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## *a tool for control of the sawmill process*

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SKELLEFTEÅ CAMPUS
Division of Wood Technology

1999:37 • ISSN: 1402 - 1544 • ISRN: LTU - DT - - 99/37 - - SE

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# *An X-ray LogScanner – a tool for control of the sawmill process*

by
Stig Grundberg

AKADEMISK AVHANDLING

Som med vederbörligt tillstånd av Tekniska Fakultetsnämnden vid Luleå tekniska universitet kommer att på svenska offentligt försvaras i hörsal, A-huset, Institutionen i Skellefteå, tosdagen den 16 december klockan 10.00.

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| Handledare: | Professor Anders Grönlund | Luleå tekniska universitet |
| Fakultetsopponent: | Professor Rolf Birkeland | Norges Lantbrukshögskole |

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1999

## Abstract

Wood is a biological material with great variability. Every piece of wood is a unique individual. The great challenge in the wood products manufacturing process has always been to select pieces of wood with properties that fulfil the product requirements. This will be even more important in the future as customers increasingly demand sawn products with special properties regarding dimension, moisture content, warp and last, but not least, biological or aesthetic features. To be able to fulfil these requirements, the right logs have to be selected for a certain product before the sawing process. This means that an accurate tool that can measure external and internal features is needed.

The main objective of this work was to develop and evaluate algorithms for nondestructive measurement of external and internal properties in sawlogs with the aid of a bidirectional X-ray LogScanner.

The LogScanner outlines and the LogScanner signals were simulated using CT (computer tomography) images from the Swedish Pine (*Pinus sylvestris*) Stem Bank and the European Spruce (*Picea abies*) Stem Bank. With the aid of data from the stem bank databases, the simulated scanner signals, the saw simulation program virtual SawMill (vSM), and statistical analysis programs, new control algorithms were developed and evaluated.

The studies show that an X-ray LogScanner with two X-ray sources has a great potential to become a powerful tool for control of the sawmill process.

The most important conclusions of work presented in this thesis were that:

- X-ray based technology is a suitable technique for nondestructive measurement of internal features in green sawlogs.
- CT scanning is a powerful research tool for measurement and visualisation of different log properties.
- Parameterisation is an efficient method for reduction of the amount of data from a CT scanner.
- It is very efficient to use data from a "Stem Bank database" based on CT scanning for simulation, analysis and development of the sawing process and different measurement technologies.
- An X-ray LogScanner with two X-ray sources can measure log features such as diameter under bark, species, log type, knot structure, rotational position of knots, density, heartwood content, annual ring width and predict strength and grade of sawn boards.

Keywords: CT scanning, density, external shape, grading, heartwood, image analysis, knots, LogScanner, MOR, MOE, nondestructive, Norway spruce, sawlogs, Scots pine, sorting, wood, X-ray.

## Preface

The work presented in this doctoral thesis was carried out at the Division of Wood Technology, Luleå University of Technology, Skellefteå Campus.

I want to thank everybody who has made my work possible and not only the ones who have assisted me regularly, but also the ones who have helped me with different things during the course of my work.

I would especially like to thank my supervisor, Professor Anders Grönlund, without whom this thesis would never been written, and my partner and friend during the debate of different issues, Olle Hagman. Special thanks also go to Johan Oja, who has supplied a lot of knowledge on the topic, to Ulla Grönlund, who gave it a quality appearance, to Owe Lindgren, who introduced the technique of tomography in Skellefteå, to Hasse Gidlöf for his programming spirit and to Göran Berggren, who kept all the data in order.

My thanks are also directed towards NUTEK, SJFR, EC FAIR-II, the Brattå Foundation and the Sawmill Foundation for financial support. I would also like to thank RemaControl AB, Moelven Eurotimber and AssiDomän, who have financed and started using the technique. Thanks are also due to Trätek for concentrating on this field and thereby enabling this development.

Finally, I want to thank my family: Kerstin for her sympathy and never-ending support when I have been working in the evenings and nights, and Aron and Nora, who don't understand what it will be used for.

Skellefteå November 1999

Stig Grundberg

## List of papers

This thesis is based on work reported in the following eleven papers, which will be referred to by their roman numerals:

I. Grundberg, S., Grönlund, A. & Lindgren, O. 1990. Noggrannhet vid detektering av stockars inre kvalitet. Avrapportering av steg 1. Trätek-rapport I-9005020. (In Swedish)

II. Grundberg, S. & Grönlund, A. 1991. Methods for reducing data when scanning for internal log defects. Proceedings of the 4th International Conference on Scanning Technology in the Wood Industry. San Francisco, USA.

III. Grundberg, S. & Grönlund, A. 1992. Log scanning - extraction of knot geometry. Seminar/Workshop on Scanning Technology and Image Processing on Wood. August 30-September 1, 1992, Skellefteå.

IV. Hagman, O. & Grundberg, S. 1995. Classification of Scots pine (*Pinus sylvestris*) knots in density images from CT scanned logs. Holz als Roh-und Werkstoff 53 (1995) 75-81.

V. Oja, J., Grundberg, S. & Grönlund, A. 1998. Measuring the outer shape of Pinus sylvestris saw logs with an X-ray LogScanner. Scandinavian Journal of Forest Research 13:340-347.

VI. Grundberg, S. & Grönlund, A. 1997. Simulated Grading of Logs with an X-ray Log Scanner - Grading Accuracy Compared with Manual Grading. Scandinavian Journal of Forest Research 12:70-76.

VII. Grundberg, S. & Grönlund, A. 1998. Feature Extraction with aid of an X-ray Log Scanner. Workshop 3rd IWSS August 17-19, 1998. IUFRO S 5.04-10, Sweden.

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

IX. Oja, J., Grundberg, S. & Grönlund, A. 1998. Simulated control of sawing position based on X-ray LogScanner measurements. Proceedings of 3rd IWSS, August 17-19 1998. IUFRO S 5.04-10, Sweden. ISSN 1402-1536.

X. Grundberg, S., & Grönlund, A. 1999. Validation of a virtual sawmill. Accepted to Holz als Roh-und Werkstoff.

XI. Grundberg, S., Grönlund, A., Oja, J. & Israelsson, M. 1999. Log models reconstructed from X-ray LogScanner signals. Proceedings from the third workshop "Connections between Silviculture and Wood Quality through Modelling Approaches and Simulation Softwares". La Londe-Les-Maures, France, September 5 – 12, 1999.

## Contents

**Appendices (Paper I-XI)**

# 1 Introduction

Wood is a biological material with great variability. Every piece of wood is a unique individual. The great challenge in the wood products manufacturing process has always been to select pieces of wood with properties that fulfil the product requirements.

In earlier days the selection process was carried out by skilled craftsmen with long experience. One example of this process was when Alfred Israelsson from Gielas needed a new pair of skis. He went to the forest and examined the birch trees. When he found the right tree he said, "This birch is ugly on the outside and has cross-grained wood in the outer parts of the stem, but it has straight grain in the middle part of the stem" (Jonsson, 1988). How could he know? He didn't have X-ray eyes but he had long experience. He had, of course, also a lot of time to select the right tree.

When the manufacturing process gradually became more and more industrialised, the time available for selection of logs and boards with the required and well-defined feature profile decreased. Process improvements were focused on high productivity in volume per hour and high volume recovery. These changes have had as a resulted that perhaps 50% of what a sawmill produces are products that no customer really wants to buy. Thus, the total value of the produced products will be low. This is called "the sawmill paradox" by Grönlund (1992).

It is commonly held in quality work that variations are the root of all evil (see e.g. Deming, 1986). The sawmill paradox is due to the fact that the sawmills today cannot control variations in the raw material. It is therefore a good example of what is called "costs for poor quality" (Grönlund, 1995).

Sawmill people have become more and more aware that what is lacking is a tool that can characterize the raw material in order to control the conversion process in an optimal way. Lönner (1989) points out that there is a large economical potential in better utilization of high quality logs if the internal and external properties of the logs are taken into consideration.

Johansson & Liljeblad (1988) showed in a simulated sawing of 51 stems of Scots pine (*Pinus sylvestris* L.) that with full knowledge of the internal knots and the outer shape of the logs, the value of the lumber could be increased by about 10%. These results were obtained with only one degree of freedom, rotational position. With more degrees of freedom the potential increase in value will be even higher. However, the increase in value is very sensitive to errors in the positioning of the logs. Also Björklund & Julin (1998) have shown that knowledge of the internal knot structure creates a great potential for increase of value recovery.

Today technology has advanced to the point that defects can be detected in the interior of logs using X-rays, nuclear magnetic resonance (NMR), ultrasound or gamma rays (Birkeland & Holöyen, 1987). Also microwaves (Kaestner & Bååth, 1998), vibration technique (Skatter & Dyrseth, 1997) or longitudinal stress waves (Aratake et al., 1992; Ross et al., 1997) can be used for nondestructive measurement of inner properties of logs.

:al X-ray computer tomograph (CT) scanners have been tested for scanning of logs (e.g.
n – Coper et al., 1982; Taylor et al., 1984; Asplund & Johansson, 1984; Roder et al.,
Davis & Wells, 1992; Grundberg, 1994). These scanners are able to detect knots and
internal defects in logs, but the CT-technique needs further development before it can be
n sawmills.

lical NMR scanner was used for scanning of hardwood logs (Chang et al., 1989; Soest ,
They showed that it is possible to detect different internal defects in logs with this
que. The medical NMR technique is, however, not possible to use in a sawmill today
low scanning speed.

ound, a cheap and nonhazardous technique, has been tested for scanning of logs (Han,
Han & Birkeland, 1992; Sandoz, 1996). The major drawbacks with the ultrasound
que are the problem of coupling the transmitter and receiver to the logs in an on-line
s and the difficulty of detecting small defects in the logs. Much development work is
l before ultrasound can be used in an industrial log scanning application.

there are several systems for scanning and automatic grading of logs used in sawmills.
systems use either optical scanners or gamma-ray scanners.

nventional optical scanners used for grading of logs measure the log diameter every 5
nm along the log in two or three directions. Recently, a new generation of optical
rs, 3D scanners that measure the "true" cross-section of the log every 5 to 10 mm has
itroduced in some sawmills. From these consecutive-diameter values or cross-sections,
riables such as taper, butt taper and bumpiness are calculated. With the aid of these
condary variables, statistical classification algorithms can be developed (Nylinder,
Grace, 1994; Jäppinen & Nylinder, 1997; Andersson, 1997; Jakobsson, 1998; Oja et al.,

mma-ray scanner called Tina is principally used in the same way. The major difference
n Tina and the optical scanners is that Tina gives information about the density and
variations in the logs and measures the diameter under the bark (Sederholm, 1988).

tical scanners are used for general sorting of logs into two or sometimes three grades.
ase of two grades, the share of correctly classified Scots pine (*Pinus sylvestris* L.) logs
out 70% (Grace, 1994).

iding accuracy for Tina was studied by Hagman (1993a, 1993b). When sorting into
ides Tina obtained 75% correct classifications for Scots pine (*Pinus sylvestris* L.) and
rrect classifications for Norway spruce (*Picea abies* (L.) Karst). The major drawbacks
na are the low signal to noise ratio and the radiation hazard from the two radioactive
s.

nals from the optical scanners and Tina are too coarse for very accurate log grading
d control of the sawing process at the single log level. The signals only give
ition about general properties and large individual defects in the axial direction of the

log. For good process control we also have to find the position of individual defects in the radial and tangential direction of the log.

This is very important, as customers increasingly demand sawn products with special properties regarding dimension, moisture content, warp and last, but not least, biological or aesthetic features (Lönner, 1989). To be able to fulfil these requirements, the right logs have to be selected for a certain product before the sawing process. This means that an accurate tool that can measure external and internal features in logs will be very much needed in the future.

# Objectives and Limitations

## .1 Objectives

he main objective of this work has been to develop and evaluate algorithms for non-estructive measurement of external and internal properties in sawlogs with aid of a idirectional X-ray LogScanner. How the different parts of the work and the different papers re connected to each other is shown in Figure 1.

he objectives of Paper I were to compare different nondestructive measurement techniques nd to investigate the requirements on the information density in order to be able to separate nd classify different internal features in logs.

he objective of Papers II and III was to study methods for reduction of the large amount of ata in CT images without losing any useful information.

he objective of Paper IV was to classify knot type in CT images with different methods.

he objective of Paper V was to compare the accuracy of an X-ray LogScanner containing vo modern industrial X-ray sources and detectors with that of three different optical scanners 'hen measuring the outer shape of Scots pine saw logs.

he objective of Paper VI was to determine the grading accuracy of an X-ray LogScanner ɔntaining two modern industrial X-ray sources and detectors. The accuracy was compared 'ith the accuracy of manual graders.

he objective of Paper VII was to determine if it is possible to develop accurate models for not volume, knot type, annual ring width and distance between whorls using a LogScanner ɔntaining two modern industrial X-ray sources and detectors.

he objectives of Paper VIII were to investigate the possibility of using an X-ray LogScanner ɔr strength grading of Norway spruce saw logs and to evaluate the accuracy of X-ray ogScanner measurements of green density and heartwood content.

he objective of paper IX was to study whether the X-ray LogScanner makes it possible to nd a better half of logs and whether this information can be used to control the sawing ɔsition.

he objectives of Paper X were to validate the saw simulation model (virtual SawMill) ʒainst the results of real sawing and real manual grading and to study how sensitive the ıodel is to errors in the knot description.

he objective of Paper XI was to develop a method for reconstruction of the outer shape and ıe internal knot structure of logs based on a bidirectional X-ray LogScanner and a 3D :anner.

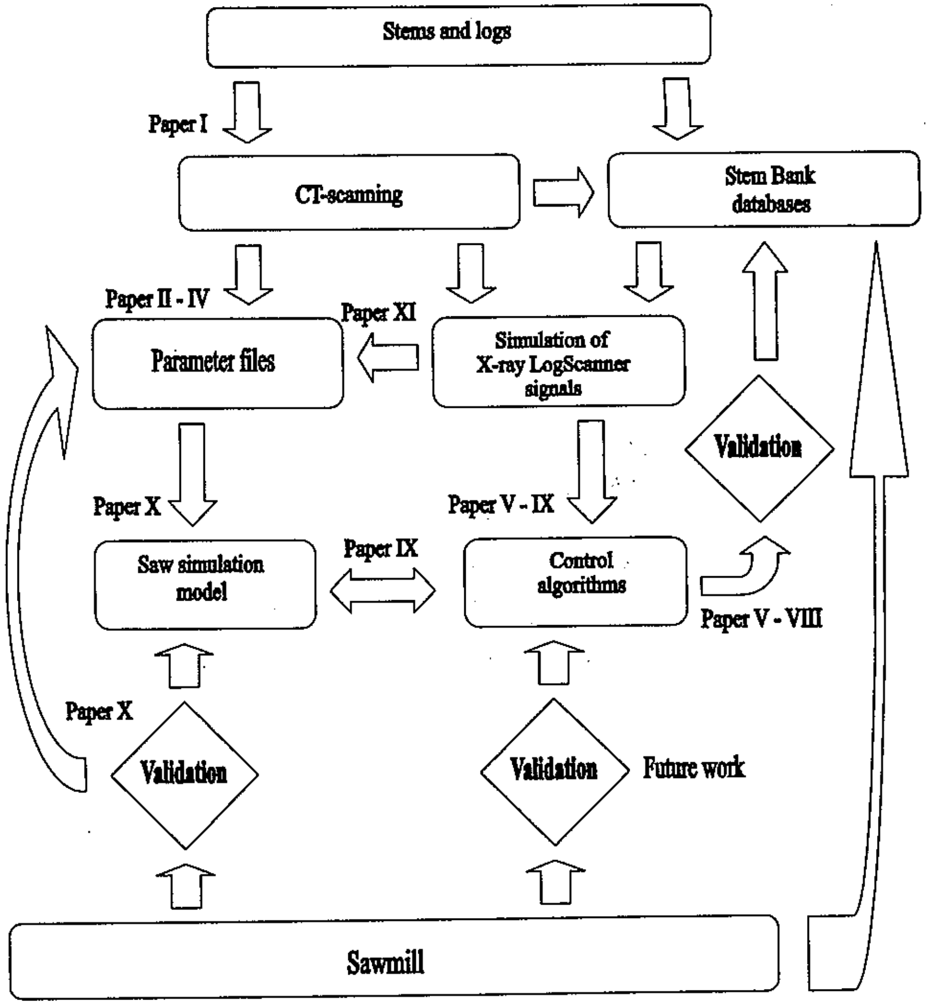

Figure 1. Schedule of how the different parts of the work and the different papers are connected to each other.

### 2.2 Limitations

No results from real X-ray scanning in an industrial environment are presented within this thesis. All results from the X-ray LogScanner are based on simulations. The simulations are based on the Swedish pine StemBank (Grundberg et al., 1995) and the European spruce Stem Bank (Anon., 1996). These comprise in total only about 1400 logs.

The classification of internal features has been limited to knots, heartwood, annual ring width, and green density. Severe defects such as compression wood, rot, pitch pockets, scar etc. are not included in this work.

## 3 Material and methods

### 3.1 CT-scanning

The theory for computed tomography (CT) is rather old. The mathematical basis of CT is usually attributed to Radon, who in 1917 established that a complete set of projection data of some relevant physical variable of an object could be used to reconstruct an image of the object. Projections are described mathematically through the Radon transform, and the process of image reconstruction from these projections is known as the inverse Radon transform.

At the time when Radon presented his transform it was not possible to build a CT scanner from a technological point of view. Hounsfield (1972) built the first CT scanner as a medical diagnostic tool for examining human heads. Cormack (1963) demonstrated the principle of image reconstruction from finite projections and discussed its potential for medical applications. Hounsfield and Cormack recieved the Nobel Prize in 1979 for their contribution to CT scanning. Since that first scanner, great advances have been made in medical CT development. In the industrial sector, industrial CT is now an established technology.

A CT scanner consists of an X-ray tube and a detector array (a great number of detectors) th rotate around the object being examined as illustrated in Figure 2.

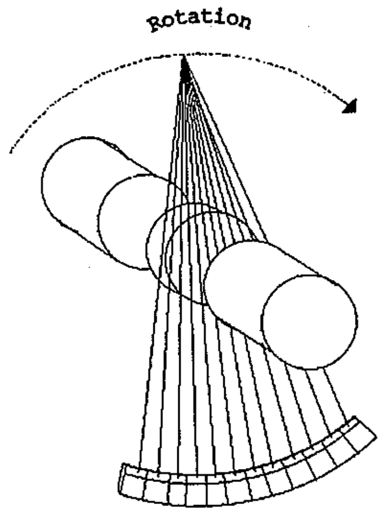

Figure 2. Rotating X-ray tube and detector array.

When the X-ray tube and the detector array have rotated around the object, a great number of measurement results for the absorption of the X-ray emission are achieved. One measurement datum is acquired for each combination of detector and angle position (720 x 900 measurement results for the CT scanner that has been used in this work).

These values are then used to reconstruct the desired cross section image of the test object. Many methods have been developed for the actual image reconstruction. The basic theoretical foundation has its origin in Radon's formula. The method most often used today is a filtered back projection. Reconstruction at the frequency domain is, however, the method that is marked by the shortest reconstruction times (Axelsson, 1992).

The image is reconstructed with the help of the measured signals and the image that is created describes the density variations in the cross section. Higher density and a longer running distance in the log cause fewer photons from the X-ray to pass through. In order to create a three-dimensional volume, the log is moved a bit forward whereupon another scan is made. This goes on until the whole log has been CT scanned.

The CT measures the density with an accuracy better than 5% and with a reproducibility better than 1% (Lindberg, 1990; Lindgren, 1992). When studying logs, the absolute levels of density are not of utmost importance. It is the differences in levels of density between different parts of the log that are of a major importance.

In Paper I, a medical CT scanner (GE 9800 Quick) has been used to study the possibility of detecting and separating knots from clear heartwood and clear sapwood in green Scots pine (*Pinus sylvestris*) logs. Also requirements for spatial resolution, beam width, geometrical configuration and compensation for differences in travel distance for the photons through the wood in a circular cross-section have been studied.

## 3.2 The Stem Bank databases

Paper I was mainly based on measurements of 20 short logs (about 0.5 m). These logs were CT scanned 6 times during a period of 40 days from harvesting. An interesting aspect was to look at drying effects during storage.

Papers II-IV were based on four pine stems harvested south of Skellefteå and crosscut to 11 logs. In order to get more severe defects, two additional logs from Arjeplog, near the Swedish mountains, were also included in the sample. These logs were scanned in a medical CT scanner (GE 9800 Quick) at the hospital in Skellefteå.

The experiences from Papers I-IV contributed to the Swedish Pine Stem Bank and the Norway spruce Stem Bank from the EC project "Improved Spruce Timber Utilization" (Anon., 1996). Papers V-XI are based on material from these two Stem Banks. A detailed description of the Pine Stem Bank is given by Grönlund et al. (1995).
The basis of the Pine Stem Bank is the CT scanning of 200 carefully selected pine stems from 33 sample plots all over Sweden. The stems were chosen from well-documented sample plots. Some of them have been observed for up to 100 years.

At every sample plot six trees were selected: two small trees, two medium-sized and two large trees. After felling and crosscutting, the logs were manually graded by two independent skilled log graders.

The logs were scanned in a medical tomograph, Siemens SOMATOM AR.T. The logs were fixed at both ends and adjusted to three laser lines so all the logs from a tree followed the same co-ordinate system. The logs were scanned every 10 mm in the whorls and every 40 mm between the whorls. After scanning, the missing images between the whorls were filled in by interpolation. All images were stored as 512 x 512 pixel images.

All the logs were sawn with a normal sawing pattern (cant sawing). The sawing position of the logs was measured and all the boards were marked with the identity of the log and the position in the sawing pattern. After sawing, all the boards were dried to 18% M.C.

All the centre boards were scanned on all 4 sides with a CCD line camera. Two skilled timber graders graded the boards independently of each other, first with the old grading system (Anon., 1982) and after that with the new grading system (Anon., 1994) used in Sweden.

All data in the Stem Bank were stored in a data base including all silvicultural and stand data, all CT images, images from sample plots, images of centre boards and all other data measured.

The Norway spruce logs were treated principally in the same way as the Scots pine logs described above. The only difference was that the Norway spruce logs were scanned every 10 mm also between the whorls.

## 3.3 The parameter files

When logs are CTscanned a tremendous amount of data is achieved. A normal CT image with a size of 512 * 512 pixels and a resolution of 4096 levels of density has an amount of data corresponding to 393 Kbytes. In order to get data that fairly well covers a whole log, the log must to be CT scanned at every 10 mm (Paper I). A log with a length of five meters then requires a memory in the computer corresponding to 196 Mbytes.

To be able to use the CT-scanned data for different type of calculations such as saw simulations, the amount of information has to be reduced. Liljeblad et al. (1988) and Samson (1993) have shown how different log features such as outer shape and knots can be described with a limited amount of data by using models of the knots and the outer shape. The input data to these models were, however, based on destructive log feature measurements.

In this work, a method for parameterisation of the CT data with the aid of digital image processing has been developed (Grönlund et al., 1995). The methods and algorithms are described in Papers I-IV. Papers I and II show different ways to reduce the amount of data.

Paper III shows how to parameterise the pith, outer shape, heartwood border and the knot geometry in the CT images. Paper IV describes two methods for classification of knots in the sapwood part of the logs. The parameter data is later used in Papers V-XI.

In the parameter files, the outer shape and the heartwood border are described by polar co-ordinates with the pith as origin. The outer shape is described by one radius at every degree every 10 mm along the log. The heartwood border is described by a mean radius for twelve-degree sectors every 10 mm along the log. The location of the pith in an x-y co-ordinate system is also described every 10 mm along the log.
The position, size and type of every knot are described by 11 parameters A-H and $r_e$, $r_d$, $r_s$. With notation according to Figure 3, the knots are described in the following way:

$$Ø_p = A+B\ (r_p)^{1/4} \qquad (1)$$

$Ø_p$ = knot angle in the tangential direction in radians.
$r_p$ = radial distance from the pith to a point on the knot axis in pixels.

As (arc = angle x radius) we will get:

$$r_k = \{(A+B\ (r_p)^{1/4})\ r_p\}\ \text{scale} \qquad (2)$$

$r_k$ = knot radius in mm.
scale = tomograph magnification/256.

The slope of the knot axis in the tangential direction is given by the following equation:

$$\Omega_{axel} = C + D \ln (r_p) \qquad (3)$$

$\Omega_{axel}$ = the tangential position in degrees for a point on the knot axis with the distance $r_p$. from the pith. Zero-position and rotation direction according to the notation in Figure 3.

The position of the knot axis in the vertical direction is given by

$$h = G + H \sqrt{r_p} \qquad (4)$$

h = Vertical position in cm for a point on the knot axis at the distance $r_p$ from the pith. Zero position at the butt end of the log.

$r_e$ = Distance from the pith to the end of the knot in mm.
$r_d$ = Distance from the pith to the dead knot border in mm.
$r_s$ = Distance from the pith to the outer face of the log at the point where the knot axis intersects the outer face. For a nonoccluded knot $r_e = r_s$.

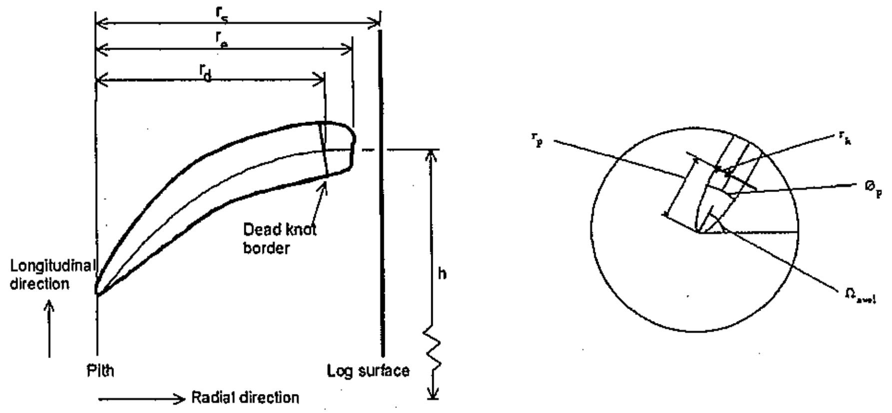

Figure 3. Notation for the knot geometry.

### 3.4 The saw simulation model

The development of the parameterized log description was in the beginning intended for a saw simulation program, OPTSAWQ, (Drake et al., 1987). The development of that program ended in 1994. After that, a new saw simulation program named virtual SawMill (vSM) was developed together with an industrial partner (Technique Program AB).

The vSM is written in the C++ language primarily for Macintosh computers. The vSM has an "open architecture", that allows users to add their own code for different applications. The program has the following standard features:

- The parameter files from the Scots pine and Norway spruce Stem Bank are used as log descriptions.
- Both cant sawing and live sawing can be performed.
- Sawing pattern, green target size and kerf width can be selected freely according to the user's need.
- Log positioning can be performed manually or automatically.
- Different degrees of curve sawing as well as straight sawing can be performed.
- The lumber is graded according to the Nordic timber grading rules (Anon., 1994).
- A module for optimization of blank production is included (Åstrand, 1996). It is possible to describe different grading rules for different parts of the blank both in the lengthwise and in the crosswise direction.
- A special programming aid, WoodScript, is included. WoodScript gives users the opportunity to adjust the program to fulfil their special needs.

The saw simulation program (vSM) was validated in Paper X. In paper IX, the vSM was used for sawing and grading centreboards in order to find a proper rotation strategy. In paper XI, vSM was used to compare two different ways to construct log models with the aid of an X-ray LogScanner in combination with a 3D scanner. The results were compared with log models from the CT scanner.

### 3.5 Simulation of LogScanner signals

In Papers I and II in the thesis, the notation "scoutview" is used for an X-ray image that is detected by an array detector during a longitudinal transport of the log. The notation "topogram" is also to be found in the literature. The established classification concerning this kind of X-ray image, however, is radiograph. The X-ray LogScanner described in this thesis produces two radiographs perpendicular to each other, Figure 4. This scanner can be described as a modern version of Tina (Sederholm, 1988) with modern detectors and X-ray tubes instead of gamma ray sources. A picture of the first X-ray LogScanner prototype is shown in Figure 5.

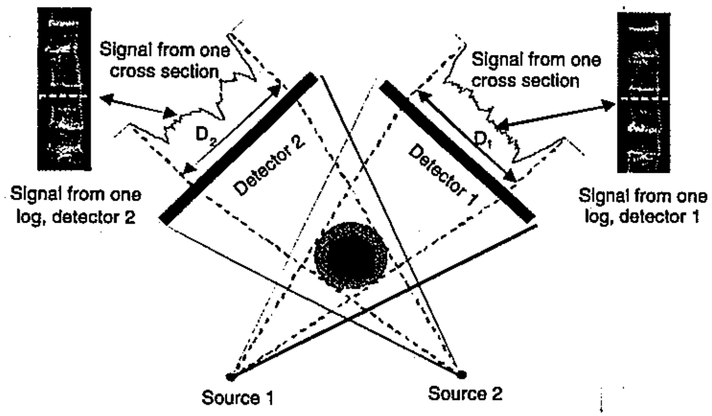

Figure 4. Schematic description of the X-ray LogScanner geometry.

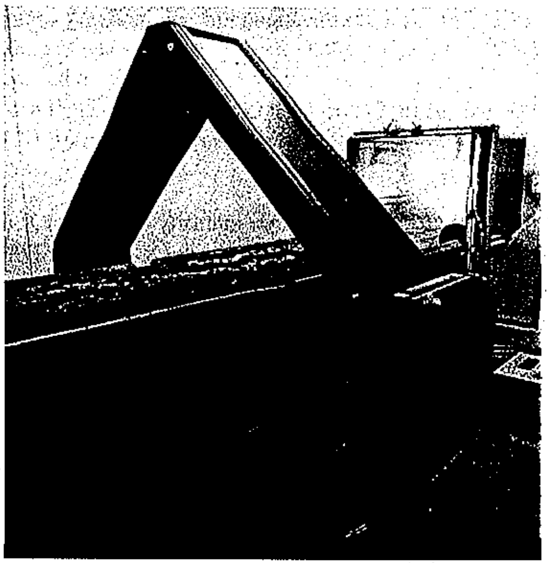

Figure 5. The first X-ray LogScanner prototype

In order to be able to develop control algorithms for the X-ray LogScanner with two X-ray sources perpendicular to each other and perpendicular to the feeding direction of the log, a method for simulation of the LogScanner signals has been developed. The simulations are based on the CT images from the Stem Bank databases. A real and a simulated signal using a modern X-ray tube and X-ray detector is shown in Figure 6. The real signal was obtained by continuous feeding of a log between a 160 kV X-ray tube and a solid state X-ray detector.

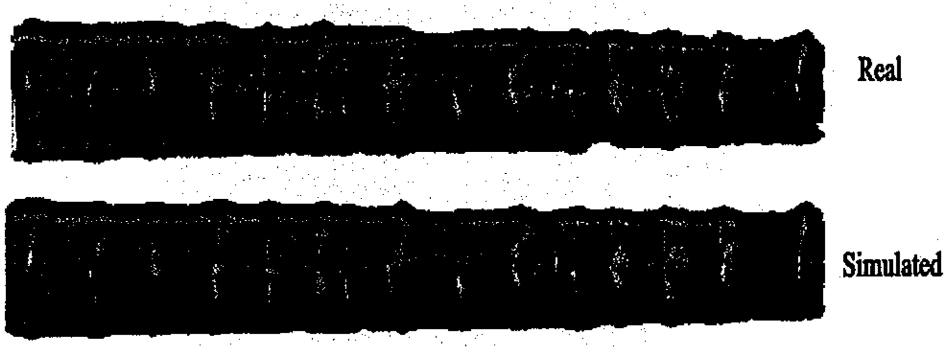

Figure 6. A real and a simulated longitudinal X-ray image (radiograph) of a log.

The simulated signals are calculated from the attenuation of the X-ray beam when it passes through the log (Figure 7) using the formula:

$$I = \int_{E1}^{E2} I_0(E)\ \exp(-\ \mu(E)\ \ d)\ dE$$

where I = intensity of transmitted X-ray beam; $I_0$ = intensity of incident X-ray beam; E1 and E2 are the lower and upper photon energy limits for the X-ray tube; μ = linear attenuation coefficient (Lindgren, 1991); d = thickness of the object at the position the beam passes through the object.

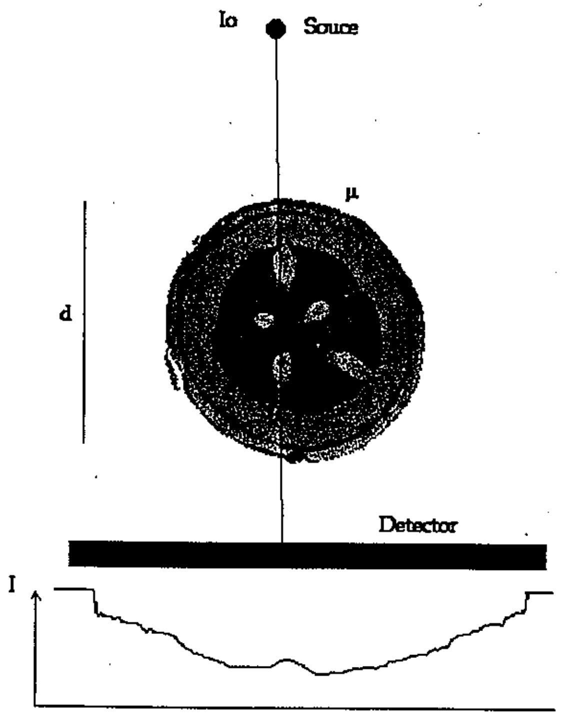

Figure 7. Simulation of X-ray attenuation in a log.

The simulated images Figure 6 consist of one row of pixels for every 10 mm of the log length, which is the same as one row for every CT image. In the transverse direction the resolution was reduced to 256 pixels, the gray-scale resolution was reduced to 256 levels, compared to the original CT images that consist of 512 pixels and 4096 gray-scale levels. Papers V-IX and XI were based on the simulated LogScanner signals from the Stem Bank material.

## 3.6 Control algorithms

The control algorithms connect the X-ray LogScanner signals with the demands the market makes on the manufactured products. The sawmill process itself can be seen as a link between the signals and the market, a link that will be controlled by the control algorithms. Which parameters that are interesting to control have been chosen in co-operation with a group of sawmill managers.

The two longitudinal X-ray images Figure 8 show the outer shape of the log in two directions perpendicular to each other and the density variations in the log. In these images, different log features are measured with the aid of image-processing techniques. Different objects, often defects, are separated from clear wood. The size and location of the objects and distances between different objects are measured. (All results in this thesis are based on simulated X-ray LogScanner signals).

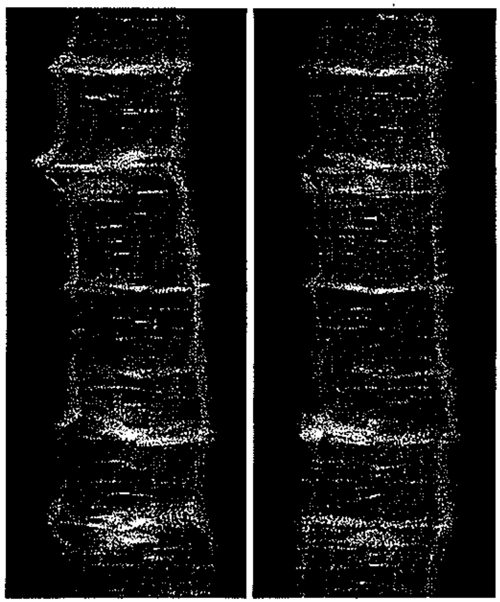

Figure 8. Radiographs X-ray images of a log in two directions perpendicular to each other.

Some log features can be measured directly in the images. Examples of such local features are knot volume, knot size, knot type, and distance between whorls. The results of these measurements are often presented as mean values and standard deviation for a whole log.

Other features are global for a whole log. Examples of such global features are species, log type, grade, strength etc. The global features are measured by combining a lot of local features in statistical models. Multiple regression and multivariate statistical methods are used as modelling tools (Box et al., 1978; Martens et al., 1989).

Control algorithms have been developed for following features:

| | |
|---|---|
| • In the thesis | Separation between Scots pine and Norway spruce. |
| • Paper IX | Type of log (butt, middle or top log). |
| • Paper V | Diameter under bark measured before debarking. |
| • Paper IX | Commodity grades for Scots pine and Norway spruce. |
| • Paper VII. | Knot volume. |
| • Paper VII | Sound knot volume. |
| • Paper VII | Dead knot volume. |
| • Paper VII | Distance between whorls. |
| • Paper VII | Annual ring width. |
| • Paper VIII | Density. |
| • Paper VIII | Strength. |
| • Paper VIII | Heartwood content. |
| • Paper IX | Rotational position of the knots. |

# 4 Results and discussions

## 4.1 Why X-ray?

In Paper I, different possible scanning techniques for detection of internal log features were studied. The study was in most cases carried out as a review of the literature.

Sound wood and anomalies can very often be separated due to differences regarding density, moisture content, speed of mechanical waves, the dielectric constant and/or the electron spin resonance. Following scanning techniques were studied.

- X-ray
- Gamma radiation
- NMR (Nuclear Magnetic Resonance ) (Chang, 1991)
- Microwaves (Kaestner & Bååth, 1998)
- Ultrasound (Han, 1991)

The literature study showed that there are, from a practical point of view, a number of awkward problems that make some of these scanning methods less attractive as far as continuous inspection of logs is concerned. Some of the major drawbacks for the different scanning techniques are:

- As far as NMR, microwaves and ultrasound are concerned, the prerequisites change when the wood is frozen. This results in two things. Either the logs have to be thawed before detection or different methods/algorithms have to be developed for frozen and nonfrozen wood. This implies that temperatures close to the freezing point will cause major problems.

- Metal parts have to be removed from the logs before being scanned with NMR; otherwise there is a risk that the magnetic coil will break down when the logs pass by.

- The damping of the microwave signal in a log is so large that the noise in the signal will be superimposed on the defects in the log to a great extent.

- When using ultrasound, there are difficulties regarding the signal transmission between the transmitter, log and receiver. The problem is that there has to be a physical contact between the units. Here among other things thin jets of water and grease have been tested as connectors. Tests of submerging the logs completely into water during detection have also been made

- As far as gamma and X-ray radiation are concerned, the mutual problem is the fact that the radiation is harmful when you are exposed to large doses. This means increased costs in order to create safety. From this point of view, X-ray is much better because it can be cut off during maintenance and when something unexpected occurs, for instance fire etc.

The conclusion resulting from the above facts was that if a scanning system for logs that is suitable for the Nordic climate is to be developed in the near future, it should be based on either X-ray or gamma radiation.

When trying to find suitable isotopes to create gamma radiation there are very few available. When it comes to isotopes with short half-life, the length of life is too short to make the system profitable. On the other hand, isotopes with long half-lives require a very large volume, which in its turn makes it hard to generate enough photons. This implies a large focus and blurred contrasts. Larger isotopes are also more difficult from a security point of view. There is today no isotope which is ideal for the scanning of logs.

The final conclusion of this study was that the X-ray tube is the source of radiation that shows the best advantages, and probably has the best possibilities to manage the inspection of logs in the future. X-ray tubes are available for industrial usage and they have a length of life more than 2000 hours depending on current settings and how often they will go on and off. The current settings depend on a lot of details, such as detector size, log speed, log diameter, the distance between source and detector, the detector's effectiveness etc. The tubes on the recently installed X-ray LogScanner have an expected lifetime of 8000 hours.

## 4.2 Validation of parameter files

Paper III shows that the knot detection algorithms can find more than 97% of the knots in Scots pine logs. Oja (1999) has shown that approximately 94% of the knots in Norway spruce with a diameter larger than 7 mm can be detected by the knot detection algorithms. The standard deviation for the difference between the real and calculated knot diameter was 3 mm.

In fact, it isn't an easy task to validate the knot parameter files, due to problems in correctly determining knot diameter and dead knot border and in determining how these parameters should be measured. Grönlund (1995) did a validation of the knot parameter files in the pine Stem Bank against real knots on the centreboards. This validation showed that there are some discrepancies between the real knots and the parameterised knots. The standard deviation for the difference between the real and the measured dead knot border was 5 mm.

In paper X the difference between the simulated and real knot diameter on the faces of sawn Scots pine boards was measured. The standard deviation for the difference between real and simulated knot diameter was 2.7 mm.

The parameter files are mainly used as input data to the saw simulation model vSM. As there are some errors in the parameter files, a natural question is: How much do these errors affect the results of the saw simulation? This has been studied in paper X.

The study has shown that random errors in the position of the dead knot border have almost no influence on the value of the sawn timber or the recovery of material (Table 1 and 2). The systematic errors in the dead knot border also have a very limited influence on the value. On the other hand, both systematic and random errors in the maximum knot diameter have a clear influence on the simulation results. As it is possible to compensate for systematic errors it will only be the random errors that will affect the simulation results in the future.

Table 1. Influence from random errors in maximum knot diameter and dead knot border (DKB) on the value of sawn timber in SEK/ m$^3$ of log volume and the recovery in % of the log volume. Random errors varied according to N(0,σ).

| Number of logs | Knot diam. σ mm | DKB σ mm | Value SEK/ m$^3$ | Recovery % |
|---|---|---|---|---|
| 628 | 0 | 0 | 951 | 50.6 |
| 628 | 0 | 5 | 951 | 50.6 |
| 628 | 0 | 10 | 952 | 50.6 |
| 628 | 3 | 0 | 933 | 50.2 |
| 628 | 3 | 5 | 930 | 50.3 |
| 628 | 3 | 10 | 935 | 50.4 |
| 628 | 6 | 0 | 889 | 49.8 |
| 628 | 6 | 5 | 891 | 50.1 |
| 628 | 6 | 10 | 889 | 49.8 |

Table 2. Influence from systematic errors in maximum knot diameter and dead knot border (DKB) on the value of sawn timber in SEK/ m$^3$ of log volume and the recovery in % of the log volume.

| Number of logs | Knot diam. mm | DKB mm | Value SEK/ m$^3$ | Recovery % |
|---|---|---|---|---|
| 628 | -3 | -5 | 1011 | 50.5 |
| 628 | -3 | 0 | 1021 | 50.5 |
| 628 | -3 | 5 | 1031 | 50.6 |
| 628 | 0 | -5 | 944 | 50.6 |
| 628 | 0 | 0 | 951 | 50.6 |
| 628 | 0 | 5 | 959 | 50.6 |
| 628 | 3 | -5 | 878 | 50.5 |
| 628 | 3 | 0 | 883 | 50.4 |
| 628 | 3 | 5 | 892 | 50.4 |

In Paper XI, parameter files based on the X-ray LogScanner signals were developed and validated against parameter files based on the CT scanner. It is quite clear that the method for acquisition of parameter files from the LogScanner has to be improved considerably (see Paper XI, Figure 4). This conclusion relies on the assumption that the CT-based parameter files and the virtual sawmill vSM produce fairly reliable results when a rather large group of logs is simulated, see Figure 9.

## 4.3 Validation of the virtual sawmill

In Paper X, the result from simulated sawing in vSM was compared with real sawing and grading. The comparison between manual grading and simulated grading showed that the vSM grading module graded the boards correctly according to the Nordic Timber grading rules (Anon., 1994).

A detailed comparison between vSM and real sawing was carried out for five logs in order to measure the magnitude of different error sources in the virtual SawMill system. A comparison between the simulated and the manual determination of the optimum combination of size and grade for the sawn timber from the five test logs is shown in Table 3 in Paper X. The sawing pattern for each log included two 50 by 125-mm centre planks and six 19-mm sideboards. Thus, there were altogether 40 test boards from the five test logs. No discrepancies regarding dimension or grade could be found on 29 of the 40 test boards. The value of sawn timber was 8% higher for the simulated sawing than for the real sawing.

The examination in paper X has shown that it is very difficult to obtain exactly the same result from a simulated sawing as from a real sawing at the single log level. The results are very sensitive for small discrepancies. As an example, there were two cases (boards) where a difference between real and simulated knot diameter was only 1 mm. This small difference changed the grade one step for these two boards.

There are mainly two error sources that cause the discrepancies between real and simulated sawing. There are differences in the log positioning in relation to the saw blades. There are also errors in the automatic generation of the parametric knot description as mentioned in chapter 4.2.

Systematic errors are in principal more serious than random errors, but as it is possible to compensate for systematic error if their magnitude is known, it will only be the random errors that affect the simulation results. After compensation for systematic errors it was shown in paper X that the random errors had a limited influence on the simulation results for groups of logs larger than 100, Figure 9. It was concluded that the simulation results have a high reliability especially for studies of the relative importance of different parameters.

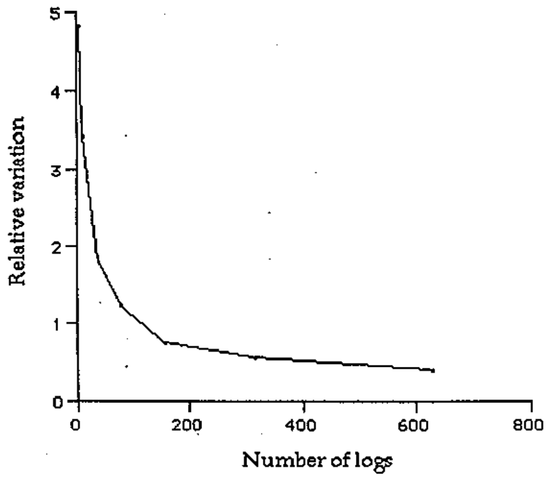

Figure 9. Relative varition in sawn timber value per m$^3$ of logs for five consecutive simulation runs with different number of logs. The relative variation = (Rmax-Rmin)/ Rmin *100 Rmax=The value for the simulation run with the highest value. Rmin= The value for the simulation run with the lowest value.

## 4.4 Accuracy of the control algorithms

In Papers V-IX, control algorithms for the X-ray LogScanner have been developed for the following features:

- Separation between Scots pine and Norway spruce
- Type of log (butt, middle or top log)
- Diameter under bark measured before debarking
- Commodity grades for Scots pine and Norway spruce
- Knot volume
- Sound knot volume
- Dead knot volume
- Distance between whorls
- Annual ring width
- Density
- Strength
- Heartwood content
- Rotational position of the knots

It was a bit surprising that separation between Scots pine and Norway spruce logs was given such high priority by the group of sawmill managers. The separation algorithm has been enhanced in several steps. The current algorithm can separate pine and spruce with an accuracy of 99.4% (Figure 10). According to the group of sawmill managers, the separation accuracy has at least to be better than 99%. The most important log features that separate pine and spruce are the small knots between the whorls in Norway spruce and the differences in heartwood content between the species.

A drawback with the current separation algorithm is that it is rather time consuming in the computer. This means that the algorithm has to be enhanced in order to reduce the computation time needed.

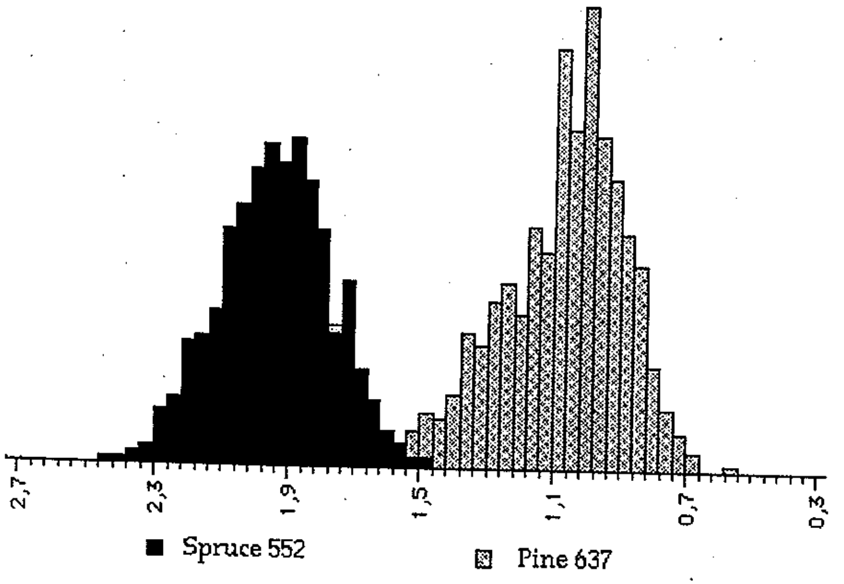

Figure 10. The ability of the X-ray LogScanner to distinguish between spruce and pine.

Paper V shows that an X-ray LogScanner measures the log diameter with good accuracy. When measuring logs with bark, the X-ray LogScanner competes very well with 3D optical scanners. The standard deviation was in both cases about 4 mm. The main error source for the X-ray LogScanner is the asymmetry of the log cross-section. The main error sources for the 3D scanner are the variations of the bark thickness and areas of missing bark on the log surface. When measuring debarked logs the 3D scanners have a much higher measurement accuracy than the X-ray LogScanner, standard deviation 0.8 mm and 3.9 mm respectively.

Paper VI makes it clear that a simulated X-ray LogScanner has a very good ability to classify logs into different log types such as butt, intermediate and top logs; 96% of the log were correctly classified. The agreement for Scots pine between manual lumber grading and the simulated X-ray LogScanner was also rather good (89%) for the training set (Paper VI, Table 7) but somewhat worse (71%) for the test set (Paper VI, Table 8). It must, however, be observed that the manual grading of the lumber in the test set also included defects such as wane, warp and checks. These kinds of defects are, of course, impossible to detect before the logs are sawn into boards. It also has to be pointed out that the discrepancy between the manual lumber grading and the simulated X-ray LogScanner also depends on errors in the manual grading, not only on imperfections in the automatic grading algorithm.

The performance of corresponding grading algorithms for Norway spruce is shown in Table 3 and 4.

Table 3. Comparison between the grading ability of the simulated X-ray LogScanner and the lumber graders for the training set of 256 Norway spruce logs.

| | Predicted log grade | | | |
|---|---|---|---|---|
| Lumber grade | a | b | c | Total |
| a | 51 | 17 | 0 | 68 |
| b | 23 | 147 | 6 | 176 |
| c | 0 | 2 | 10 | 12 |
| Total | 74 | 166 | 16 | 256 |
| Percent correct | 69 | 89 | 62 | 81 |

Table 4. Comparison between the grading ability of the simulated X-ray LogScanner and the lumber graders for the test set of 168 Norway spruce logs.

| | Predicted log grade | | | |
|---|---|---|---|---|
| Lumber grade | a | b | c | Total |
| a | 66 | 8 | 1 | 75 |
| b | 16 | 69 | 5 | 90 |
| c | 1 | 1 | 1 | 3 |
| Total | 83 | 78 | 7 | 168 |
| Percent correct | 80 | 88 | 14 | 81 |

In Paper VII, models have been developed for the following log features.

- Mean knot volume per whorl in $cm^3$ for Scots pine.
- Mean sound knot volume per whorl in $cm^3$ for Scots pine.
- Mean dead knot volume per whorl in $cm^3$ for Scots pine.
- Mean knot diameter in mm for Scots pine.
- Mean of the largest knot diameter in each whorl in mm for Scots pine.
- Mean distance between whorls in m for Scots pine.
- Mean distance between whorls in m Norway spruces.
- The distance between the pith and the tenth annual ring in mm for Scots pine.
- The distance between the pith and the twentieth annual ring in mm for Scots pine.
- The distance between the pith and the tenth annual ring in mm for Norway spruce.
- The distance between the pith and the twentieth annual ring in mm for Norway spruce.

The results show that the X-ray LogScanner probably never will give one hundred percent correct predictions. The prediction ability is, however, fairly good for some of the features. For instance, the prediction model for the distance between whorls in Scots pine logs explains 95 to 96% of the variations. The knot volume per whorl in Scots pine can also be modelled with a high degree of explanation ($R^2$ greater than 0.80). The annual ring width will be explained with an $R^2$ between 0.66 –0.76 for the test set; the lower explanation is for spruce.

The most difficult aspect to model is the knot diameter. In this case, $R^2 = 0.70$ for the training set and 0.66 for the test set. Björklund and Petterson (1998) have developed a model for the mean diameter of the thickest knot in each whorl in the constant-growth section of the stem. Their model explained 63% of the variations. The model was based on the annual ring width for annual ring 11 to annual ring 20 and the latitude where the tree had grown.

The models for Norway spruce are generally weaker than the models for Scots pine. The differences in $R^2$ values for the training set and the test set are greater for Norway spruce. This indicates that there is more noise in the LogScanner signals for Norway spruce than for Scots pine. One explanation of this behaviour is that the small knots between the whorls in Norway spruce disturb the extraction of the secondary variables from the LogScanner signals. Another explanation can be that most of the image analysis algorithms were originally developed for Scots pine and in a second step adapted to Norway spruce. So the algorithms might still be more efficient and better adapted to Scots pine than to Norway spruce.

The study described in Paper VIII showed that the simulated X-ray LogScanner measured the percentage of heartwood and the green heartwood density with high accuracy ($R^2$=0.94 and $R^2$=0.73, respectively). These and other variables measured by the simulated X-ray LogScanner were used to predict the average bending stiffness of the centreboards and to sort the logs according to the predicted module of elasticity, MOE. When sorting out 50% of the logs ("high-strength" logs) the percentage of C30 boards increased from 73% (all logs in the study) to 100% (only "high-strength" logs). The rest of the logs could then be divided into two groups, one of them with 100% boards that had a strength of at least C24.

In Paper IX, the LogScanner was used to control the sawing position by measuring the amount of knots in the logs in different rotational directions. The half of the logs that was supposed to be the better half gave equal or higher quality for 95% of the logs. The amount of high-quality boards (Grade 1) increased by 11% when the sawing position was controlled by the X-ray LogScanner compared with a random position. However, the amount of low quality boards (Grade 3) also increased.

These results show that in order to benefit from knowledge of the tangential knot distribution in the log, information about knot sizes and grading rules has to be included in the algorithm.

# 5 Conclusion and future work

The most important conclusions of this thesis were that:

- X-ray is a suitable technique for nondestructive measurement of internal features in green sawlogs.
- CT scanning is a powerful research tool for measurement and visualisation of different log properties.
- Parameterisation is an efficient method for reduction of the amount of data from a CT scanner.
- It is very efficient to use data from a "Stem Bank database" based on CT scanning for simulation, analysis and development of the sawing process and different measurement technologies.
- An X-ray LogScanner with two X-ray sources can measure log features such as diameter under bark, species, log type, knot structure, rotational position of knots, density, heart-wood content, annual ring width and can predict strength and grade of the sawn boards.

It is very important to point out that all results and conclusions regarding the performance of the X-ray LogScanner in this thesis are purely based on simulations. The next steps will therefore be to validate the simulated results against results from real measurements with an X-ray LogScanner in a sawmill environment, correct for systematic errors and gradually improve its performance.

Another very important task for the future is to instruct and teach the users how to use the new equipment in order to get a proper result and utilize all possibilities that the X-ray LogScanner can provide. The virtual SawMill, vSM, will be a very important tool in this work. For instance, the vSM can be used for finding the most suitable logs for specific customer requirements for the sawn timber. This is very important as it is expected that in the future, the selection of sawn timber for a specific customer will be more and more based on the customer's demands, i.e. on a specific feature or some specific features. In order to improve the connections between the X-ray LogScanner, the vSm and the market demands on the sawn timber, the methods for creation of parametric log descriptions, as described in paper XI, have to be enhanced considerably.

There many important and interesting log features that not have been described, modelled or analyzed in this thesis. It is also quite certain that all algorithms that have been presented in this thesis can be further improved even if the scanner probably never will give one hundred percent correct predictions. However, the possibilities it opens up compared with the standard way logs are measured today are dramatic. It is important to concentrate on the scope of economic benefits this entails.

In summary, the work presented in this thesis has shown that an X-ray LogScanner with two X-ray sources has a great potential to become a powerful tool for controlling the sawmill process. However, a lot of work remains to be done before the full potential of the scanner can be utilized.

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