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X-ray measurement of properties of saw logs

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Akademisk avhandling

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ABSTRACT

A nondestructive method of measuring knot parameters for research purposes has been compared to alternative, destructive methods. The method is based on automatic analysis of CT-images. The image analysis algorithms were adjusted to and evaluated on Norway spruce *(Picea abies* (L.) Karst.). The possibilities of measuring resin pockets in CT-images have been studied and stereological methods have been applied to volume estimation of resin pockets in saw logs.

Data from CT-scanned logs was used to simulate an industrial X-ray LogScanner. The X-ray LogScanner was based on two X-ray sources and designed for scanning at 3 m/s. The possibility of using this X-ray LogScanner to make nondestructive measurements of properties of saw logs has been investigated.

For research purposes, the study showed that compared to destructive methods, both the accuracy and the speed of the CT method were competitive. Comparisons between real centerboards and reconstructions based on knot parameters measured in CT-images and simulated sawing showed that the reconstructions compared well to the corresponding real boards in terms of position, number, size and type of knots.

It was shown that resin pockets can be detected and measured in CT-images of Norway spruce and that implementation of stereology on wood can be a good tool for quantitative analysis of resin pockets.

The study showed that the X-ray LogScanner measures minimum shadow diameter under bark before debarking with an accuracy comparable to a 3D-scanner. The X-ray LogScanner handled the problems that can be ascribed to the presence of bark, and the conclusion was that the potential of combining the X-ray LogScanner with a 3-D optical scanner should be investigated.

It was also shown that the sawing position could be controlled based on X-ray LogScanner measurements of the best halves of the logs. The total amount of high-quality boards increased by 11% (2.5 percentage units) when the sawing position was controlled. The fact that the amount of low-quality boards also increases makes the economic potential very dependent on the price differences between the different qualities.

The X-ray LogScanner could be used to measure the percentage of heartwood and the green heartwood density with relatively high accuracy (R^2=0.94 and R^2=0.73, respectively). Based on the X-ray LogScanner measurements, it was also possible to calibrate PLS-models for prediction of the bending stiffness of the centerboards. These predictions could be used to sort logs according to the predicted strength of the centerboards. By sorting out 50% of the logs it was possible to increase the percentage of C30-boards from 73% to 100%. The rest of the logs could then divided into two groups, one of them with 100% C24- and C30-boards.

Keywords: CT-scanning, density, diameter, external shape, heartwood, image analysis, knots, MOR, MOE, nondestructive, Norway spruce, PLS, resin pockets, saw logs, Scots pine, sorting, stereology, wood, X-ray.

PREFACE

The work presented in this doctoral thesis was carried out at the Division of Wood Technology, Luleå University of Technology, under the supervision of Professor Anders Grönlund. It was also a project within the framework of Wood and Wood Fibre, a post graduate school sponsored by the Swedish Council for Forestry and Agricultural Research and the Swedish University of Agricultural Sciences. Parts of the work was financed by the EC FAIR-II program.

Since 1995, I have been working at the Division of Wood Technology in Skellefteå. I would like to thank all of my colleagues at the Skellefteå Campus that have helped and inspired me during these years. Nice colleagues make the workplace enjoyable!

Special thanks to Anders Grönlund for excellent and inspiring supervision and to Stig Grundberg for advice, ideas and for keeping me on track. Thanks to Olle Hagman for multivariate discussions and to Micael Öhman for advice and cleansing talks.

Thanks also to Göran Berggren for keeping computers and data in order, to Eva-Stina Nordlund for keeping people and paper in order and to Brian Reedy for correcting my English.

Thanks to my fellow PhD students in Wood and Wood Fibre. I really have enjoyed your company!

Finally, I would like to thank Malin, my wife, for encouragement, support and for giving life more dimensions.

Skellefteå, May 1999

Johan Oja

LIST OF PAPERS

This thesis is based on work reported in the following nine papers, referred to by roman numerals:

I. Oja, J. 1997. A comparison between three different methods of measuring knot parameters in Picea abies (L.) Karst. Scand. J. For. Res. 12: 311-315.

II. Oja, J. 1996. Validation of knot models on Norway spruce. Proceedings of the second IUFRO workshop "Connection between silviculture and wood quality through modelling approaches and simulation software", pp. 49-56. Nepveu, G. (Ed.). August 26-31 1996, Kruger National Park, South Africa.

III. Oja, J. 1998. Evaluation of knot parameters measured automatically in CT-images of Norway spruce *(Picea abies* (L.) Karst.). Accepted for publication in Holz als Roh- und Werkstoff.

IV. Oja, J. & Temnerud, E. 1998. The appearance of resin pockets in CT-images of Norway spruce (*Picea abies* (L.) Karst.). Accepted for publication in Holz als Roh- und Werkstoff.

V. Temnerud, E. & Oja, J. 1998. A preliminary study on unbiased volume estimation of resin pockets using stereology to interpret CT-scanned images from one spruce log. Holz als Roh- und Werkstoff 56: 193-200.

VI. Oja, J., Grundberg, S. & Grönlund, A. 1998. Measuring the outer shape of Pinus sylvestris saw logs with an X-ray LogScanner. Scand. J. For. Res. 13: 340-347.

VII. Oja, J., Grundberg, S. & Grönlund, A. 1998. Simulated control of sawing position based on X-ray LogScanner measurements. Proceedings of the 3rd IWSS. Grönlund, A., Hagman, O. & Lindgren, O. (Eds.). August 17-19 1998, Lövånger, Sweden. Technical report 1998:27, pp. 51-58, Luleå university of technology. ISSN 1402-1536.

VIII. Oja, J., Grundberg, S. & Grönlund, A. 1999. Predicting the strength of sawn products by X-ray scanning of logs-a preliminary study. Submitted to Wood and Fiber Science.

IX. Oja, J., Grundberg, S. & Grönlund, A. 1999. Predicting the strength of sawn products by X-ray scanning of green Norway spruce saw logs. Submitted to Scandinavian Journal of Forest Research.

CONTENTS

1. INTRODUCTION

Wood is a biological material. Every log or stem has its individual properties. These individual variations cause problems in modern sawmills because controlling the properties of the sawn product means controlling the properties of the raw material. Today, individual saw logs are not properly characterized before sawing and because of this a large part, maybe half, of the production in a normal sawmill consists of products that are in very low demand and, because of this, command very low prices (Grönlund 1995). Lönner (1989) points out that there is a large economical potential in better utilization of the high-quality logs. Concerning quality improvements in sawmills, Grönlund (1995) concludes, "without any doubt the fact that the raw material is not efficiently utilized is the largest cost for poor quality". Efficient utilization of the raw material can only be reached through optimization based on knowledge of both the properties of the raw material and the demands of the customers (Fig. 1).

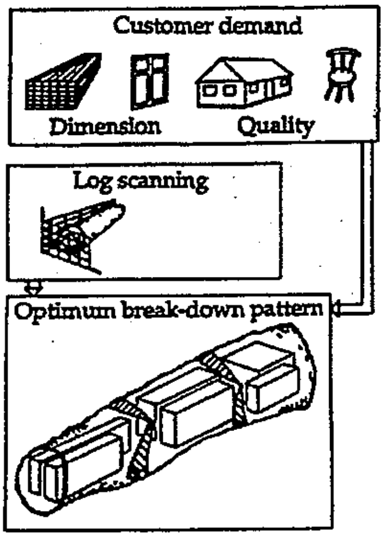

Fig. 1. *Optimizing the utilization of the raw material based on knowledge of both the properties of the raw material and the demands of the customers (from Grönlund 1992).*

Grönlund (1995) mentions three main needs that must be satisfied in order to reduce the cost of poor quality: "a tool that describes every piece of wood by its properties; new equipment for scanning the interior; knowledge of the customers' needs and behaviour." Fulfilling these needs will make it possible to make a stronger integration between Market-Forest-Industry and thereby to optimize the utilization of the raw material.

As optimized utilization of the raw material in a sawmill requires knowledge of the properties of individual logs, it becomes necessary to develop methods of measuring these properties in an industrial environment. Such methods should measure the important properties with acceptable speed and accuracy. It is also important that the large variations of a biological material can be handled. To be able to develop such methods, it is necessary to have knowledge of both the properties of saw logs and the variations of these properties. Consequently, the first step must be to develop methods of measuring properties of saw logs for research purposes.

1.1. *Methods of measuring inner properties of logs for research purposes*

Destructive methods
Traditional methods of measuring inner properties of logs, e.g. the knot structure, are destructive (Koehler 1936; Maguire & Hann 1987). The most straightforward way to measure inner properties of logs is to make knots and defects visible by cutting the log into cross-sections, veneer or flitches. Then it is possible to measure external shape, knots and defects and to make computer reconstructions of the log based on these measurements. This has been done by several researchers, for instance in Finland (Usenius & Song 1996), New Zealand (Todoroki 1996), Sweden (Liljeblad et al. 1988) and the USA (Harless et al. 1991; Occeña 1992). Quite extensive databases with very detailed descriptions of logs have been built up in this way. Such a database can then be used for different simulations, e.g. of how to optimize the utilization of the raw material (cf. Usenius 1996).

The drawback is of course that in order to do detailed measurements it is necessary to cut the log into relatively thin flitches or cross-sections. Hence it will be impossible to make any measurements on real boards from the logs in the database. Such measurements are necessary for validation of simulations, and it is also often of interest to measure different properties of the boards, such as strength or visual appearance, in order to model the relation between these properties and the properties of the log or stem. Because of this, it is of highest interest to find a nondestructive method of measuring inner properties of logs.

Nondestructive methods
Nondestructive measurements of inner properties of logs can be made using gamma ray (Sederholm 1988), X-ray (Lindgren 1991), nuclear magnetic resonance (Chang et al. 1989; Soest 1996), microwaves (Kaestner & Bååth 1998), ultrasound (Han & Birkeland 1992; Sandoz 1996), vibration (Skatter & Dyrseth 1997) or longitudinal stress waves (Aratake et al. 1992; Ross et al. 1997). Good overviews and descriptions of different methods are found in Grundberg (1994), Skatter (1998a) and Saint-Andre (1998).

For research purposes, X-ray computed tomography (CT) has been the most successful method of imaging inner properties of logs, and studies are described by several researchers (e.g. Benson-Cooper et al. 1982; Taylor et al. 1983; Asplund & Johansson 1984; Birkeland & Holøyen 1987; Davis & Wells 1992). For green wood there is a linear relationship between the X-ray attenuation coefficient and density (Lindgren 1991). Knots and green sapwood have higher density than green heartwood.

In CT-images of green logs, it is therefore easy to separate knots and sapwood from heartwood, while it is more difficult to separate knots, especially sound knots, from green sapwood (Fig. 2). For Scots pine (Pinus sylvestris L.), a more detailed study of the contrast in CT-images is described by Grundberg (1994).

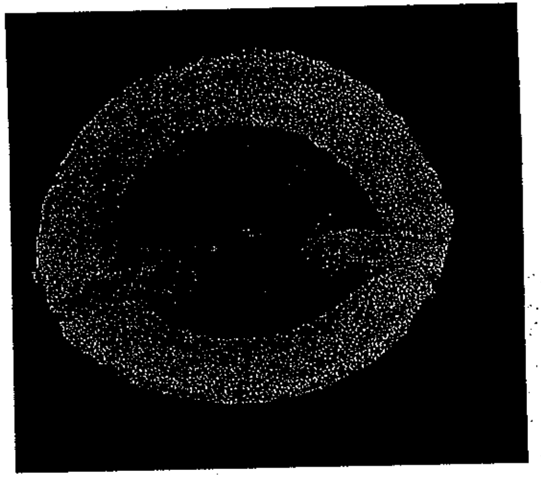

Fig. 2. *CT-image of a green Norway spruce log. Dark pixels represent low CT-numbers (low density) while bright pixels represent high CT-numbers (high density).*

CT-scanning of logs produces a great amount of data from which the essential information, e.g. the knot structure, has to be extracted. This can be done automatically by image analysis (see for instance Funt & Bryan 1987; Grundberg 1994, Schmoldt et al. 1995; Svalbe et al. 1995) and it is also possible to reduce the amount of data by using knot models to describe the knot structure of a log in an efficient way (cf. Samson 1993). Grundberg (1994) has developed image analysis algorithms that use knot models to extract the knot structure of CT-scanned Scots pine saw logs automatically. These routines were used when creating the Swedish Stem Bank (Grundberg et al. 1995).

1.2 *Methods of characterizing saw logs for industrial applications*

"The modeling approach"
The way to better utilization of the raw material is, as mentioned earlier, optimization based on detailed descriptions of the raw material and product specifications provided by the customers. For industrial applications, Björklund et al. (1996) suggest that tree models based on stand characteristics (site index, age, latitude etc.), silvicultural parameters (regeneration, spacing, thinning etc.) and tree characteristics (diameter at breast height, tree height, live crown limit etc.) could be used to predict the properties

of a log or a stem. These predictions should then be used to optimize the utilization of the raw material. Similar approaches have been described by, for instance, Nepveu (1996) and Saint-Andre (1998).

The idea of using tree models has its origin among the foresters. It is well known that it is possible to find general models that describe, for instance, how different silvicultural treatments affect the average properties of a population of trees. The problem with "The modeling approach" is of course that the large variation between properties of individual logs or stems makes it difficult to find models that make detailed and accurate predictions on the individual level. For predictions of the properties of individual logs or stems, the alternative and more straightforward way to go would be to do actual measurements using a nondestructive method.

Nondestructive measurements

Much work has been done to find nondestructive methods of measuring properties of logs in industrial applications. One alternative is to measure the shape of the log with a 2-axis shadow scanner (Fig. 11) or 3D-scanner ("true shape") and to use these measurements to predict inner properties of the log. Several researchers have shown that it is possible to control the choice of raw material based on measurements of the outer shape of logs and that it is possible to implement these methods in industry (e.g. Nylinder 1990; Grace 1994; Jäppinen & Nylinder 1997; Andersson 1997; Jakobsson 1998; Oja et al. 1999).

The good results that have been achieved with CT-scanning of logs for research purposes have of course encouraged attempts at using CT-scanners in industrial applications. The main problem for industrial applications is the high speed that is required. Today a scanner in a softwood sawmill should manage speeds up to 3 m/s, which is far beyond the scanning speed of a normal medical CT-scanner. With the Siemens SOMATOM AR.T. CT-scanner which has been used in the Swedish Stem Bank project (Grundberg et al. 1995), it is possible to acquire one image every 12-15 seconds. Including the positioning of a log in the scanner, it takes approximately 2.5 hours to scan one log.

Typical hardwood sawmills, for example in the USA, have more valuable raw material and run the process with lower speed. This make an industrial application of an actual CT-scanner more likely. Wagner et al. (1989) scanned an oak log with a scanning electron beam CT-scanner. With this scanner it was possible to acquire 34 images per second, corresponding to 0.34 m/s with a longitudinal resolution of 1 scan/cm. However, this scanner is not designed for continuous operation (it requires time to allow the x-ray tube to cool down) and because of this, its industrial use is limited (Guddanti & Chang 1995). Guddanti & Chang (1995) scanned red oak logs with another type of high-speed CT-scanner, primarily designed for airport security purposes. This scanner is designed for continuous operation and makes it possible to acquire 1 image/second, which still is quite slow. One way to increase the scanning speed is to increase the distance between the scans, but wider slice spacing gives less information and thereby also less improvement of the value recovery (Persson 1997).

In order to increase the scanning speed, different designs have been suggested. Gupta et al. (1998) suggest tangential scanning and describe a project aiming at speeds compatible with industrial processing of hardwood logs. According to Danielsson et al. (1998) it should be possible to scan logs at 5 m/s, using a cone-beam (2D-detector) and a helical source path ("spiral scanning"). This seems to be the most promising design for industrial CT-scanning of logs, but much work has to be done to develop large 2D-detectors and reconstruction algorithms.

To date, the most successful methods of measuring inner properties of logs at high speed, i.e. at a speed compatible with industrial processing of softwood logs, have been to use two or three fixed gamma ray or X-ray sources. Sikanen (1989) and Grundberg (1994) both have investigated the possibility of reconstructing a log based on very few projections. According to Sikanen, approximately six projections are needed to detect branches larger than 10 mm. The fact that gamma ray and X-ray sources produce a fan-beam makes it necessary to have at least two projections (or one projection in combination with knowledge about the position of the log) to make any useful measurements (cf. Skatter 1998b). As early as 1980, an industrial gamma ray scanner called Tina was put into operation (Sederholm 1988). Tina uses two gamma ray sources to measure two projections of the log (cf. Fig. 3). By analysis of these signals it is possible to measure variables such as diameter under bark, taper, density and density variations. Hagman (1993) uses the Tina scanner in combination with PLS-models to sort logs according to the quality of the centerboards.

MacMillan Bloedel Ltd has developed a prototype X-ray scanner with three X-ray sources in combination with an optical 3D-scanner. This scanner makes it possible to detect the knotty core and is designed to scan logs with a speed of 36 m/minute (Aune 1995).

Pietikäinen (1996) and Skatter (1998b) both have developed algorithms for analysis of data from scanners with three X-ray sources. Pietikäinen (1996) shows that the use of a scanner with three X-ray sources in combination with a new sector oriented reconstructing technique (SORT) makes it possible to detect 88% of the knots in a sample of Scots pine logs. Skatter (1998b) has used material from the Swedish stem bank to simulate a scanner with three X-ray sources and has developed algorithms that measure the outer shape of Scots pine saw logs.

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The X-ray LogScanner

Grundberg & Grönlund (1997) describe an X-ray LogScanner which is based on two X-ray sources (Fig. 3) and designed for scanning at 3 m/s (Anon. 1996b). This X-ray LogScanner can be described as a modern version of Tina with modern detectors and X-ray tubes instead of gamma ray sources.

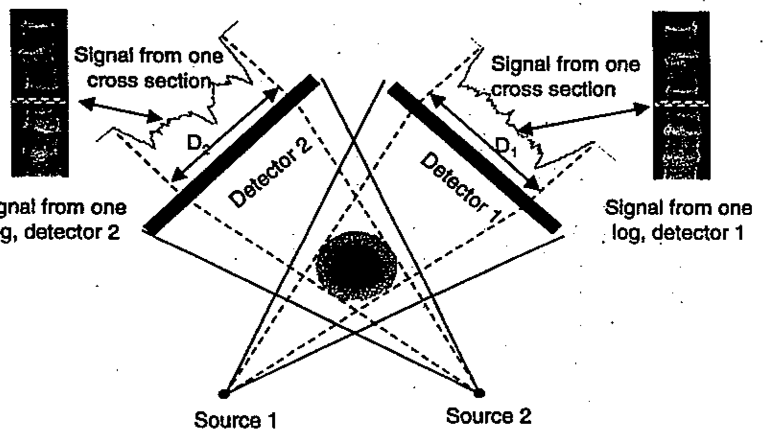


Fig. 3. *Schematic description of the X-ray LogScanner described by Grundberg & Grönlund (1997).*

When suggesting the use of tree models, Björklund et al. (1996) mention important properties that should be predicted by the models. These important properties are growth characteristics (average ring width, distance between whorls etc.), knot structure (average knot diameter, knot type etc.) and wood properties (basic density and percentage of heartwood).

Grundberg & Grönlund (1997, 1998b) show that the X-ray LogScanner can be used to predict centerboard quality according to Nordic timber (Anon. 1994) as well as specific properties such as average ring width, knot diameter and distance between the whorls. This means that many of the properties mentioned by Björklund et al. (1996) can be measured for every individual log, directly when the logs arrive at the sawmill.

Wang (1998) shows that for Scots pine there is a correlation between dry density of the log and green heartwood density. Hence the possibility of measuring the percentage of heartwood and the green heartwood density with an X-ray LogScanner should be studied (Paper IX).

If both knot parameters and density of saw logs can be measured with an X-ray LogScanner, then might it not be possible to predict the strength of sawn products based on X-ray scanning of the green logs (Paper VIII and IX)?

A very important property of a log is the diameter (or volume). The X-ray LogScanner measures diameter under bark (cf. Sederholm 1988 and Skatter 1998b) and it would be interesting to compare these measurements with those of different optical scanners (Paper VI).

Another interesting question is whether the X-ray LogScanner can be used to control sawing position. It has been shown that there is an uneven distribution of knots around the log circumference for both Scots pine (Björklund 1994) and Norway spruce (*Picea abies* (L.) Karst.) (Lemieux et al. 1997). Can value recovery be increased by rotating the log according to X-ray LogScanner measurements of this uneven distribution (Paper VII)?

A general problem for researchers working with studies on biological materials such as wood is that it is time consuming, difficult and expensive to find a material which is both representative and well-characterized. This becomes very evident when planning studies of the type in Papers VI-IX. One way to deal with this problem is to create a database with just such a representative and well-characterized material. This database can then be used in many different ways and for many different studies. This was the idea behind the Swedish Stem Bank.

1.3. *The Swedish Stem Bank*

The Swedish Stem Bank (Grundberg et al. 1995) is based on 200 CT-scanned Scots pine (*Pinus sylvestris* L.) trees, carefully selected from 33 well-documented sample plots all over Sweden. Two small, two medium-sized and two large trees, six trees in total, where taken from each sample plot. After felling and crosscutting, the logs were transported to Luleå university of technology, Skellefteå Campus, where the logs were graded by skilled log graders and then CT-scanned in a medical CT-scanner (Siemens SOMATOM AR.T.). The logs were scanned every 10 mm within the whorls and every 40 mm between the whorls. The CT-images were stored in two different formats, 8-bit 256×256 pixels and 16-bit 512×512 pixels.

After CT-scanning, all logs were sawn with normal sawing pattern (cant sawing) and the sawing position was documented for every log. All boards were marked with log identity and position in the sawing pattern and then dried to 18% M.C. All centerboards were scanned on all four sides with a CCD line camera and graded according to both the old (Anon. 1982) and the new (Anon. 1994) grading system.

The CT-images were analyzed automatically with the image analysis algorithms described by Grundberg (1994). These algorithms produce a parameter file where diameter (d), tangential position (Φ) and height position (h) of the knots in the analysed log are described as functions of the radial distance to the pith:

$$d = r \cdot (c_1 + c_2 \cdot r^{1/4}) \qquad (1)$$

$$\Phi = c_3 + c_4 \cdot \ln(r) \qquad (2)$$

$$h = c_5 + c_6 \cdot r^{1/2} \qquad (3)$$

Knot length, dead knot border and the distance from the pith to the log surface are given explicitly (Fig. 4). In this way it is possible to describe an individual knot with only 9 parameters (c_1–c_6, r_d, r_e, r_s). The algorithms also produce parametric descriptions of the position of the pith, the border between sapwood and heartwood and the external shape of the log. These parametric descriptions make it possible to reduce the amount of data considerable (Grundberg 1994) and still give detailed descriptions of individual knots.

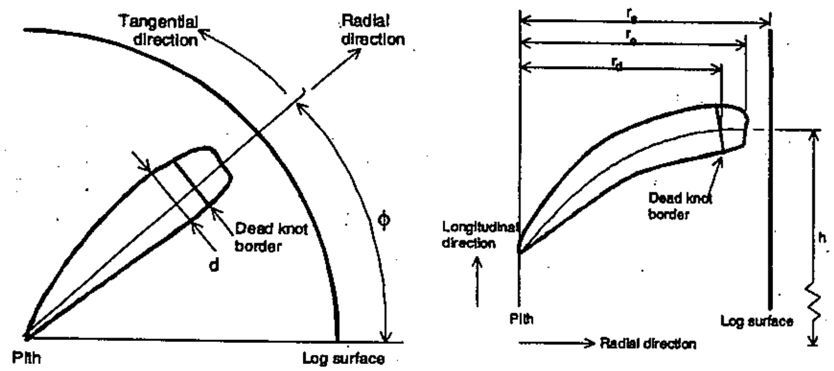


Fig. 4. *Parametric description of knots using knot models.*

All silvicultural data, all measurements and all images are combined in one database. The large amount of information in this database can of course be used in many different ways. Foresters can, for instance, use the database to model the effect of silvicultural treatments on different wood properties (Moberg 1996) or to model the knot structure (Björklund 1997). It is also possible to use the parametric descriptions for sawing simulation (Fig. 5) and to study the possibilities of optimizing crosscutting and sawing (Björklund & Julin 1998). The fact that the database is based on nondestructive measurements gives the advantage of making it possible to validate the sawing simulations (Grundberg & Grönlund 1998a; Björklund & Julin 1998).

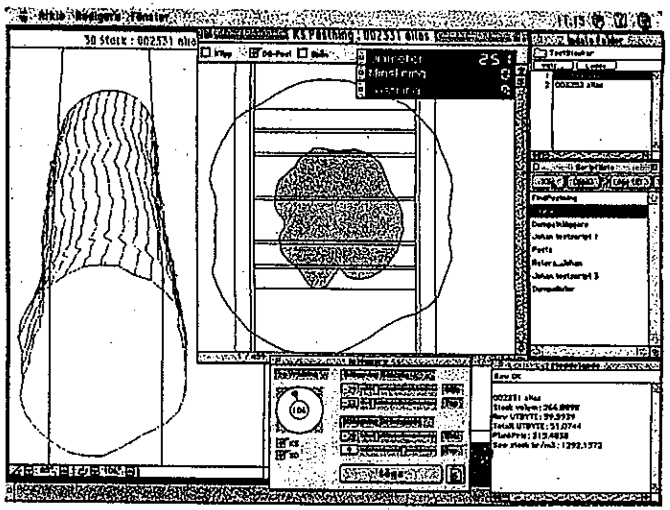


Fig. 5. *The parametric descriptions of logs can be used for sawing simulations. The figure shows an example of the user interface of the simulation software virtual SawMill (Grundberg & Grönlund 1998a).*

During the development of the X-ray LogScanner, the Swedish Stem Bank has been the key tool and it has been used in many different ways. First of all, the CT-images can be used to simulate the X-ray LogScanner with high accuracy (Fig. 6). The detailed descriptions of the logs in the database also make it possible to compare the simulated X-ray LogScanner measurements with different properties of the logs. These properties can be different measures of the knot structure (knot diameter, distance between whorls etc.), results of sawing simulations or properties of the real boards.

MATERIALS AND METHODS

1 *Measuring knot parameters in CT-images of Norway spruce*

ıper I and II were based on the measurements of the knot structure in two Norway ıruce stems; one tree (P1) from southern Sweden and one tree (P2) from northern weden. After felling and cross-cutting, both stems were transported to the laboratory ıd scanned in a medical CT-scanner (Siemens SOMATOM AR.T). All logs were :anned every 10 mm with a 5 mm wide X-ray beam. The data from each log were ıen analyzed by computer algorithms described by Grundberg (1994). After CT-:anning, stem P1 was sent to VTT in Espoo, Finland and stem P2 to the Agricultural Jniversity of Norway, Ås, Norway. At VTT and the Agricultural University of Norway he knot parameters were measured with two different destructive methods. The two nethods are referred to as the flitch method (Finland) and the whorl method (Norway), espectively (Fig. 7).

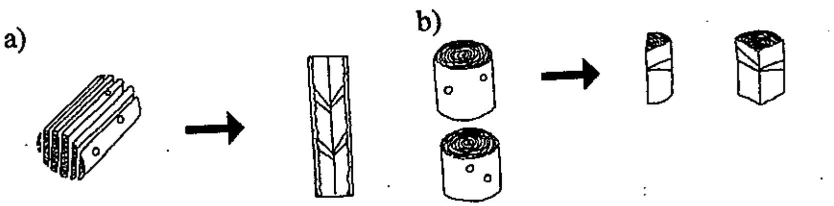


Fig. 7. The two destructive methods, the flitch method (a) and the whorl method (b).

The knot structure of the logs was measured with three different methods, two destructive methods and one nondestructive (CT-scanning). Paper I is a comparison between the three different methods of measuring knot parameters.

In Paper I the CT-images were analyzed with algorithms originally developed for Scots pine (Grundberg 1994). Paper II describes how the image analysis algorithms were adjusted to Norway spruce, based on the results from Paper I.

As Paper I and II were based only on two stems, it was very important to evaluate the accuracy of the measured knot parameters on a larger material. Paper III describes such an evaluation based on material from sample plots 1-4 in the Norway spruce stem bank. The logs from these plots were CT-scanned in the same way as the Scots pine logs in the Swedish Stem Bank (Grundberg et al. 1995), except that the Norway spruce logs were scanned every 10 mm also between the whorls.

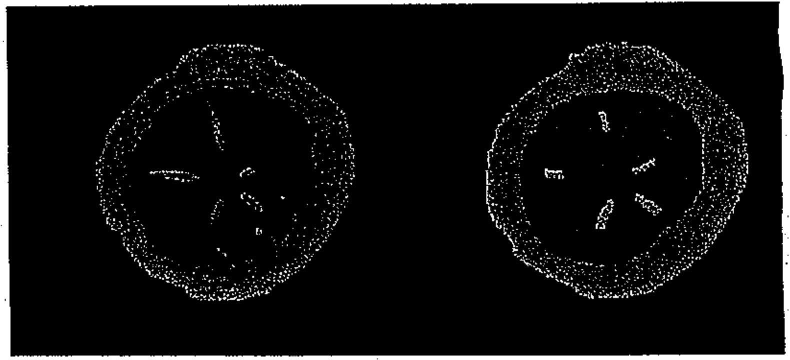


Fig. 8. Comparison between the original CT-image and a reconstruction of the cross section based on the parameter descriptions of log shape and knots.

To evaluate the accuracy of the measured knot parameters, reconstructed logs were created (Fig. 8). These reconstructed logs were based on the parameter descriptions of knot structure and outer shape. Using the simulation software *virtual SawMill* (Grundberg & Grönlund 1998a), the saw pattern was positioned in the reconstructed log in the same position as during the real sawing (Fig. 9).

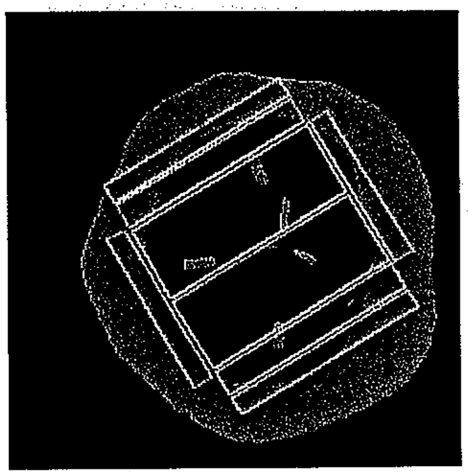


Fig. 9. During simulated sawing of a reconstructed log, the position of the saw pattern in the cross section was the same as during the real sawing.

[he reconstructed logs were sawn using *virtual SawMill*, with an image of the
›nstructed board as result. These reconstructed boards could then be compared with
'scale images (scanned with a CCD line camera) of the real centerboards (Fig. 10).
: accuracy of the automatically measured knot parameters was evaluated by
ıparisons between measurements on real and on reconstructed boards.

10. *Example of a real board compared to a reconstruction based on simulated sawing and parameter descriptions of knots and log shape*

Measuring resin pockets in CT-images of Norway spruce

er IV and V were based on CT-scanning of resin samples and on measurements of
ı pockets in one of the logs from stem P1 (Paper I). Theoretical calculations of the
ay attenuation of resin in Norway spruce were compared to measurements in CT-
ges of small samples of fresh and dry resin (Paper IV).

ls described in Paper I, all logs from stem P1 were cut into flitches. One of these logs
chosen for the studies in Papers IV and V. Resin pockets visible on the sawn
ıces were measured manually and their position on the sawn surfaces were
sformed to the corresponding position in the CT-images. Three resin pockets of
:rent sizes were selected from both heartwood and sapwood. These six resin pockets
e cut out from the flitches and CT-scanned in dry condition. After that, the six resin
cets were cleaned of resin and scanned again. The X-ray attenuation profiles (in
ıl direction) were then measured for each resin pocket and each condition (green
ıd, dry wood before cleansing from resin and dry wood after cleansing from resin).
se measurements made it possible to analyze the appearance of resin pockets in CT-
ges of Norway spruce (Paper IV).

ıll CT-images of the green log were then manually inspected and each resin pocket
marked. The amount of resin pockets in the log was then estimated using
:ological methods and samples of transverse and longitudinal sections with different
length. The relationship between step length and the accuracy of the estimations
then analyzed for both transverse and longitudinal sections (Paper V).

'apers IV and V are the result of cooperation between Temnerud and Oja where
ınerud provided experience of stereology and resin pockets while Oja provided
:rience of CT-scanning and image analysis.

4.3 *Measuring the outer shape of Scots pine saw logs*

Paper VI was based on simulations of three different optical scanners and the X-ray LogScanner described by Grundberg & Grönlund (1997). The simulations were carried out using CT-images of 60 Scots pine logs (20 butt logs, 20 middle logs and 20 top logs) from the Swedish Stem Bank (Grundberg et al. 1995). The outer shape (under bark) was measured every third centimeter for each log. These measurements were used to simulate three different optical scanners: a 2-axis, a 3-axis and an idealized 3D scanner.

The errors caused by variations in bark thickness when using optical methods were simulated for each cross section using a normally distributed error. The standard deviation of the normally distributed error was chosen according to Zacco (1974) for the corresponding diameter, bark type and geographical origin. The effect of missing bark was simulated by decreasing the measured diameter with the corresponding bark thickness.

The X-ray LogScanner was simulated using algorithms described by Grundberg & Grönlund (1997). Thus, the LogScanner simulation is an accurate simulation of real measurements on bark (Fig. 6).

For each cross section and scanner, the measured minimum shadow diameter was compared to the true minimum shadow diameter measured under bark (Fig. 11).

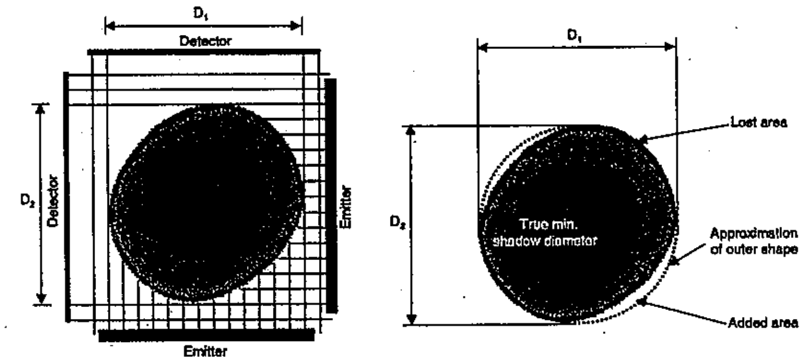
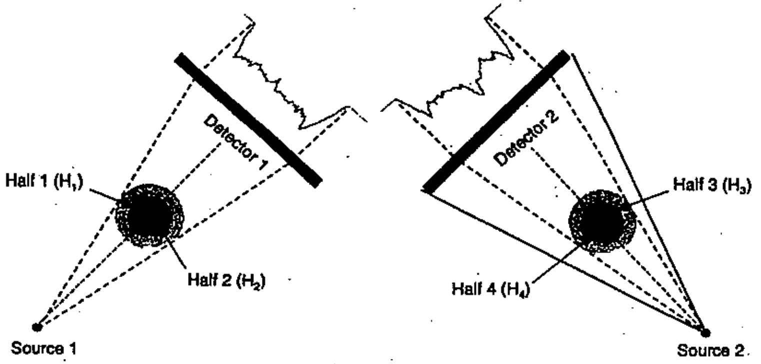


Fig. 11. *Schematic description of a 2-axis optical shadow scanner and definitions of true minimum shadow diameter and lost and added area.*

Based on the true and measured minimum shadow diameters, the accuracy of sorting logs into diameter classes was simulated. The amount of correctly sorted logs was calculated as a function of the standard deviation of the error when measuring minimum shadow diameter. These calculations were repeated for diameter classes with 5, 10 and 20 mm intervals respectively.

Controlling the sawing position based on X-ray LogScanner measurements

er VII was based on simulations of the X-ray LogScanner (Grundberg & Grönlund 7) and simulations of sawing 204 Scots pine saw logs from the Swedish Stem Bank. he objective was to control the rotational sawing position based on the knot cture, only logs with a bow height less than 10 mm were included in the study.



12. *Schematic description of the four halves of the log, in which the X-ray LogScanner is able to measure knot volume.*

he simulated X-ray LogScanner made it possible to measure the knot volume in different halves of the log (Fig. 12). Finding the "best" half of the log was then sidered to be the same as finding the two halves with the largest difference in knot ume between each other. The hypothesis was that sawing all logs with the "best" half n in the first saw would result in boards with higher quality in the lower board and er quality in the upper board.

fter analyzing the X-ray LogScanner measurements, the sawing was simulated using *al SawMill* (Fig. 5). Each log was sawn in two positions, one random and one based he result from the X-ray LogScanner. After sawing, the centerboards were graded rding to Nordiskt trä (Anon. 1994). Finally, the results of sawing the 204 logs in lom position was compared to the results when controlling the sawing position rding to the results from the X-ray LogScanner ("best" half down in the first saw).

4.5 *Predicting the strength of sawn products based on X-ray scanning of green logs*

Paper VIII describes a preliminary study, based on only eight logs. The logs were CT-scanned, four centerboards were sawn from each log and the bending stiffness (modulus of elasticity, MOE) and strength (modulus of rupture, MOR) of the boards were measured. The CT-images were used for simulations of the X-ray LogScanner (Grundberg & Grönlund 1997), resulting in simulated measurements of knot volume and the green heartwood density. Multivariate models were then calibrated using Partial Least Squares (PLS) regression (Geladi & Kowalski 1986; Eriksson et al. 1996).

Traditionally, Multiple Linear Regression (MLR) has been the most widely used regression method. MLR is based on the assumptions that the predictor variables (x-variables) are independent and exact (no noise exists) and that residuals of the predicted variable (y) should be randomly distributed (Lindgren 1994). When predicting the strength and stiffness of boards it is clear that the measured variables (X) most certainly are both collinear and noisy. Most probably, there are also important factors that are not measured, which means that the y-residuals are not randomly distributed. The reason for using PLS-regression is that PLS handles these problems, i.e. collinear and noisy data with structures in the residuals.

The PLS-models predict bending strength and stiffness of the centerboards based on the variables measured by the simulated X-ray LogScanner. Both bending strength and stiffness were defined as the mean value of the four boards from each log.

The study described in Paper IX is similar to Paper VIII, but is based on a larger material and also includes an evaluation of X-ray LogScanner measurements of percentage of heartwood and green heartwood density. Paper IX was based on logs from the Norway spruce stem bank (Anon. 1996a), 272 logs for the study on prediction of strength and 29 logs for measurements of heartwood and green heartwood density. The logs in the Norway spruce stem bank were basically treated in the same way as the Scots pine logs in the Swedish Stem Bank. After CT-scanning, sawing and drying, the centerboards from 272 logs were machine strength-graded. The strength grading resulted in measurements of bending stiffness (MOE$_{machine}$) and grading into strength classes (C12, C18, C24 and C30) for each individual board.

PLS-models were then calibrated to predict the bending stiffness of the centerboards based on X-ray LogScanner measurements of variables such as density, density variations and shape of the log. Predicted and observed MOE$_{machine}$ were then compared and the predicted MOE$_{machine}$ was used to simulate sorting of logs according to the strength of the centerboards

Paper VI-IX were all planned together by Oja, Grundberg and Grönlund. Oja and Grundberg did the simulations, while Oja analyzed the results, calibrated models etc.

RESULTS AND DISCUSSION

Measuring knot parameters in CT-images of Norway spruce

er I makes clear that, compared to destructive methods, the automatic analysis of -images was a competitive method for the measurement of knot parameters in way spruce logs (Table 1). Large knots were detected and position and diameter e measured with acceptable accuracy. The accuracy of the detection of small knots the measurement of dead knot border and knot length were low and had to be roved.

***le 1.** A relative comparison between the CT-method and two different destructive methods. The relative grading (high/low) is based on the discussion in Paper I. High accuracy (+), acceptable (0), low accuracy (–).*

	CT-method	Flitch method	Whorl method
ıdestructive method	Yes	No	No
ection of large knots	0	+	0
ection of small knots	–	+	–
ular orientation	+	0	0
ght position	0	0	0
ıt diameter	0	–	+
ıt length	–	–	+
d knot border	–	–	+
rage time per log ept reconstruction)	2.5 h	2 h	4-5 h

aper II describes the adjustments of the image analysis algorithms that were made in r to improve the accuracy of these measurements. Small knots were detected ugh an analysis of cross sections instead of concentric surfaces and new models for ht position and dead knot border were suggested. It was shown that the accuracy of t detection and the prediction of dead knot border were improved, while the error ıeasured knot length remained relatively large.

aper III shows that the measured knot parameters make it possible to reconstruct with acceptable accuracy. Approximately 94 % of the knots with a diameter larger ı 7 mm were detected. The diameter of the knots was measured with a mean error 2 mm and a standard deviation of 3 mm. The mean error is most probably an effect hanges of the threshold levels that were made in order to make the algorithms more ıst. When simulating sawing in the reconstructed logs, the resulting centerboards ıpared well to the real centerboards in terms of position, number, size and type of knots (Fig. 10). The exception is knot type for small knots in large butt logs. The evaluation indicated that the real dead knot border is closer to the pith than the predicted dead knot border for these logs. It is also possible that the low accuracy when measuring knot length would have more influence on the results if the study had been made on sideboards instead of centerboards.

The results from Paper III show that the simulation software *virtual SawMill* makes it possible to perform reliable simulations of the sawing process based on the parametric descriptions of logs in the database.

5.2 *Measuring resin pockets in CT-images of Norway spruce*

Paper IV shows that the contrast between resin and the surrounding wood, in combination with the typical geometrical properties of resin pockets, makes it possible to detect and measure resin pockets in CT-images of Norway spruce. One important advantage with CT-scanning compared to traditional destructive methods is that the result is a 3D description of the resin pocket (Fig. 13).

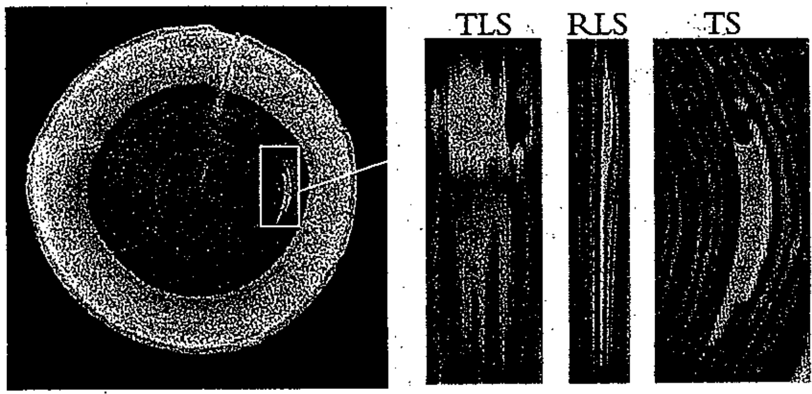


***Fig. 13.** Example of resin pocket in CT-images of a green Norway spruce log. Tangential longitudinal (TLS), radial longitudinal (RLS) and transverse (TS) sections. Dark pixels represent low CT-numbers (low density), while bright pixels represent high CT-numbers (high density).*

Paper IV also concludes that it should be possible to create algorithms that automatically detect large resin pockets in CT-images of Norway spruce. Compared to resin pockets in heartwood, resin pockets in green sapwood were more difficult to detect due to the high density of the surrounding wood. The study also showed that it was possible to use the same function for conversion between CT-number and density for both green wood and resin.

Paper V shows that implementation of stereology on wood can be a useful tool for ntitative analysis of resin pockets. Stereology provides theories of geometrical bability and statistical sampling that make precise and unbiased measurements sible. This means that the methods are a suitable tool for estimation of the volume of n pockets in sawn timber. Paper V is also an example of how a database of CT-nned logs, i.e. the stem bank, can be used.

Measuring the outer shape of Scots pine saw logs

er VI shows that the accuracy of the X-ray LogScanner was comparable to the uracy of a 3D-scanner when measuring minimum shadow diameter under bark ore debarking (simulations B and F in Table 2). It should be noted that the relatively istic simulation of the X-ray LogScanner (Fig. 6) was compared to a simulation of an l 3D-scanner.

le 2. *The Table shows the results from the simulation. Mean and standard deviation (STD) for the error when measuring the minimum shadow diameter (MSDE) and the amount of correctly sorted logs when sorting into diameter classes with the intervals 5, 10 and 20 mm are shown for all simulations.*

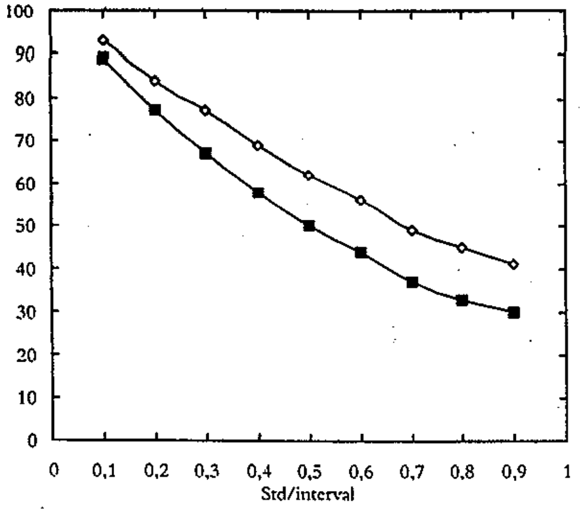
		MSDE		Correctly sorted logs (diameter classes)		
Simulation	Simulated equipment	STD mm	Mean mm	5 mm %	10 mm %	20 mm %
-ray LogScanner dry logs excluded	LogScanner	3.9	3.1	45	69	84
ptical methods without rrors due to variations in ark thickness	2-axis optical	3.6	3.7	48	71	86
	3-axis optical	2.8	2.7	57	78	89
	3-D optical	0.8	0.6	87	93	97
ptical methods with rrors due to variations in ark thickness	2-axis optical	4.7	3.7	39	63	81
	3-axis optical	4.2	2.6	42	67	83
	3-D optical	3.2	0.6	52	74	87
ptical methods with rrors due to variations in ark thickness and 25 % issing bark	2-axis optical	5.1	2.5	36	60	80
	3-axis optical	4.7	1.4	39	63	81
	3-D optical	4.0	-0.6	44	68	84

Simulations B and C (Table 2) showed that the X-ray LogScanner measurements (which are measured before debarking) were comparable with a 2-axis shadow scanner measuring after debarking. This means that the X-ray LogScanner handled the problems that are due to bark but also that the accuracy was limited by the fact that the X-ray LogScanner only measures in two directions. The conclusion was that the potential of combining the X-ray LogScanner with a 3-D optical scanner should be investigated.

Today many sawmills sort logs into diameter classes and then saw all logs in one diameter class with the same sawing pattern. This makes it very important to sort the logs correctly, i.e. to measure the diameter as accurately as possible. At a sawmill it can be quite difficult to estimate the accuracy of the diameter measurements. To manually measure the percentage of correctly sorted logs in one bin is both time consuming and difficult to do with high accuracy.

One suggestion would be to use the theoretical calculations of the percentage of correctly sorted logs that are described in Paper VI. These calculations are based on the assumptions that the diameters of the logs are uniformly distributed, that the diameter is measured with a random, normally distributed error and that the measurements are compensated for systematic errors (mean error). Using the same type of simulation as in Paper VI, it is also possible to simulate what happens when logs from one bin (supposed to belong to one and the same diameter class) are sorted once again. The result from such a simulation is shown in Fig. 14. To re-sort logs from one bin and then use the calculations presented in Fig. 14 can be a usable and relatively easy way to estimate the accuracy of diameter measurements.

An example: all logs from one bin (supposed to belong to a diameter class with 10 mm interval, e.g. 200-209 mm) are sorted once again. When sorting the logs a second time, 58% of the logs were sorted into the same bin (diameter class) once again. According to Fig. 14, 58% of the logs in the same bin after re-sorting corresponds to a standard deviation of 4 mm of the error when measuring diameter (diameter class with 10 mm interval gives std/interval=0.4). Fig. 14 also shows that in this case, 69% of the logs are sorted correctly during normal operation (when the logs are sorted only once). Observe that it is only the standard deviation that is estimated. This means that the diameter definition is not evaluated and that the estimation of the percentage of correctly sorted logs is valid only when the mean error for the diameter measurements is equal to zero.



. 14. Percentage of correctly sorted logs during normal operation (◇)and percentage of logs which were sorted into the same diameter class when sorting logs from one diameter class once again (■). Both values are the results of simulations with different relations between the interval of the diameter class (interval) and the standard deviation of the error when measuring diameter (std).

Controlling the sawing position based on X-ray LogScanner measurements

?aper VII shows that it was possible to control the sawing position based on X-ray ;Scanner measurements of the best halves of the logs. The high quality boards (Q1) 'e almost equally distributed between upper and lower boards (42 upper boards and ower boards) when sawing the log in random position (Table 3). The result of trolling the sawing position (best half down in the first saw) was a much more qual distribution of Q1-boards, 36 upper boards and 64 lower boards (Table 3). The l amount of high quality boards increased by 11% (2.5 percentage units) when the ing position was contolled based on the X-ray LogScanner measurements. The fact : the amount of low quality boards (Q3) also increases when controlling the sawing ition makes the economic potential very dependent on the price differences between different qualities. One way to go further with this study would be to investigate the ibility of finding out for which logs the value recovery increases with controlled ing position.

***Table 3.** The quality distribution of the boards when sawing the logs in random position and when controlling the sawing position, respectively. The quality distribution is presented separately for the upper and lower boards.*

Board	Quality	Random sawing position (number of boards)	Controlled sawing position (number of boards)
Upper board	Q1	42	36
	Q2	83	74
	Q3	79	94
Lower board	Q1	48	64
	Q2	88	67
	Q3	68	73
Total	Q1	90	100
	Q2	171	141
	Q3	147	167

Paper VII can also be seen as a validation of both the data base and the different simulations. The study was based on two different simulations, X-ray LogScanner simulations and sawing simulations. These two simulations use the CT-data in two completely different ways (Fig. 15). The study included the results of the two different simulations and thereby also all errors from both simulations. The study can consequently be seen as a validation of the results from both simulations.

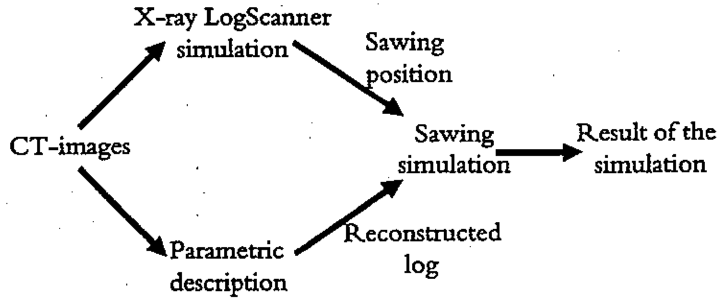
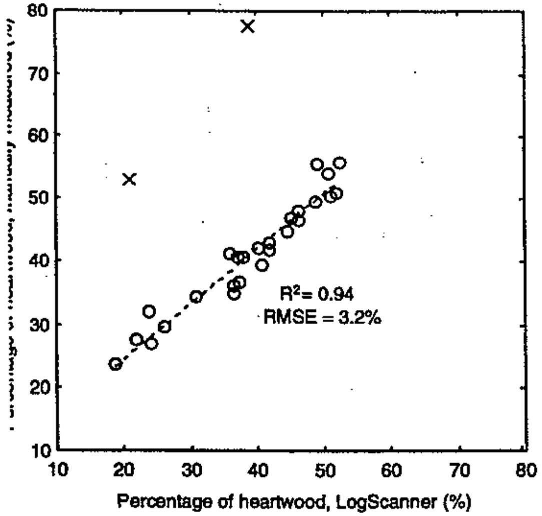


***Fig. 15.** Schematic description of how the database and simulation software were used in Paper VII.*

Predicting the strength of sawn products based on X-ray scanning of green logs

he results of the preliminary study presented in Paper VIII were very promising, . strong models for prediction of both bending strength (R^2=0.73) and stiffness =0.94). The conclusion was that a similar study should be done on a larger material. aper IX describes such a study, which also included an evaluation of the X-ray Scanner measurements of percentage of heartwood and green heartwood density. study showed that the X-ray LogScanner measured percentage of heartwood 16) and green heartwood density with relatively high accuracy (R^2=0.94 and 0.73, respectively).



16. *Percentage of heartwood measured manually in the CT-images and with the simulated X-ray LogScanner, respectively. The outliners (X) were excluded when calculating R^2 and RMSE.*

he study also showed that it was possible to calibrate PLS-models for prediction of ling stiffness of the centerboards based on the variables measured by the X-ray Scanner. The large variation in the material made it necessary to divide the material four groups; small logs (top diameter D<190 mm), medium logs (190 mm<D<260 , large butt logs (D>260 mm) and large middle logs (D>260 mm). There are several ble explanations as to why it was necessary to group the material in this manner. is the fact that the strength-grading machine is influenced by the dimensions of the d (Boström 1994). Another possible explanation is the variation in moisture content e heartwood between logs of different types and dimensions.

After calibrating the models, it was possible to predict the average bending stiffness of the centerboards from a log and to sort the logs according to the predicted bending stiffness. By sorting out 50% of the logs ("high-strength" logs) it was possible to increase the percentage of C30-boards from 73% (all logs in the study) to 100% (only "high-strength" logs). The rest of the logs could then divided into two groups, one of them with 100% C24- and C30-boards (Table 4).

Table 4. *Percentage of boards of strength class C12, C18, C24 and C30 when sorting the boards according to the predicted bending stiffness, $MOE_{machine}$ (based on simulated X-ray scanning of the green logs).*

	Percentage of boards (machine graded)				
Predicted $MOE_{machine}$	C30	C24	C18	C12	Total
>9700 MPa	50	-	-	-	50
8330-9700 MPa	21	10	-	-	31
<8330 MPa	2	12	4	1	19
Total	73	22	4	1	100

6. CONCLUSIONS AND FUTURE WORK

The most important conclusions of this thesis were that:

- CT-scanning is a nondestructive and accurate method of measuring inner properties of saw logs for research purposes.
- The X-ray LogScanner makes it possible to measure several important properties of saw logs nondestructively and with a speed that fulfills the demands of modern softwood sawmills.
- A "Stem Bank" based on CT-scanning of logs is a powerful research tool that makes it possible to analyze properties of logs and to simulate and develop both the sawing process and different measurement technologies.

The studies of industrial X-ray scanning of saw logs presented in this thesis are all based on simulations. Consequently, it is very important to validate these results with real measurements with an X-ray LogScanner in an industrial environment. This will also be possible to do in the near future, as two X-ray LogScanners will be in operation in Swedish sawmills before the end of 1999.

fter validating the results, the next step will be to use the new possibilities to control process. That means to specify the demands of the customers and to use the X-ray Scanner to find the right raw material for every individual product or customer. This be an interesting but difficult task.

s the X-ray LogScanner can be used to measure properties of individual logs, it ld also be possible to use these measurements to decide the value of the saw logs. s evaluation is done manually by the Measurement Society today, but work is being e to develop technical aids (Oja et al. 1999).

he X-ray LogScanner opens a lot of possibilities. One is to use the X-ray Scanner to optimize the crosscutting of stems, i.e. to transport whole stems to the mill and use information about both the properties of the stems and product ifications when deciding how to crosscut the stem. As a start, the Stem Bank can be to investigate the potential of this approach.

s properties of individual saw logs will be possible to measure by X-ray scanning, use of tree models will be less interesting for characterization of individual logs or s. Instead, tree models can be used on a larger scale for the planning of silviculture, ing operations etc. For a company that uses tree models in this way, an X-ray Scanner can provide important input data to the models.

uture work also includes development of image analysis algorithms that detect and sure other properties of saw logs. Important properties that can be possible to detect easure are spiral grain, compression wood, rot and spike knots. When developing algorithms, it would also be interesting to investigate the potential of combining an ay scanner with a 3D optical scanner.

n summary, the results presented in this thesis show that the X-ray LogScanner sures important properties of saw logs. By using this information it should be ible for a sawmill to control the large variations between individual logs and thereby to improve the utilization of the raw material.

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Paper I