of the log can be evaluated. The time for a grader to evaluate all grading aspects, bark parameters and species is approximately two seconds. This could be considered a relatively short time to evaluate all the aspects of a log, especially compression wood and properties with a small correlation to log shape e.g. rot and bole scar. Flinkman (1985) demonstrated how hard it is for the log grader to recognize such defects. Four graders evaluated 474 pine- and spruce saw logs under normal conditions. A grading inspector evaluated the same logs under optimal conditions creating control. According to control, 161 logs had defects, whereas according to the graders, 90 logs had defects. Of the latter 90 logs only 69 were the same logs as the logs having defects according to control. In deliveries of logs from large suppliers sometimes only a random sample is measured completely. The remaining logs are graded on basis of that sample (Orvér, 2002). In northern Sweden two-thirds of logs are measured in this manner, whereas in south and middle Sweden it is not that common.

Automatic methods

Log scanning

The most common technique, shadow scanning, comprises a sheet of light from one side of the log with light sensors on the other. If two sets of light- and sensor beams are placed perpendicular to each other, the diameter will be measured in two directions and accuracy is improved (Fig 1). Although the shadow scanning technique is stable, it is not as accurate as 3D log scanning technique. The main reason for improved accuracy in the diameter measurement between the different techniques is that 3D log scanners better considers out-of-roundness in a log (Möller et al., 2002). Studies using the 3D log scanning to predict log type and properties in sawn boards have been conducted by e.g. Jäppinen and Lundgren (2000), and the method has reached commercial implementation.

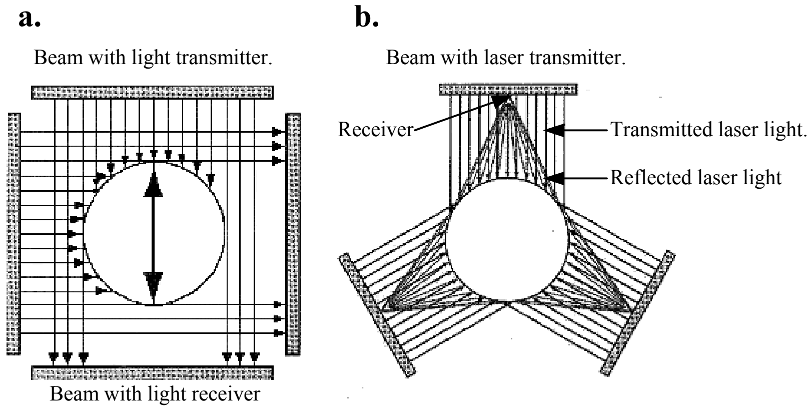

Fig. 1. Principles of two directional shadow scanner (a) and 3D laser scanner (b) (adapted from Möller et al. (2002)).

The most common 3D log scanner in Sweden uses 48-point lasers distributed on three beams. The laser light reflects onto the log surface and a detector measures the reflection. Using triangulation, the distance from the light source to the log can be calculated for all 48 points (Fig 1). These data are used to create a cross section of the log and when the log is conveyed through the log scanner at a fixed speed the shape and length of the whole log can be estimated. The shadow system uses a sheet of light across the log instead of point lasers. The laser point method provides fewer measurements around the log but lengthwise resolution is dependent on the feeding speed.

In 2000 (Staland et al., 2002), 90 % of all sawmills (production > 10 000 m^3) had some sort of log scanner for sorting and grading for pricing. Of these 176 sawmills, 26 had 3D log scanners and one had an X-ray log scanner. The other had shadow scanners measuring the log in one or two directions. In addition, 138 sawmills used log scanners before sawing to adjust log position to the sawing blades.

X-ray log scanning

When using a X- ray log scanner the density variation in the log can be retrieved, which can be used to predict a number of important properties, such as sound knot volume, dead knot volume, species (separates pine and spruce), presence of compression wood within the heart wood, heart wood content, presence of resin pockets and severe rot (Grundberg, 1999; Oja, 1999). Oja et al. (1998) have also shown that an X-ray log scanner has the same accuracy as a 3D log scanner for measuring the diameter, and that accuracy could be further improved if a 3D log scanner is combined with an X-ray log scanner. The reason that the X-ray technique is not used more frequently is that it is expensive and difficult to handle.

Acoustics

The way a sound wave propagates through a body is correlated with the body's intrinsic strength and other properties and has been demonstrated for homogenous materials such as plastics, metals and wood. Many methods using different wavelengths have been studied and are used on wood products to measure strength or defects in logs (Pellerin & Ross, 2002).

Ultrasonic techniques use vibrations similar to sound waves but at a higher frequency (>18 kHz), to detect defects in logs, board and wood products. This method includes analysing the wave pattern of a sound wave to detect defects. Han & Birkeland (1992) concluded that ultrasonic techniques detecting defects in logs include two methods: through-transmission, where the sound wave is transported radially through the log; and the grain sound tracing-method, where sound is sent from the log end and the receivers are led along the log surface to probe for knots. The through-transmission method is time consuming and not very reliable and the attempts to built a tomograph based on this method has not been successful.

Sound at normal frequencies can also be used to estimate the intrinsic strength and stiffness properties of wood. The equation $\mathrm{MOE(Dynamic)}=\rho V^2$ (Huang et al., 2003) describes the basic relation between speed of sound (V), density (ρ) and modulus of elasticity (MOE), and is valid for all materials. Using a sound transmitter on one end of the log and a receiver on the other end, the time between sending and receiving can be measured. The time and the distance between the sender and receiver are used to calculate the speed of sound through the log. Since sound waves propagate the shortest distance between sender and receiver, only the properties directly between them will be measured. An alternative is to measure sound arising from tapping on the log end using a hammer and a signal analyser. The sound that occurs is equivalent to the longitudinal frequency of the log and is dependent on the time taken for the sonic wave to propagate backwards and forwards through the log. This speed of sound corresponds to the average properties of the whole log. Since knot volume is small compared to wood volume surrounding the knots, it is microfibril angle, tracheid length and basic density in the wood surrounding the knots that are measured, which have been shown to be good predictors of strength (Tsehaye et al., 2000; Xu & Walker, 2004).

Image analysis

Cameras have been used for several years to detect various properties in clear wood (Hagman, 1996), and could also be used to detect properties on log ends. Jonsson (1992) used cameras to try to estimate annual ring width in saw logs and concluded that it was possible if log ends were clean cut or washed with high pressure air or water. Clean cut log ends would make it possible to use other methods such as NIR spectroscopy (Hauksson et al., 2001), UV-fluorescence (Sum et al., 1991) and IR light (Arnerup, 2002) to predict various properties, e.g. species, rot and heartwood content. Laser light can be projected to the wood surface and the reflection of this light will have an elliptical shape as the light spreads in the direction of the fibres. A camera registers the reflection and the fibre orientation can be estimated. This method is an accurate and simple way out of sorting logs with spiral grain, which causes warp in sawn timber (Nyström, 2002).

Materials and methods

Data collection

The work presented in this thesis was based on five studies using data from six sawmills and two sites in Sweden. In total 3707 spruce logs and 8474 pine logs were evaluated. The log supply and evaluation methods differed among the five studies (Table 2, Figure 2). In the pilot study and studies I and IV the logs were sampled from the sawmills normal catchment area in order to obtain a broad distribution of properties. In Study II and III, the logs were sampled from individual stands in order to obtain data from exceptionally curved logs.

Table 2. *List of studies, materials and methods.*

Study	**Property**	**Number of logs**		**Measurement method**	**Location/ Sawmill**	**Statistical analysis**
		Pine	**Spruce**			
Pilot	- Board grade distribution within log grades - Cause of downgrade of logs	433	289	Manual evaluation of log grades and board grade distribution	Martinson (s.) Aneby (s.) Boxholm (s.)	-
I	Log grades	3706	7537	3D scanning of log shape and manual evaluation of log grade	Martinson (s.) Aneby (s.) Boxholm (s.) Forssjö (s.) Heby (s.)	Discrim. analysis/ Cohen's kappa
II	Curvature		56	Log scanning	Uppsala (f.s) Heby (s.)	Discrim. analysis/ Cohen's kappa
III	Comp. wood		53	Log scanning	Garpenberg(f.s) Uppsala (f.s) Heby (s.)	Reg. analysis
IV	Dynamic log MOE vs. board strength		828	Acoustics	Karbenning (s.)	ANOVA Chi-Square

s.=sawmill
f.s.=forest site

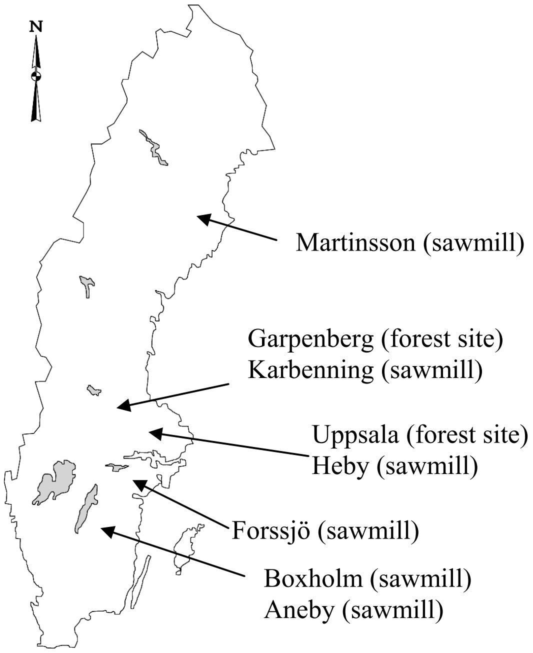

Fig. 2. Locations of forest sites and sawmills used in the thesis

Pilot study

The main objective of the pilot study was to investigate the properties of the log grades according to the National Log Grading Instruction (VMR, 1999) and the distribution of board grades (FSS, 1994) within each log grade. This information was to be used in subsequent studies.

A broad range of logs with different properties from three diameter classes were collected from Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea Abies* (L.) Karst) and from normal catchment areas of three sawmills in different parts of Sweden: Martinssons Trä (north), Aneby (south) and Boxholms (south). The aim was to collect approximately 40 logs from each combination of diameter-class, log grade and species, during five weeks in order to obtain logs with different properties (Study I, Table 1). Final amount of logs in the data set consisted of 433 pine logs and 289 spruce logs (Table 2). All logs were numbered, graded and the causes of downgrading were recorded by a grading inspector. This data was also used for model development in Study I.

The logs were sawn according to a commercial sawing pattern and the boards were dried according to commercial drying schemes. The boards were graded according to the Nordic timber rules (FSS, 1994). The distribution of board grades within the log grades was calculated for both centre- and sideboards.

Methods in Studies I-IV

Commercial Rema 3D log scanners were used in Studies I-III. The lengthwise resolution was about 20 mm. The data was used to calculate external log geometry variables in four main groups: bumpiness, log taper, sweep, and out-of-roundness. The log geometry variables used were: log taper and bumpiness (Study I) and sweep and out of roundness (Studies II and III). The variables were adapted from Lundgren (2000).

In Study IV, the resonance frequency in the logs was measured with a Rion SA-77 signal analyser. The resonance frequency was used to calculate the velocity of sound, which was used to calculate the dynamic MOE by the length of the logs and the assumed raw density of 1000 kg/ m^3 for all logs.

In Studies I and IV, the grades and causes of downgrading were estimated by grading inspectors from the log measuring organisations. All grading was conducted with sufficient time to evaluate all grading aspects of the log; hence, this was considered as a true grading. In study I, grading was performed by ordinary log graders under normal production conditions. The time to assess the log grade was approximately two seconds. In Studies II and III the curvature type was measured manually. No objective rules were found or used to estimate these classes.

Estimation of compression wood content in the log and pith eccentricity and compression wood content in log ends (Study III) was conducted with image analysis on discs representing log ends and given lengths intervals along the log. In Study IV, the internal properties of the logs was evaluated by sawing the logs in a commercial sawing pattern and grading the centre yield into structural grade classes describing mainly board strength.

Statistical methods

Various statistical methods were used throughout the thesis as the aims and the nature of the explanatory variables and response variables differed. The models for predicting log grades and curvature classes in Studies I and II were produced by using continuous log geometry variables and linear discriminant analysis. Discriminant analysis is suitable when more than two classes/grades are selected as known classes and rules can be developed by which new observations can be graded into the same classes.

The agreement between gradings was evaluated using unweighted Cohen's kappa coefficient (Cohen, 1960) (Studies I, II). Cohen's kappa is the proportion of observed agreement between two independent gradings adjusted for chance. The adjustment made the comparisons between different sawmills, with different distribution of grades, reasonable. In Study I, the kappa coefficient between the manual grader and the grading performed by the grading inspector was calculated and then the kappa coefficient between the automatic grading and the grading performed by the grading inspector was calculated. These coefficients were calculated for the different sawmills and diameter classes, and the kappa values were compared with Chi-Square tests. Bowker´s test for bias tested for significant variations between observers rating.

In Study II, the repeatability of the automatic method was tested and the agreement was calculated for four grading runs. This differed from the calculations in Study I, where only two gradings were compared. The formula for the simple kappa coefficient remained the same for comparing more than two gradings, but the formulas for the proportion of observed agreement and the chance factor were altered according to a method developed by Fleiss (1971).

The evaluation between individual variables describing log shape and distribution of compression wood in Study III was done with the Spearman rank correlation coefficient. The prediction of models was conducted by regression analysis since both response and explanatory variables were continuous.

The aim of Study IV was to explore the agreement between dynamic MOE and structural board grade and visual log grade. ANOVA (analysis of variance) evaluated the correlation between the MOE, which was regarded as a response variable, and the visual log grades, regarded as explanatory variables. The evaluation between board strength class and closeness to pith in intervals of MOE were done with Chi-square tests.

All statistical analyses were made in SAS 8.2 (http://statdist.its.uu.se/sas/SASOnlineDocV8/sasdoc/sashtml/onldoc.htm, 3-Oct-2004).

Results and discussion

Pilot study

Figure 3 displays the proportions of different downgrading properties for pine and spruce in the pilot study. Dry knot followed by sound knots and bumps were the properties that had the largest impact on log grades, a result that could be considered reasonable as the size number and distribution of knots are the most important aspect in the final product for most applications. Annual ring width was also an important cause of downgrading, though mostly on spruce and only in southern Sweden. The annual ring width was measured as the number of growth rings between 2-8 cm from pith and provided a good indication of the knot dimension (Orvér, 1970) and amount of juvenile and low-density wood, properties that is negative for most end-use applications (Desch, 1981). Compression wood content was the fifth most important cause of downgrading and curvature was ranked as tenth (long bow) and twelfth (top failure). Since compression wood and curvature interact, the ranking in Figure 3 can only be seen as a very rough estimate. This also implies for the interaction of other properties, e.g. knots and bumps.

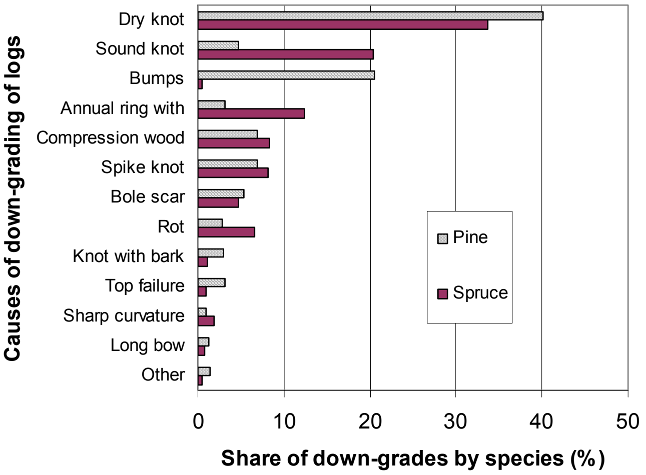

Fig. 3. Causes and percentage of down grading of logs by species

Figure 4 displays the outcome of board grades in the study according to the Nordic Timber grading rules for sawn wood (FSS, 1994). According to these results the pine log grades 1 and 3 are equal with respect to sawn wood grade distribution. Log grades 2 and 4 are of poorer but mutually equal sawn wood grade distribution. In the poorest log grades the share of the poorest board grade D is relatively high. For spruce, the board grade distribution was equal between log grades, with the exception of log grade 1.

However, Johansson et al. (1994) highlighted that most grading rules including Nordic timber (FSS, 1994), are produced by timber manufacturers, which is why they comply better with the manufacturers quality criteria than with the end users' quality criteria. Thus, any distribution should be evaluated with this in mind. One of the drawbacks with these grading rules is that they do not separate sound knot- from dry knot lumber, and therefore board grades from log grades 2 and 4 appeared similar. A deeper analysis of the boards showed that log grade 2, which was a sound knot grade, had more sound knots than boards from log grade 4, which had more dry knots.

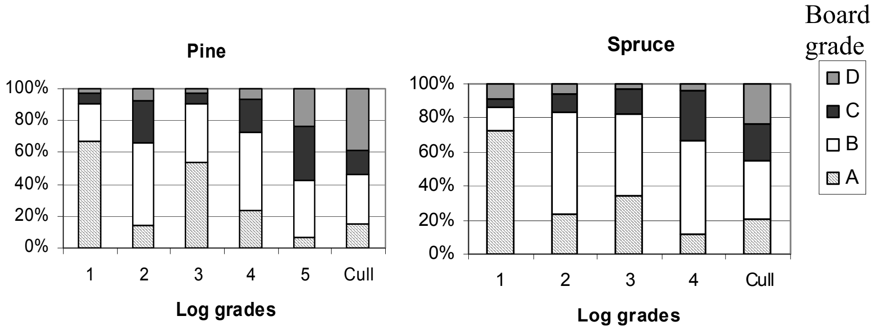

Fig. 4: Board grade distribution in percent of total board volume by log grade and species.

Boards from pine logs with grades 1 and 3 had relatively equal board grade distribution. These logs were, with few exceptions, smooth butt logs. Many downgrading properties that caused logs to become grade 5 or cull had little correlation with log shape, e.g. rot and bole scar. If no such property caused the log to become a low-grade log, the logs were generally crooked or bumpy. The conclusion was that with automatic grading based on log shape, pine log-grades 1 and 3 should be combined, and the same with grades 4, 5 and cull. Price reducing penalties for logs with downgrading properties not correlated to log shape would then have to be dealt with separately.

The results indicated similarities between spruce- and pine log grades, which led to a similar process for spruce log grades. This resulted in the same merging in three log grades: 1+3, 2 and 4+cull. There were though two exceptions. The first was the large share of high board grade in spruce log grade 1 relative to log grade 3. Log grade 1 is quite rare in practical log grading why grades 1 and 3 were combined in subsequent analyses. The second exception was that the distributions of board grades between log grades were more similar for spruce than for pine. Thus, the present grading system appeared less relevant for spruce than for pine.

Results Studies I-IV

Study I

Automatic grading of logs using external geometry was performed according to present log grading system and with the joint grades suggested in the pilot study. The automatic grading method was considered less accurate than manual grading. However, downgrading causes not correlated to log shape were not considered in the automatic grading. This meant that many logs might automatically have been given a high grade because of their outer shape whereas the true grade set by the grading inspector was low-grade because of e.g. rot. A lower level of accuracy was detected in the automatic measurements for the largest logs. This is probably due to that the smoothness of the logs increases with increasing diameter, which implies that it becomes more difficult to use log shape as a predictor for board properties on logs with large diameter.

The symmetry in the automatic grading was significant ($P<0.0001$), meaning that the distribution of estimated log grades was similar to the true distribution. The symmetry was generated through adjusting the discriminant models so the chance for a log becoming a certain grade was altered. This changed the distribution of logs into different grades so that it became equal to the distribution generated by the grading inspector.

Study II

The results of this study showed that it was possible to sort logs by curve type with a 3D log scanner. However, grading by curve type was largely dependent on curve severity and the grading only worked for logs with a bow height larger than 0.8 %. The repeatability test determined that the chance of a curved log being graded identically two consecutive times was 0.40, measured as kappa. The best repeatability was obtained for end sweep logs, although the results were affected by how curvature types and severity were defined, which was difficult to do in a fully objective manner.

Study III

The study indicated that log end information was a better predictor of compression wood than log shape variables. The most important variable for predicting compression wood was severe compression wood in butt end followed by pith eccentricity. Bow height and ovality were the most important log shape variables. Models using log shape variables described 27-30 % of the variation in compression wood content, and models using log end information explained 36-59 % of the variation.

Log position in the stem was an important variable for predicting compression wood content, since butt logs more frequently contained compression wood than other logs. The distribution of compression wood in straight logs did not differ from curved logs as much as expected, and logs with end sweep contained more severe compression wood compared to other logs.

This study showed that log shape variables obtained from a 3D laser scanner could be used for automatic detection of logs that are prone to contain compression wood. However, if only log shape variables are used many straight logs with compression wood will be missed. Information obtained from log end gave a better approximation of compression wood content in the log, though log ends are hard to evaluate under normal log measuring routines.

Study IV

Study IV showed a large span in MOE (c. 9-24 GPa) between the logs. A fair congruence was seen between the MOE of saw logs (representing two common diameter classes/sawing patterns) and the structural grade of the sawn lumber (according to SS-EN 519 and SPCR 078). For instance the share of C30 boards increased from 23 % for logs with MOE < 10 GPa to 91 % for logs with MOE > 20 GPa. Boards cut close to pith had overall lower stiffness compared with boards from more mature wood. However, for the logs in the best structural group interval (log MOE >18 GPa), no statistically significant difference in lumber grade was detected for lumber cut close to vs. away from pith. The differences in lumber grade were significant and differed from those in the lowest (p=0.057) and especially in the intermediate (p=0.0002) log MOE intervals.

The mean MOE varied significantly at the 5 % level for the classes in the registered variables: compression wood, log grades, annual ring width and log type. This was expected since logs with properties that cause downgrading normally have low MOE. Nevertheless, it was clear from the wide log MOE variation seen within each given visual grade class, that log MOE was not a good predictor of a log's visual grade. Likewise, the visual grade could not be used to predict the MOE of an individual log. This could be interpreted as visual grading being a poor indicator of board strength, which is an important property for spruce mainly used for construction purposes. Knot volume and the raw density of logs were not measured in this study, which also could have explained some of the variation in log MOE. It would also have been useful if the machine stress grading were designed to produce a continuous value on lumber stiffness rather than direct grading the lumber into strength classes (cull, C18, C24, and C30).

Based on the results from this study, the possibility to sort logs with acoustics may lie in separating logs having low MOE from the rest. Moreover, the results indicated possibilities for grading logs into MOE intervals linked to the structural grade of the sawn lumber. This may increase strategic and operational options for using logs in lumber production i.e. matching a given customer order with the current wood resource in the log yard or using the method for log grading.

Discussion

Log supply

In the pilot study and Study I, spruce and pine logs from several sawmills were collected from the sawmill's normal catchment areas over a long period of time. This was done in order to assure that the conclusions from the studies and the models were valid nationally. The supply of spruce logs in Study IV was also collected over a longer period, in order to guarantee a variety of stands within the sawmill's catchment area, which was in central Sweden. However, further studies using acoustic techniques are needed in the south and north of Sweden before conclusions can be drawn on a national level.

The aims in study II and III was mainly to se if it was possible to sort logs by curve type using a 3D log scanner and whether curvature could be used to estimate compression wood content. The logs used in these two studies came from one resp. two sites and were not randomly selected since mostly curved trees were chosen. The positive effect of selecting trees from more sites when studying compression wood was considered limited, since stand variables as site index and latitude is of less importance. Soil conditions and exposure to wind could though be important. Timell (1986) concluded from an extensive literature review that compression wood and curvature is induced in two major ways. First, trees can become displaced by different agencies, such as wind and snow, especially in unstable ground conditions such as in slopes and in wet conditions. The second equally important way involves injury or loss of the leader causing the adjacent branch to bend upward and become the new crooked leader. This can be caused by e.g. snow, insects, fungus and mammals.

The relatively high occurrence of curved logs in study III probably affected the results with generally better correlations than if a normal log data set had been used as in studies by Öhman (2001) and Warensjö (2003). However, the rank of the correlations of the variables was similar. It was considered better to study the correlation in an extreme sample rather than in a normal sample because of the extensive amount of work that would have been needed to collect data from a normal sample. Given that all types of log curvature types would have been included.

Measuring techniques

Studies I-III was conducted with commercial Rema 3D log scanners. The models and results are therefore applicable for all sawmills using this type of scanner and the models could also be adjusted to similar log scanners. Variables calculated from the log scanner data have also been studied by Jäppinen (2000) and Lundgren (2000) who sorted logs by different grades with good results. Most measurements were done at normal feeding speed (2 m/s), giving a resolution of 20 x 20 mm. Although a slower speed could possibly increase grading accuracy, this was not the case for curved logs graded at various speeds (Study III).

In study I the ability of the log scanner to grade the logs according to the present log grading system were investigated. This grading system consider primary knot properties, which are the most important type of property according to most grading systems for log and lumber (VMR, 1999; FSS, 1994). Other studies concerning automatic grading of saw logs for the purpose of sorting logs yielding high- vs. low-grade boards has been conducted. Grace (1994) sorted barked pine saw logs by log type and board grade using shadow scanners. The accuracy in the sorting with similar grading criteria was improved when 3D log scanners were used (Jäppinen, 2000; Lundgren, 2000) and even further improved when X-ray log scanners were used (Grundberg, 1999; Oja, 1999). The grading criteria's in this thesis are somewhat different and therefore it is hard to compare the accuracy with other studies. Even though X-ray log scanners probably are the best equipment for most log sorting purposes, the main issue among sawmills is whether it is cost efficient or not. Considering that there is only one X-ray log scanner in use in the Swedish sawmill industry, this seems not to be the case. Since grading systems for pricing should utilize systems that are widely used, X ray log scanners can at present not be considered an option. 3D log scanner with one X-ray beam added has also been suggested (Oja, 1999), an application that might be more frequently used. The application of knot models based on stand information (Moberg, 1999) could also be considered in pricing systems of logs. Such models is though more applicable in pricing methods when the grade and price is set in the forest.

In study IV, the log grading was performed using an acoustic technique where frequencies were measured. From these frequencies the MOE was calculated. This method was used on spruce since MOE is normally closer correlated to strength than variables visible or measurable on the outside. Strength is an important criterion for spruce lumber since it mainly is used for construction. The method is considered stable with high accuracy and industrial applications could probably be implemented at a low cost, the on-line implementation needs to be evaluated in future studies. This method is though already used commercially in New Zealand even though it has not been fully automated yet (Huang et al., 2003).

The acoustic measuring equipment (Rion SA-77) used (study IV) was a multipurpose signal analyser not adapted for timber measurement. This was probably of less importance since the measuring method is very basic. The logs were measured lying on the ground and because of the dampening acoustic effect the supporting material might have on the logs, there was reason to believe that the logs have to be measured lying on a cushioned base to avoid disturbing vibrations. However, Kliger et al. (2003) found that this disturbing effect is very small and that the MOE is similar between logs measured on the ground or logs measured on a cushioned base.

Grading of Norway spruce logs into high and low strength timber classes has also been proven feasible by other techniques. Jäppinen (2000) sorted spruce saw log using a 3D log scanner. This technique relies on the relation between strength and log shape, which in turn mostly is correlated to the knot properties of the log. Oja et al. (2001) used the X-ray log scanner, which is a technique that relies on the strong correlation between density and strength.

Analysis

In studies I and II linear discriminant analysis was used to grade the logs. This method was chosen partly because initial analysis with PLS (Projections to Latent Structures), logistic regression and quadratic discriminant analysis showed poorer predictive power. In addition, the discriminant analysis was considered better since more than two grades/classes was used. PLS is a good alternative if there are many independent variables such as in image analysis (Hagman & Grundberg, 1995). The drawback using PLS is the fuzzy relationships between variables in the models (Grönlund, 1995), and these relations were also interesting in these studies. Linear discriminant analysis may only be used if the explanatory variables are normally distributed and the underlying covariance matrices are equal, which was the case in these studies.

The evaluation of the grading accuracy in studies I and II was done using Cohens Kappa (Cohen, 1960). In other studies evaluating the correspondence between true and predicted grade (Öhman, 1998; Gjerdrum et al., 2001) the total share of corresponding classifications between true grade and predicted grade has been used as the measure of the grading accuracy. This way of evaluating the grading accuracy does not consider the chance factor and thereby the distribution of logs in different grades. E.g. in a log delivery of 100 logs where one log has rot, the grader could grade all logs as rot free and thus achieve 99 % correctly graded logs. If Cohens kappa is used the accuracy would be 0 %, which would be a more fair measure. The Cohens kappa should though not be used if the marginals are asymmetric. This was though tested in the studies.

General reflections

This thesis investigated how log grading for pricing could be performed automatically using 3D log scanners and acoustics. Thus, the grading conducted was not for process control, why this thesis differs from most similar work on automatic grading of logs. As previously has been stated, grading for pricing differs from grading for process control in the need for transparency. This means that the grading should be able to be evaluated so that buyers and sellers of wood are confident that grading has been performed in a fair manner. This is why the base grading criteria in this thesis has been the current Swedish grading system for pricing.

In the pilot study the present log grading system has been investigated including the causes of downgrading and properties of the board grades. This was done in order to evaluate the grading system in an end-user perspective. The results indicated that the log grades agreed poorly with board grade according to Nordic timber (FSS, 1994), especially for spruce. This was in line with previous studies evaluating the current Swedish log grading system (Grönlund, 1995; Chiorescu & Grönlund, 2003). The results from the pilot study also indicated that some of the log grades could be merged. Merging of the grades in the current log grading system has also been conducted in practice among sawmills during the last couple of years.

According to the pilot study, the second most important downgrading property was compression wood. In study III the possibility of automatically estimating the amount of compression using log shape wood was evaluated. The compression wood content in the logs was strongly correlated to the amount of compression wood in log ends and the curvature. Other conclusion that could be drawn was that compression wood was more common in butt logs and that also straight logs could contain large amounts of compression wood, this has also been reported by Mork (1928) and Koch (1990). The occurrence of compression wood in straight logs is probably dependent on that the curvature has been concealed by radial growth (Warensjö, 2003). Curved log without compression wood was not found in the studies.

The pilot study showed that the distribution of board grades was similar between different log grades of spruce, which indicated that the present log grading system is inefficient for sorting spruce logs. Additionally, spruce lumber is more often used commercially for constructional purposes and important end user criterias are strength and shape stability. This is why MOE was used as the predictive variable and acoustic as the measuring technique.

Application

Log properties

There are also other properties important for log grading that not have been investigated in this thesis but should be considered in a grading system. Some of those properties can be estimated manually on log ends, e.g. rot and shake. Such properties can only be automatically measured in optimal conditions and due to the rough environment at the sawmill and due to dirt on log ends this does not work in practice. However, discs could be cut from log ends and the log clean-cut side of the disc could be analysed separately. This method is however probably too complicated to use during ordinary grading and until better techniques are available, these properties have to be considered manually as in the current grading system.

Proposed log grading system

As the evaluation of the grading is more complex and automatic methods are less transparent a grading system that is based on automatic measurement should be simpler than one that is based on manual measuring methods The grading system in Sweden is complicated and it is in its current form not suitable for automation. Many sawmills combine grades indicating that the current system is too complicated. Furthermore it is important that the log grading system is well adapted to new grading technologies

Based on the findings in this thesis, a base for a new grading system for pine and spruce is proposed. In the proposed system Cull and second rate logs are recognized in a first step using both automatic and manual methods. In a second step the first rate logs are sorted using automatic methods (Fig 5). The second rate logs are equivalent to the poorest grade in the current system, that is logs with compression wood, curvature, very large knots, very low dynamic MOE and mild rot. These logs yield low-grade lumber. With the proposed grading system, curved logs and logs with large branches are sorted automatically using a 3 D log scanner, whereas logs with rot and shakes must be sorted manually. The first rate logs can be further sorted with a 3D log scanner using the method presented in Study I. This would mainly be suitable for pine where sound knot lumber is an important grade. The first rate spruce logs can be further sorted with the acoustic method presented in Study IV.

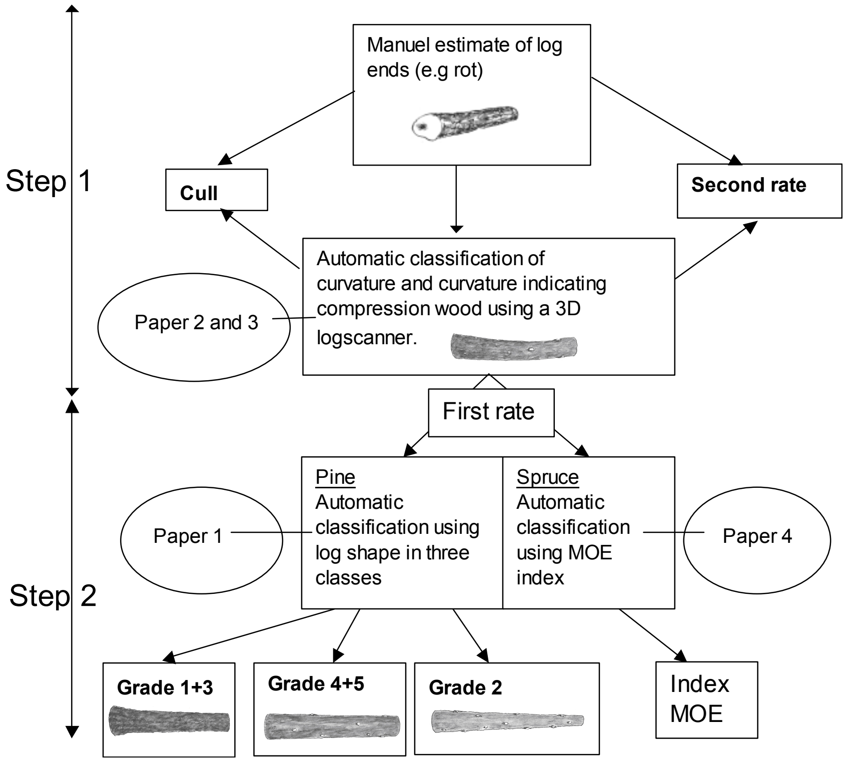

Fig. 5. Proposed log grading system

Spiral grain has also been shown to be important since this often leads to warp and especially twists (Forsberg, 1999; Woxblom, 1999; Säll, 2002). Although this is not really considered in the current grading system, findings by Perstorper (Perstorper, 1994) indicate that warp and, in particular twist, is a big problem for users of construction lumber. Methods that measure spiral grain in logs have been developed by Nyström (2002), and could be used in an automatic grading system.

Evaluation

A problem with automatic grading is the evaluation. The demand for accuracy of grading for pricing is stricter than for grading for production purposes, since both buying and selling parties must approve of the method. An incorrect grading leads to incorrect compensation and methods for grading and control and evaluation are therefore a sensitive issue.

The present grading system is evaluated by grading inspectors. These inspectors grade a small random sample subsequent to ordinary grading. The grading performed by ordinary graders and grading inspectors can then be compared and accuracy of the grading can be calculated where the grading from the inspectors is considered true grading. This system is accepted by both parties and is transparent. An automatic system needs another approach and although not as transparent as a manual approach it must still be approved by the sellers and buyers.

With automatic grading by 3D scanning two approaches for evaluation can be used. The first is to evaluate the log scanner itself; this can be done using e.g. plastic logs with different degrees of bumpiness and curvature. Data from these logs should always result in equal values for the variables used e.g. bow height and bumpiness. If the same log grading models are used, the grading should be identical at all sawmills. The advantage of using this method is that grading rules can be adapted to automatic methods; the disadvantage is that models are fixed and cannot be adjusted to obtain the best possible result.

The second approach is to manually evaluate grading with grading rules that can be used for both automatic and manual grading: this approach was adopted in Study I in this thesis. The advantage with this method is that models and hardware can be adjusted so that grading results agree as far as possible with the control grading. For example, if the amount of grade 2 logs is too small compared to the control grading, the models can be adjusted to improve the match. The disadvantage is that a system applicable to both automatic and manual methods cannot be optimized for both methods, possible resulting in a poorer grading accuracy.

Log measuring based on acoustics differs from log grading with 3D log scanner and manual grading. 3D log scanning and manual grading estimates the internal properties of the log based on log shape and properties visible on the surface. An acoustic method uses a relatively simple and stable method to measure the demanded properties more directly, which is also why any evaluation should be less complicated. A well-calibrated hand-held sound analyser operated by an inspector can be used to control and evaluate the speed of sound on logs that is measured for grading.

Conclusion

Log grading for pricing is important to compensate the foresters' for logs that yield high-grade lumber. The aim should therefore be to recognize properties that are important for end users of lumber. Two methods that recognize such properties are models based on data enhanced from a 3D log scanner using log shape and acoustics using the frequency of the log. These two methods have been proven feasible to grade logs and could also be considered for log grading for pricing based on the following results.

- The accuracy of 3D log scanning for grading logs according to the current regulations was comparable but somewhat lower than for manual log grading.

- Models based on log scanner data can differentiate between curvature types, if curvature is severe and bow height larger than 0.8 %.

- Log shape could be used to predict compression wood but using information from log ends are often better.

- Acoustics has a potential to sort logs yielding high and/or low strength lumber. The technique can probably be implemented to a moderate cost in most sawmills and can then be used for pricing and/or for process control.

The two methods investigated measure properties that are important in log grading for pricing and for most end-users of sawn timber and could therefore be implemented in an automatic grading system for pricing. However, new methods need to be developed to accomplish a fully automated system. The proposed system should therefore not be considered as a final system since new techniques could be added and other properties could be measured.

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