X-RAY CT-SCANNING RESEARCH IN THE UNITED STATES FOR IMPROVED HARDWOOD PROCESSING

JUN-LI YANG

1996 GOTTSTEIN FELLOWSHIP REPORT

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Bill Gottstein was an outstanding forest products research scientist working with the Division of Forest Products of the Commonwealth Scientific Industrial Research Organization (CSIRO) when tragically he was killed in 1971 photographing a tree-felling operation in New Guinea. He was held in such high esteem by the industry that he had assisted for many years that substantial financial support to establish an Educational Trust Fund to perpetuate his name was promptly forthcoming.

The Trust's major forms of activity are,

1. Fellowships - each year applications are invited from eligible candidates to submit a study programme in an area considered to be of benefit to the Australian forestry and forest industries. Study tours undertaken by Fellows have usually been to overseas countries but several have been within Australia. Fellows are obliged to submit reports on completion of their programme. These are then distributed to industry if appropriate.

2. Seminars - the information gained by Fellows is often best disseminated by seminars as well as through the written reports.

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The Secretary,
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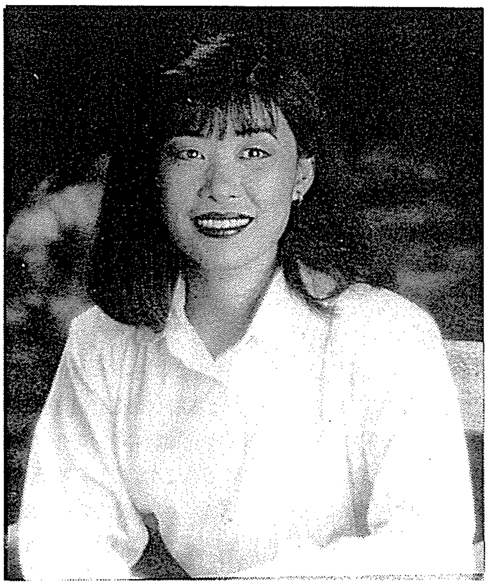
About the Author



Dr. Jun-Li Yang is a research scientist with CSIRO Forestry and Forest Products. She is an integral member of a multi-disciplinary research group in the Wood Processing and Products Program. Dr. Yang's research has covered a broad range, namely timber resource evaluation, relationships between wood properties and drying and strength characteristics of timber, growth stresses and the associated log defects such as brittleheart and log end splitting. Her current interests include improved log grading based on both external and internal log information, log quality assessment, and optimal hardwood utilisation. She gained her PhD in Wood Science from University of Melbourne in 1991 for her thesis "The Occurrence of Brittleheart in *Eucalyptus regnans* and its Effect on Various Wood Properties", and B.Sc in Forest Products from Beijing Forestry University of China in 1983.

The purpose of Dr. Yang's Gottstein Fellowship was to learn about the X-ray CT log scanning research in the USA. The focus was on approaches and accomplishments of American researchers in utilising internal log information to improve hardwood log processing.

Dr. Yang's contact details are:

Jun-Li Yang
CSIRO Forestry and Forest Products
Private Bag 10
Clayton South MDC
Victoria 3169
AUSTRALIA

Tel: 61-3-9542 2124 (w)
Fax: 61-3-9542-2133 (w)
email: Junli.Yang@ffp.csiro.au

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I would also like to thank Mr. Gary Waugh and Mr. John Sutherland of CSIRO Forestry and Forest Products, Mr. William G. Keating of the Joseph William Gottstein Memorial Trust Fund, Dr. John Davis and Dr. Imants Svalbe of Monash University for their encouragement and trust, and their helpful discussions with me prior to my departure and after my return.

I hope the knowledge I gained from this trip will be found beneficial by the Australian hardwood timber industry. The trip itself has no doubt broadened my own career perspective.

Preface

The future world demand for wood will increase in the long term as a result of shortage of logs and an increasing demand for wood materials. At the same time, the forest products industry is facing a changing resource, characterised by an increasing proportion of smaller and fast-grown trees, and increasing competition from the non-wood product industries.

The Australian hardwood timber industry has been under increasing pressure to reduce its use of native eucalypt forests; it is in strong competition with the softwood industry in the structural product market.

The future of the hardwood timber industry depends on not only the supply of hardwood logs with required quality, but also "Making More From Less" - recover more or higher value products from decreasing and lower quality resources. The later can be achieved through optimising utilisation of sawlog resources, improving value yield of saw logs, and optimising usage of the products.

Optimal log utilisation encompasses a series of concepts such as optimal log allocation (sending logs to the mills they are ideal for) and optimal log processing (maximising log value yield by means of optimal methods). In practice, each concept can be implemented independently from other concepts. However, mills are likely to make most profit if all concepts are integrated.

As a crucial step towards realisation of the above concept(s), accurate external and internal log information must be obtained prior to processing by using appropriate log scanners; this information must then be processed to generate various log handling and processing options by using decision-making computer software.

Investigation of the potential and feasibility of applying X-ray CT-scanning technology to the forest products industry has had a 15-year or so history. It covers two distinct areas: hardware development (building internal log scanners) and software development (writing computer software to process data and generate log processing solutions). Research has been taken on by various groups to varying scales targeting different problems. Currently there are two groups in the USA working directly in this area. The Australian effort in developing an X-ray CT-scanning technology for the veneer and timber industry, the Glass Log Project, is comparatively more recent. Its primary goal is to build a prototype X-ray CT-scanner for logs. This effort has attracted a vast amount of attention and positive response from the local industries.

The author's research interest has been hardwood log grading, log quality assessment, and optimal hardwood utilisation, in particular the decision-making software operating on internal log data generated by X-ray CT-scanning methods. She was involved with the Glass Log Project during 1995. The Gottstein Fellowship and additional financial support from the Glass Log Project and CSIRO Forestry and Forest Products enabled the author to visit a number of researchers in the USA during 1996. The trip focused on internal log scanning research for improved hardwood processing. This report documents her findings. It also contains recommendations for future research with reference to Australian circumstances.

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1 Introduction

A Glimpse of the Overall Picture

The future world demand for wood will increase in the long term as a result of:

Shortage of logs	Continuing pressure from the conservation movement to reduce the amount of forest resource available to the forest products industry. A limitation on the amount of sustainable land available for plantations in the future.
Increasing demand for wood materials	Rising population (the current world population is over 5 billion and this is doubling every 50 years. The per capita consumption of wood remains constant at about 0.7 m^3 per annum). Higher incomes in many parts of the world therefore more consuming power.

At the same time, the forest products industry is facing a changing resource, characterised by an increasing proportion of smaller and fast-grown trees, and increasing competition from the non-wood product industries.

To cope with this situation, one approach the forest products industry can take is to optimise the utilisation of log resources and the usage of the products produced. The Australian hardwood sawmilling industry has recognised that value-adding is the path leading to its survival and success in the long term. The hardwood industry has been under increasing pressure to reduce its use of the native eucalypt forests; it is in strong competition with the softwood industry in the structural product market.

Optimal utilisation of log resources involves two aspects.

(1) Improved log grading and optimal log allocation - logs are accurately assessed for their optimal end use and correctly allocated to the right mills to assure their best end use. This approach appears to be particularly needed by hardwood mills that do not have integrated log processing;

(2) Optimal log processing.

As a key step to improved log grading, optimal log allocation and optimal log processing, both external and internal information of logs must be identified and quantified with an efficiency acceptable to the industry. This information must then be processed to generate various log handling and processing options by using decision-making computer software.

Currently, mills have neither log scanners to obtain internal log information (eg. internal defects and wood grain pattern), nor decision-making software to make full use of this information even if it was available.

The R&D discipline is completely different between internal log scanners and decision-making computer software. The success in each field is equally important. Neither has more meaning for its ultimate existence without the existence of the other. Decision-making software needs log scanners to supply internal log information to operate on. A scanning system needs decision-making software to make use of the data that it generates.

Both hardwood and softwood mills need internal log information in order to maximise their product value yield. However, this need is probably more pressing and certainly more practicable for the hardwood industry.

Benefits Internal Log Information May Bring to the Industry

Solid wood

Accurate log grading	Current hardwood log grading in Australia, like in many other parts of the world, is based on visual assessment of log dimension, log form, and the type, size and distribution of various defects which are visible on the log surface. Visual grading has two problems. Firstly, external defects are not always a reliable indicator of internal defects, especially in larger logs. Thus it is impossible for even highly experienced log graders to make correct judgements on internal defects on every occasion. This problem is inevitable as long as visual grading continues to be practised. The second problem is associated with human performance such as lack of experience, subjectivity in making a judgement, insufficient care, and an urge to grade as many logs per unit time as possible. Both problems result in an unnecessary loss of raw material and productivity because the logs are processed in a way which does not match the raw material. An industrial log scanning technology, for instance based on X-ray CT-scanning methodology, will provide the internal log information needed for accurate log grading as well as consistent grading performance so that these two problems can be effectively solved.

To supply mills with logs correctly graded according to the existing log grading rules is one issue; to develop appropriate log grading rules or segregation criteria is a second issue. To supply the mills with logs that satisfy their demands is yet a third issue. These three issues should not be confused with one another. The availability of internal log information will enable only the first two issues to be addressed.

Optimal log allocation

With external and internal log information, log owners can determine by using various computer programs the optimal usage or the best potential of each log. Log owners will have a far better idea of what logs they have and how much they are worth. Logs can be sent to where their value can be best recovered. In addition, mills will have an opportunity to purchase logs which suit their equipment and product requirement.

Suggest cutting strategy for primary sawlog conversion

The cost of hardwood raw material accounts for 30 - 40% of the price of the green sawn boards (pers. comm. G. Waugh). Improving both grade and volume recovery by using improved technology therefore has significant implications for mill profit. Knowledge of the presence, type, and size of internal defects in logs, followed by optimal log conversion based on this knowledge, will enable sawmills to effectively minimise the down-grading effect of internal defects on timber grade yield and to improve value yield (Adkins et al., 1980; Chang and Guddanti, 1993; Harless et al., 1991; Peter and Bamping, 1962; Pnevmaticos et al., 1974; Pnevmaticos and Mouland, 1978; Richards, 1977; Richards et al. 1979, 1980; Steele et al., 1994; Tsolakides, 1969; Wagner and Taylor, 1975).

For example, Harless et al. (1991) found by computer live sawing a southern red oak log that the lumber value increase at the best log orientation was 10.8% higher than the average lumber value at all orientations (the log was sawn at every 15^0 rotation), and that the value improvement was largely attributed to better grade yield rather than better volume yield. Steele et al. (1994) found by simulated sawing that optimum sawing orientation of 24 red oak logs gave about 10.1% increase in sawn board value for both live and grade sawing over sawyer sawing, and that a higher value increase from optimum sawing orientation was achieved with better grade logs, although the difference was not statistically significant due to a large variance between the value yields at each orientation. Chang and Guddanti (pers. comm.) found a

	50% increase in sawn board value between the worst and the best sawing orientation of the same hardwood log. The average increase in value yield of their hardwood study logs was 12-15%., but it was the mid-quality logs that benefited most from optimal sawing orientation. With external and internal log information (such as knots and decay), the sawyer can decide with the assistance of various computer programs how to orientate each log, what sequence to follow to convert each log, and what size of boards to cut from each log in order to meet the requirement of the mills in producing various products. (The mills will have the choice of either simply maximising the value return of their logs, or finding an economically sensible combination of product grades and dimension in conjunction with an economically sensible conversion process). Internal log information can be generated either before logs are delivered, or at the mills.
Detect internal checks during and after drying	Some eucalypt species are prone to internal collapse checking during drying. Softwood timber, eg. Australian-grown radiata pine, is not immune to the development of internal drying checks depending on the circumstances. A scanner which is able to detect the presence of internal checks will be a very useful research and monitoring tool to help us understand and control the development of internal checks during drying.
Detect wetwood in logs or unseasoned boards	Wetwood is relatively common in Australian hoop pine. It dries much more slowly than normal wood. As a result, patches of wet zones appear in dried boards. One approach to handle the wetwood problem is to identify its location either in logs or in sawn boards and to segregate it from the normal wood. Higher moisture content of wetwood, hence higher green density, makes the identification of wetwood relatively easy when using such method as X-ray CT-scanning.

Sliced-veneer

Log selection	With external and internal log information, mills can use computer programs to assess the grade, quantity, and size of sliced veneer that each log can produce. The mills can then use this data together with information on the raw material cost and the production cost to determine the profitability of slicing each log. Hence an economic criterion (threshold) can be established to select logs

	profitable for veneer slicing. Actual profit for each veneer log can also be determined. The mills can then be confident that the logs sliced will yield a profit and not a loss. They will also have a clear indication of how much profit each veneer log will produce.
Optimal flitch preparation and appropriate slicing method	Knowing the types of defects, their size and distribution, and the size of logs, the mills can evaluate and decide flitching options and slicing methods by using computer programs, and at the same time relegate unsuitable flitch segments to sawmilling.
Control of grain pattern	The internal log data such as those generated by the X-ray CT-scanning method contains information on growth rings and thus can be used to reveal wood grain patterns in any specified plane within a log. This aspect of internal log information enables the mills to determine how to orientate a flitch and what method to use to slice this flitch in order to generate the wood grain pattern which is more valued or demanded by the market (Schmoldt et al., 1995).

Plantation management

Monitoring the incidence of decay	More and more eucalypt plantations will be established in Australia for sawlog production. In order to produce a higher proportion or a wider band of clearwood and to minimise the size of the knotty core in tree stems, mechanical pruning is required at an early stage of tree growth. This is especially the case for species which do not self-prune well such as *Eucalyptus nitens*. The branch stubs and pruning wounds are easy invasion points for fungi. Concern has been expressed by Tasmanian foresters of the possible close association between increased incidence of decay in tree stems and mechanical pruning. Non-destructively obtained information on decay in living trees will help foresters to assess and modify their forest management scheme, and consequently to produce sawlogs with a quality the trees are managed to provide. A portable X-ray CT-scanner is already available in Australia for non-destructive detection of decay and termite infestation in electricity power poles and standing trees (Davis et al., 1995).

Brief Overview of Internal Log Scanning Research

Several scanning methods initially developed for other fields such as medical diagnostics can be adapted to nondestructively detect log internal defects. Since the early 1980's, forest products researchers have been studying, and investigating the potential and industrial feasibility of these methods (Benson-Cooper et al., 1982; Birkeland and Holoyen, 1987; Chang, 1989, 1992; Chang and Guddanti, 1993, 1995; Chang et al., 1989; Davis, 1986; Davis et al., 1993, 1995; Funt and Bryant, 1987; Guddanti and Chang, 1995; Han and Birkeland, 1992; Hodges et al., 1990; Li et al., 1996; Schad et al., 1996; Schmoldt et al., 1993,1996b; Som et al., 1992, 1993; Svalbe et al., 1995; Taylor et al., 1984; Wagner et al., 1989a, 1989b; Wang and Chang, 1986; Wells et al., 1991; Zhu et al. 1991, 1996). The research covers two distinct areas: hardware development (building internal log scanners) and software development (writing computer software to process data and generate log processing solutions). Various groups have taken on the research to varying scales targeting different problems. The quality of the raw data generated depends on the method, the equipment itself, the wood species, and the size of the logs, etc.

Relatively fast progress has been made in determining external geometry of logs and the technology is now commonly used in softwood timber industry. However, due to more technical difficulties, it will take a longer time to achieve satisfactory and practical methods to quantify internal defects in both logs and sawn boards. Until now, no industrial technology for detecting individual internal defects in logs is commercially available. The eventual commercialisation of such a technology will depend on its technical performance and the amount of profit mills can gain from using it.

Of these methods, the X-ray CT-scanning is probably the best in terms of resolution and contrast required in feature recognition. It is also probably the most practicable. The potential of X-ray CT-scanning in detecting internal log defects was recognised in the early 1980's. Currently in the USA, there are two research groups active in X-ray CT-scanning research for hardwood logs. They are the Advanced Sawing Technology Laboratory, School of Forestry, Wildlife and Fisheries of Louisiana State University, and the *Primary Hardwood Processing and Products Research Unit*, the Southern Research Station of USDA Forest Service at Blacksburg in the State of Virginia.

The Australian interest in log X-ray scanning evolved from a collaborative project between the Faculty of Technology of Chisholm Institute of Technology[1] and CSIRO Division of Chemical and Wood Technology[2] in 1985, which led to the construction of a direct X-ray scanning densitometer for acquiring microdensity of wood.

In 1986-87, as a 1986 Gottstein Fellow, John Davis of the Faculty of Technology of Chisholm Institute of Technology took an overseas study of the progress being made in industrial computerised tomography (CT) to ascertain the significance of this technology for the timber industry and with a special interest in the application potential for the forest product industries in Australia (Davis, 1986). This study tour involved visits to various government, universities and private organisations in Japan, the U.K., Federal Republic of Germany, Sweden, Canada, the USA, and New Zealand. The focus of Davis' visit was scanning methods and equipment, and the R&D status of the overseas groups in this aspect. In his report, Davis noted the considerable interest and progress in the non-

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[1] Now merged with the Department of Physics of Monash University, Australia.

[2] Now CSIRO Forestry and Forest Products.

invasive X-ray log scanning at that time in Scandinavia and North America. He strongly recommended X-ray CT log scanning to be undertaken in Australia.

In 1993, Davis (1993) initiated The Glass Log Project. The project officially started in 1994 with financial support from the Commonwealth Government and the participating Australian companies associated with the timber industry. The objective of the project is to build a prototype pilot plant, which is a combination of X-ray CT-scanning equipment, image processing techniques, computer hardware and software, and a log handling system. The ultimate aim of the project is to help the timber and the sliced-veneer industry to improve log grading, log merchandising, and subsequent log conversion by providing meaningful log internal information to the industry at a satisfactory speed.

The research is headed by the Department of Physics of Monash University, and involved CSIRO Forestry and Forest Products and CSIRO Division of Information Technology. Timco Technologies Pty Ltd was formed as the representative of the participating industry companies. Its purpose is to provide the research team with a strong industry-driven focus and to foster the R&D results at the earliest possible time when opportunities arise. Log scanning has been focused mainly on commercially important eucalypt timber species such as *Eucalyptus marginata* and *E. regnans*. Most of the research so far has been directed towards defect detection and the engineering design of an industrial X-ray CT log scanning system. The Australian effort (Davis et al., 1993, 1995; Som et al., 1992, 1993; Svalbe et al., 1995; Wells et al., 1991) has attracted a vast amount of attention and positive response from the local industries. It has also become well-known overseas.

What is in This Report

As mentioned earlier, internal log scanning covers two areas: developing a hardware system to obtain internal log information, and developing decision-making software based on internal log information to assist log processing. The latter stage addresses a question that is constantly asked: what do we do with log internal information or how should we use this information to help the veneer and sawn timber industry?

The author's main interest lies in the second area. In this regard, the author's visit was not simply a follow-up or an extension of the 1986 Davis' trip. Rather, the intention of her visit was to learn about utilisation of log internal information in optimal log processing, approaches taken by the American researchers and their progress in this field, economical impact of CT-scanning technology on the timber industry, hardwood log grading based on both external and internal log information, etc.

This introduction is followed by two chapters. Chapter 2 is a brief overview of the hardwood forest resources and the hardwood industry in the USA. Chapter 3 provides information on the latest research activities and progress associated with X-ray CT log scanning and hardwood log processing undertaken by the research groups the author visited. Investigation of world-wide research in non-invasive detection of internal defects in both logs and sawn boards has not been intended by the author, therefore similar international research accomplishments by others is seldom cited in this report. Chapter 3 is followed by a summary, some of the author's thoughts, and recommendations.

2

Hardwood Resources and Hardwood Sawmilling Industry in the USA

Hardwood Forest Resources

There are approximately 737 million acres of forests in the United States, accounting for about 33% of the USA land area. Of the total forests, 490 million acres (198 million hectares) are classified as timberland. Timberland are forests capable of growing 20 cubic feet (0.57 m^3) of industrial wood per acre per year and not reserved from timber harvest; 70% of it is located in the Eastern US (Powell et al. 1992). Of the total timberland, 454 million acres (184 million hectares) are allowed for commercial harvest, while the remaining 36 million acres (14 million hectares) are set aside as wilderness areas, parks, and other classifications (pers. comm. Taylor[1]). Some timberland contains only hardwood and some only softwoods. However much of the timberland contains mixed species (pers. comm. Taylor).

Currently hardwood forests make up 43% of the growing stock (Powell et al. 1992). By deduction, 43% of the 454 million acres of commercial timberland are commercial hardwood forests, which equal 195 million acres (79 million hectares).

Some of the above information is summarised in Figure 1.

Ninety percent of hardwood forests are grown in the Eastern regions. The quantity and quality of the hardwood resource continue to improve because hardwood growth greatly exceeds harvest (Powell et al. 1992). Another source (Wengert) quoted that about 800 billion BF (1888 million m^3) hardwood forest resources in the East and West have diameters of 11 in and above at breast height, and this inventory is increasing at 2.3% per annum. Hardwood forests are almost all naturally regenerated because natural-look hardwood forests are preferred and the forests naturally regenerate well themselves. There are very few hardwood plantations in the USA (pers. comm. Wengert).

Of the commercial timberland, 28% is owned by the public, 57% is in non-industrial private ownership, and the remaining 15% is owned by forest industry (Pitcher, 1992). Most of the forests in the Southern states are privately owned; forests in the West are largely government owned (pers. comm. Taylor).

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[1] Full names of the people quoted in this report are found in the Itinerary at the end of this report.

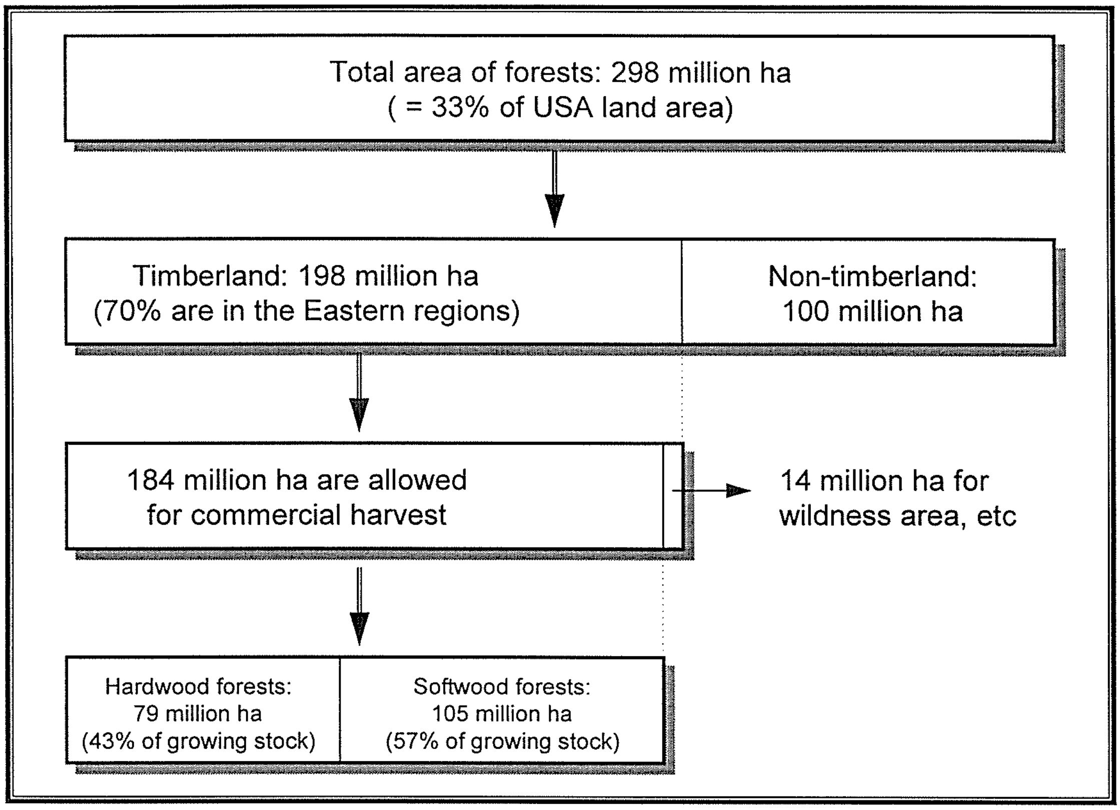


Figure 1. Forest stock of the USA.

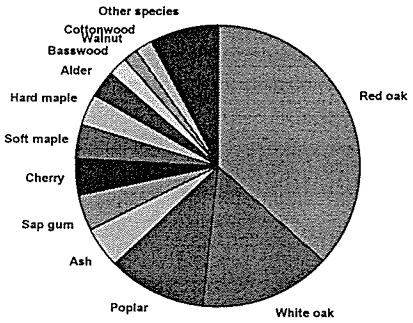
Approximately 70% of the hardwood forest resources are privately owned, accounting for 67% of the volume of hardwood harvest (Powell et al. 1992). Because of this, log harvesting and log merchandising are more or less a matter determined by private owners. They decide when, where, and how much to harvest their forests. There is some level of clear felling in the South, whilst selective harvesting is practiced in North-east to provide required shade to new seedlings (pers. comm. Wengert).

The proportion of hardwood to softwood volume removals has remained approximately stable for a number of years, being 33% to 67%. Sawlogs accounted for approximately 40% of the wood volume harvested, the highest in comparison to other categories (Powell et al. 1992).

The common hardwood species for timber production in the USA are, in order of the share of sawn timber production: red oak, white oak, poplar, ash, sap gum, cherry, soft maple, hard maple, alder, basswood, walnut, cottonwood, hackberry, hickory, pecan, birch, beech, tupelo, and elm.

Red oak is the most important single hardwood species in the USA followed by white oak (Figure 2). Oak groups contribute more than half of the hardwood timber produced in the USA, with red oak accounting for about 36% on average (Pitcher, 1992). Some mills' log supply comprises 60% red oak. Commercial red oak comprises 10 or more species, which are not usually differentiated on the market; white oak comprises 9 or more species (Rendle, 1969). Oak trees vary in size according to species and locality, and so does the wood quality. For commercial red oak trees, the average large end diameter is 16 in -18 in (41-47 cm) for butt logs, usually 6 in (15 cm) for top logs, and the useable sawlog trunk length is about 40 ft (pers. comm. Wengert).

Hardwood Review Estimates of the Total Production of North American Hardwood Lumber...



	Production (%)	Production in Thousand Board Feet
Red oak	36.6	4,796
White oak	15.1	1,979
Poplar	11.2	1,467
Ash	4.6	604
Sap gum	4.3	566
Cherry	3.9	512
Soft maple	3.9	506
Hard maple	3.8	494
Alder	2.9	381
Basswood	2.2	286
Walnut	1.9	246
Cottonwood	1.7	228
Hackberry	1.3	169
Hickory	1.2	157
Pecan	1.0	124
Birch	0.7	89
Beech	0.4	58
Tupelo	0.3	42
Elm	0.0	4
Other species	3.0	393
	100.0	13,100,000

...And Where It Is Used.

Market Breakdown	MMBF Consumed 1994	1995 Estimates
Furniture	3.02	3.14
Cabinets	0.52	0.50
Millwork/Moulding	0.76	0.78
Roofing	0.46	0.44
Pallets/Crating	4.70	4.70
Thru Distribution Yards	1.30	1.30
Railroads	0.70	0.70
Exports	1.00	1.05
Other	0.65	0.65
Totals	13.10	13.27

Hardwood Review Weekly
1994 Yearbook
published in 1995

Figure 2. Hardwood sawn timber production in the USA (reproduced with permission from Hardwood Review Weekly).

Cherry and walnut are the highest priced hardwood species in the USA. The State of Missouri is the largest producer of walnut in the USA. Walnut appears to have useable corewood, and the logs can be sawn all the way to the pith. Walnut shares some similar appearance with Australian sassafras, having dark coloured inner zone and pale outer zone.

Oak and cherry forests are somewhat shade tolerant. New seedlings can regenerate under the canopy of larger trees. Younger, smaller trees can move from understorey to mid, and eventually, upper canopy when released by disturbance or overstorey mortality. This release must occur earlier than more shade-tolerant species, such as maples, else the smaller oak and cherry trees will succumb to competition. Because of this natural regeneration, oak and cherry forests are not even-aged (pers. comm. Schmoldt).

Because many private hardwood forest owners have chosen to manage their forests not for timber production, but for purposes such as recreation, scenery, and hunting, many trees grow as old as their natural life takes. As a result, both the total volume of hardwood forests and the hardwood tree diameter have been increasing. On the other hand, the amount of hardwood forest resources available for logging and the average diameter of hardwood trees logged have been decreasing! The timber industry is now paying more money for smaller logs (pers. comm. Wengert).

In many rural states, particularly the Southern and central states, commercial forests often represent the number one cash crop in terms of value at the point of delivery. Sawmilling generates many jobs for the local areas. Subsequent distribution of lumber and secondary manufacturing create additional jobs. A richly diverse renewable forest resource has enabled the United States to command an enviable position in international trade.

Hardwood Log Merchandising

Rotation age for hardwood species vary widely, from 30-35 years for cottonwood to 80-100 years for most of the temperate hardwoods. Red oak are typically harvested around 60-80 years of age (pers. comm. Chang).

The average length of the useable trunk of hardwood trees is 2 to 4 times 16 ft (pers. comm. McDonald). The standard lengths of hardwood logs are 8, 10, 12, 14, and 16 ft, and tree trunks are cut to the lengths selected from these to maximise the value from the trees. Whilst it is a customary to cut hardwood logs into 16 ft, one common length is 8 ft and the reasons are[2]: (1) Many hardwood sawmills were traditionally set up to handle only short length logs. It costs to change equipment therefore mills have continued to process short logs; (2) Logs are laid crosswise because of the historic familiarity with hauling pulpwood logs in that manner (pers. comm. Wengert).

When making a deal with forest/log owners[3], the log buyers (they do not have to be sawmills or other mills) either send a forester to the forests to assess the value of the trees before harvesting, or make an assessment on the value of logs at the time when the logs are delivered to the mill. Cash is usually paid on the spot with little delay if mills decide to purchase the logs delivered to them (pers. comm. Wengert).

According to Missouri Pacific Lumbers Pty Ltd[4], logs are graded according to the Doyle Scale[5], which lists a relationship between log small end diameter and timber yield. Mills do not pay for the volume of logs, but the volume of timber they are expected to extract out of the logs. If a mill processes logs well, it gets more timber out of their logs than the amount the logs are sold for (for example, the actual recovery is 45% whilst the mill pay for the logs under an assumption of a 42% recovery rate according to the Doyle Scale). In this case, some of the mill's timber bears no cost of raw material.

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[2] This information refers to Wisconsin, and may vary in other states.

[3] This log selling practice refers to Wisconsin, and may vary in other states.

[4] A sawmill about 40 minutes drive from Columbia of Missouri, producing 3 million BF sawn timber per annum. Most of its sawlogs are walnut.

[5] The Doyle Scale is a log scale estimating the board footage of hardwood logs. It underestimates the volume of small logs (< 8 in) by probably as much as half of the actual volume, but is proportionally better as the log size increases to about 18 in. The reason for this trend is that it costs more to handle smaller logs, so one needs to have a system that will reflect the lower net cost to be paid for small logs (pers. comm. with Wengert).

Hardwood log grading rules (Hanks et al. 1980; Vaughan et al. 1966) have rarely been used by industry. The rules themselves are workable but complicated, and there has been a lack of training for using these rules (pers. comm. Briggs and McDonald). Hardwood log grading training workshops occasionally are run, but there has never been a requirement or reinforcement for people to obtain grading certificates. Whilst hardwood sawn timber, plywood, and other engineered products are all graded by certified graders, no certificates are required in grading hardwood logs (pers. comm. Briggs). Another explanation on why the industry hardly uses log grading rules is that log grade itself is not a factor in providing logs to the mills (pers. comm. Wengert). Forest owners, either government or private, usually sell their logs by volume. It is up to log buyers to decide whether to buy the logs and how much to pay for them. Log buyers may later sell these logs to the next buyer. The industry does grade and segregate logs in their own way, a kind of short cut in comparison to the log grading rules, prior to processing logs. Log grading research was discontinued in late 1970's as the grading rules were hardly used by the industry. Research on X-ray CT log scanning started around that time; the log grading researchers thought that scanning methods would replace visual log grading (pers. comm. McDonald).

Most hardwood species have about 20 m useable trunk. Workers who cross-cut tree stems in the field are probably doing one of the most important jobs - making decisions for sawmills. The workers know how to fell trees and how to cross-cut tree stem. However, they have not been trained to understand how log bucking affects lumber grade or log value yield therefore do not have good knowledge of where to cross-cut. Their job is basically to cut tree stems into some standard log length. On a few occasions, hardwood tree stems are kept in full length if the truck is able to transport these full length stems, or the stems might be halved if they are too long, then transported to sawmills; then an experienced worker at the sawmills will buck these stems or semi-stems (pers. comm. Briggs).

Log grading and merchandising can be influenced to a large extent by species. For instance, walnut and cherry are so valuable that they are sold in a different manner: the straight and large walnut and cherry logs are sold by auction while the smaller logs are sold to veneer log buyers on an individual basis. Quite often there are a few bidders at the site to bid for either the trees or the logs. For these premium species, the hardwood log grading system may never apply, as the trees are so much sought after therefore are treated differently from the rest of the hardwood species. Another example is that red alder, which grows in the West coast, self prune at quite an early age; these trees have nice clean bole and small knots. Thus log grading in Washington for this species is more or less solely dependent on log diameter. But if the trees grow in the open with quite a space between them, they tend to have crooked bole when growing tall. As a result, only the butt log (about 3 m in length) is useable as sawlogs, and the rest of the bole goes for pulping. Nevertheless, there is some advantage to have one set of log grading rules for all the hardwood species. It establishes a clear understanding between buyers and sellers, and minimises confusion, when everyone uses the same set of rules. With respect to some individual species, the buyers and sellers may make some small refinement to the grading between themselves (pers. comm. Briggs).

Grading forest stands for timber was attempted in the early days (Hanks, 1976). The tree grading system grades the bottom 16 ft stem identical to the hardwood log grading system (Vaughan et al. 1966). The USDA Forest Service has been using the existing tree grading system in their inventory work for the forest resources of each state; however, there are rarely other users of this grading system (pers. comm. Briggs). The grading result is quite variable because little consideration has been given to anything above 16 ft (pers. comm.

Wengert) and also because grading trees cannot be more accurate than grading logs (pers. comm. Steele). Although further work on tree grading is needed, governments are not willing to spend money to support this research. There has been no one working on tree grading since Hanks retired. On the other hand, there was some doubt concerning the workability of the tree grading system developed by Hanks (1976). Briggs considers that (pers. comm.) it is important to know the history of tree growth, silvicultural management, and the site conditions in order to gain some insight into tree quality, and consequently to assess the value of trees (grading trees). There has been some level of interest in grading trees in New Zealand for some time.

The Hardwood Sawmilling Industry

The hardwood industry in the USA is highly diverse, in terms of raw material requirements and products produced (pallets, sawn board, furniture, flooring, dimension, veneer, plywood, etc).

There are about 4,500 -5,000 hardwood sawmills in the USA. Most of the hardwood sawmills are distributed in the Eastern states because of the location of hardwood forests. Most hardwood sawmills are small in comparison to the softwood mills. Weyerhaeuser is a rare example of having large hardwood sawn timber production. Most hardwood mills produce below 10 million BF (23,600 m^3) of sawn timber products per annum, and mills producing more than 20 million BF (47,200 m^3) per annum are rare (pers. comm. Steele). Some extremely small mills carry portable operations producing a few thousand board feet a day (Powell et al. 1992). About 1,500 hardwood sawmills are considered to have a serious operation in terms of running a business. Only about 20-25 individual hardwood sawmills have output larger than 10 million BF (23,600 m^3). Roy O. Martin Lumber Company is the most advanced hardwood sawmill in the USA (pers. comm. Chang). About 11 billion BF (26 million m^3) of hardwood sawn timber are produced annually in the USA (pers. comm. Wengert). In Australia, 80% of hardwood sawmills process less than 10,000 m3 logs. If conversion rate is 40%, the annual output of most Australian sawmills is 4,000 m3, equivalent to 1,7 million BF. This scale of operation is less than half of the size of the smallest hardwood mills in the USA (producing 4 million BF per annum).

Many hardwood sawmills are passed down from generation to generation within the same family. The mill managers have a modest level of education (eg. high school). The mills are run in the old traditional manner, and reluctant to some degree to make relatively large capital investments to improve their operational efficiency and product yields (pers. comm. Wengert). From this aspect, the hardwood sawmilling industry in general is characterised as being conservative and slow to change. The reasons for this are: there is a relatively abundant raw material widely available at low prices, there is a lack of competition for alternate uses of this resource, many sawmill owners/operators have a conservative nature (Pitcher, 1992), and the small size of hardwood mills makes it difficult to invest and pick up high technology. As the hardwood mills are falling more and more behind high technology, it is too far ahead for them to think of and to implement such ideas as optimal log allocation and optimal log processing. For most of the small hardwood mills, the next step to take is to install drying kilns to increase profitability while still keeping the existing sawing equipment (pers. comm. Wengert), or to install thin kerf bandsaw for resawing (pers. comm. Steele). The situation of hardwood mills in USA is so similar to that in Australia!!

Hardwood log conversion rate is 45-55% at circular sawmills, and can reach 60% at band sawmills. The saw dust takes about 8% (band saw) to 12% (circular saw) of log volume, and slabs take up about 25% of log volume. The highest conversion rate may reach 70% when using band saw, and saw 1 in thick boards (pers. comm. Wengert).

Sawmills aim to cut large size boards out of logs during sawing. Heavy wanes are removed and some edging and trimming follow. The boards are cut to thickness varying in quarter-inch increments (e.g. 5/4 inch and 7/4 inch), but tend to be 1 in thick at least. The width is random and length varies in 1 ft increment. According to the NHLA rules, the grade of a hardwood board is determined by the size of the board, the quality (clear face or sound), number, size, and proportion of cuttings that can be cut from the board (Smith, 1989). Some sawmills also saw dimension, which refers to furniture and cabinet parts. In many occasions, dimension mills are separate from hardwood sawmills. Sawmills may sell their sawn boards green, or dry their boards and sell the dried boards to dimension mills. Some dimension mills have their own kilns, which enable them to buy green boards from sawmills (pers. comm. Schmoldt).

Professor B. Richards of University of Kentucky found, by computer-sawing hypothetical hardwood logs, that live sawing generally equals or exceeds other sawing methods (similar or close to grade sawing) in value yield on an average (Richards, 1977). Chang had worked with Richards on hardwood sawing and agrees with Richards' results. However, nearly 20 years have past, and the hardwood industry in the USA still uses grading sawing most of the time (pers. comm. Chang). Chang believes that live sawing is definitely better for some hardwood logs, whilst grade sawing is definitely better for other hardwood logs. The clear cut, which might be influenced by log diameter, is not known. In Europe, hardwood logs are very expensive therefore are all live sawn to ensure high volume recovery (pers. comm. Chang).

In the USA, the log price has been in steadily increasing. In the last 10 years, hardwood log price has tripled. In 1960, 1/3 of the production cost was due to logs. Nowadays, up to 75% of the production cost is due to logs. As logs become more expensive in the future, hardwood mills in the USA will be forced to improve their efficiency and may have to follow what is being done in Europe. Many hardwood sawmills start to feel this pressure but tend to think that their inefficiency is caused by their workers' poor skills and went to the researchers for training courses. The inefficiency of many mills, however, is due more to inefficient production rather than the employees' skills (pers. comm. Wengert).

The future trend of hardwood products will be similar to that now, i.e. pallets, furniture, flooring (Figure 2), although relative importance may change (pers. comm. Chang).

The future of hardwood sawmills depend on: (1) supply of hardwood sawlogs with a quality that makes the sawmill operation profitable; (2) price of hardwood sawn timber. If the price of hardwood timber increases, it will help inefficient sawmills stay in business (pers. comm. Wengert).

3

X-ray CT Log Scanning Research in the USA

Introduction

It was in the early 1980's when an inspiring question came to the mind of some forest products researchers: can X-ray CT-scanners be used to detect internal defects of logs and subsequently adapted to the wood industry? Investigation soon started (Benson-Cooper et al., 1982; Funt and Bryant, 1985; Taylor et al., 1984) and has been taken up by various groups targeting different aspects in the following years. More knowledge and experiences have been gained since then. Significant achievement has been made in the USA in developing computer techniques for CT data processing and analysing, and in developing decision-making software for log processing. Accomplishments in the automation area (scanning system for both logs and sawn boards, and decision-making computer software) up to early 1990's is outlined by Schmoldt (1992).

Log scanning research has never been conducted on a large scale in the USA in terms of the number of people involved. Reasons are high cost of log scanning (a number of images are needed for each log) and subsequent handling of massive data without ready-for-use data processing techniques. American researchers would wish to build an internal log scanner parallel to their development of computer integrated decision-making software tools. However, their progress towards building internal log scanners is not comparable to that made by the Australian Glass Log Project. No funds have been committed yet in the USA to build such a scanner. Researchers are therefore temporarily taking an involuntary approach, that is to concentrate on developing computer integrated decision-making software tools. The outcome of this strategy is that software tools will be ready for the users when internal log scanners (in particular X-ray CT-scanner) become available.

Currently in the USA, two research groups are active in X-ray CT-scanning research for hardwood logs. They are the Advanced Sawing Technology Laboratory, School of Forestry, Wildlife and Fisheries of Louisiana State University, and the Primary Hardwood Processing and Products Research Unit, Southern Research Station of USDA Forest Service at Blacksburg, Virginia. A group from University of Missouri-Columbia have been collaborating with the USDA group and used X-ray CT data in their computer integrated hardwood processing research.

This Chapter starts with a brief account of the pioneering work on X-ray CT log scanning in the USA. It then provides up-to-date information on the progress and the current status of the research by the Louisiana State University group and the USDA Forest Service group. This Chapter also provides an overview of the research by the group from the University of Missouri-Columbia.

Mississippi State University

History of X-ray CT log scanning research

Professor Fred W. Taylor's group at the Forest Products Laboratory of Mississippi State University (MSU) were the very first in the USA in evaluating the potential of various X-ray CT scanners for detecting internal defects of both softwood and hardwood logs.

Their first study investigated the practicality and feasibility of using industrial tomography and automatic image analysis to nondestructively identify and locate internal knots within freshly harvested southern pine and red oak logs (Taylor et al., 1984). Log sections of 1 ft long were scanned. The slice planes were 1 cm apart along the longitudinal axis of the log sections. After scanning, the scanned portion of each log section was crosscut into 1 cm thick disks (including saw kerf) which corresponded to the scanned slice planes. A cursory image analysis technique and a computer program were developed to identify knots and log perimeters from the scan data. The study demonstrated that internal knots were visible in tomographic images. It also demonstrated, by comparing photographs of the log cross sections and results of the image analysis of the tomograms, that most knots could be relatively accurately identified and located. Taylor et al. (1984) perceived at that time that some other requirements must be met in commercial installations of a scanning system. The scanning system must be designed to withstand the mill environment, and logs must be translated through the scanner with little undesired motion.

Since satisfactory scanning speed is critical for commercial installation of a scanning system, Wagner et al. (1989) investigated the suitability of an ultrafast X-ray CT scanner for revealing internal log defects. This scanner was able to acquire 34 cross-sectional log scans per second, which translates to a linear log feed rate of 26 m per minute at 0.5 inch (1.27 cm) scan interval. A water oak log was cut into sections and each section was scanned at 8 mm intervals in the ultrafast mode. After scanning, the log sections were crosscut into 8 mm disks (including saw kerf) near the tomographic slice planes for validation of the CT images. By visual comparison of the CT images and the corresponding log disks, they found that all log defects could be seen in the tomographic images. If defects were "visible" in tomograms, it should be possible to recognise them automatically by using image analysis techniques.

The MSU group at one stage considered building an industrial X-ray CT log scanner, but later abandoned the idea. They could not obtain enough funds to purchase the equipment, and to employ the required expertise and extra staff. General Electronic offered one X-ray CT-scanner of an older model at one stage, but MSU decided not to take it, as the running and maintaining cost is high in equipment of this type.

The MSU group decided to discontinue their X-ray CT-scanning research in late 1980's. The scan data are very costly to acquire, no further funding came in, and the computers and computing methods existing at that time were not able to process and analyse the massive data fast enough. Their goal then became to make the advantage of this technology known to the industry and to encourage others to further this research.

The following effort of this group went to demonstrate the impact of log orientation on timber value yield (Harless et al., 1991; Steele et al., 1994) using actual log data. A method for collecting real log data was developed by Harless et al. (1991). It involved crosscutting a log into a series of 1/4 inch (0.635 cm) thick disks (including saw kerf), digitising defects in each disk, collecting log periphery, and assembling the processed log data into a 3-D array. One major reason for generating real log data was that the industry has doubts in hypothetical logs, although they take the points that researchers demonstrated to them using hypothetical log data. One great advantage of the real log model of the MSU's group is its accuracy. The internal log defects were actually seen, their sizes were actually measured, and there were no interpretation or assumptions. In a CT-data based log model, each individual defect is detected and its dimension determined by using various computer techniques in an automatic procedure. However, the accuracy has remained as a real question.

Harless et al. (1991) found, by computer live sawing a southern red oak log, that the lumber value increase at the best log orientation was 10.8% higher than the average lumber value at all orientations (the log was sawn at every 15^0 rotation), and that value improvement was largely attributed to better grade yield rather than better volume yield.

Steele et al. (1994) furthered their investigation of the impact of optimum orientation of internal defects on lumber value increase, using a relatively large sample size (24 red oak sawlogs) and the same log-data-collection method. The purpose of this study was two fold. One was to compare the value yield by optimum sawing, which was based on computer analysis and decision, with the value yield by experienced sawyer decisions. The other was to determine whether logs of all grades would benefit from optimum sawlog orientation. Optimum sawing orientation gave about 10.1% increase in sawn timber value for both live and grade sawing over sawyer sawing, and that a higher value increase from optimum sawing orientation was achieved with better grade logs although the difference was not statistically significant due to a large variance between the value yields at each orientation. No X-ray log scanning was involved in both these studies.

Taylor does not think they will resume log scanning work again (pers. comm.). Steele believes that X-ray CT log scanning will become a reality for the industry through the vision and dedicated efforts of the researchers (pers. comm.).

Current research on optimal log utilisation

The on-going research projects at the Forest Products Laboratory of MSU that are closely related to optimal log utilisation are:

- Optimal log allocation for softwood sawmills and veneer mills, undertaken by Professor R.D. Seale;
- Non-contact lumber scanning associated with optimising furniture component cuttings from hardwood lumber; development of various computer software to analyse hardwood manufacturing operations, rough mill operations, and financial feasibility of investments in thin kerf sawing machines, undertaken by Professor P. H. Steele.

Louisiana State University

The resource

Currently there are two people in this group. Professor S. Joseph Chang, leader of Forestry Program of School of Forestry, Wildlife and Fisheries, has a wide background and extensive research experiences in hardwood management and utilisation. Dr. Suresh Guddanti has a mechanical engineering background and has skills of computer graphics, neural networks, and electronics.

Twenty percent of the funding on this project came from the Federal Government and the other 80% from industry. The industry in general is not prepared to financially commit themselves to long-term or "endless" research. They want tasks to be completed in a relatively short period, and the promised concrete outcome delivered at the end of each funding period. Chang has had good contacts with industry. However, the turning point for Chang to get industry funding occurred only about 3 or 4 years ago when he proposed to develop a computer training program to show how much gain in product value can be achieved through optimal log processing by cutting logs on computer using real log data (X-ray CT data). This training program was viewed by industry as achievable, short-term, and highly useful.

There have been 11 sponsoring companies, ranging from very small (producing 4 million BF timber with conversion rate of 55%) and very large (producing 70 million BF timber with conversion rate of 55%). Chang's work has been mentioned in a publicity video of the most advanced hardwood mill in the USA, Roy O. Martin Lumber Company.

Log scanning

Earlier log scanning involved scanning a 16 ft red oak log with a hospital X-ray CT-scanner (GE High Speed Advantage). Hospital scanners have two limitations that physically inhibit full-length log scanning. Firstly, the patient table can not withstand a fresh log. Secondly, there is not enough room in a hospital scanning room to carry out full-length log scanning. This study log was thus cross-cut into 2 ft sections, and each section was scanned at 0.5 in intervals. These earlier CT images were used to develop a CT based sawing training program, *TOPSAW-HW* (see following section for details of this program).

One major procedure of *TOPSAW-HW* is to grade computer images of full-length sawn boards. In order to generate the most appropriate data for this procedure, this group tried full-length log scanning. Up to now, they have successfully scanned 8 Southern red oak fresh logs, 12 ft (3.65 m) in length and 12-14 inch (300-350 mm) in diameter. To get around the weight and space limitations, they built a log conveyer system which could carry and translate full-length fresh logs, and scanned these logs with an industrial scanner. This scanner was the Invision Technologies CTX-

5000, designed to detect bombs in airport baggage. It has a 1 m opening and provides image resolution of 512x512 pixels.

It appears that full-length X-ray CT hardwood log scanning has been conducted only by this group anywhere in the world so far.

This group has not attempted to generate a hypothetical log database as many people did in the past and presently. Hypothetical logs are not convincing enough to the industry for a simple reason: no one has shown how well simulated logs represent a log resource.

They have neither attempted to manually generate real log model by cutting logs and digitising true log information. Between-log variation can be large. No two logs are similar. Many sample logs are therefore needed in order to build a reliable log database. However, collecting log data by manual methods is time and cost prohibitive[1], especially if many logs are involved.

Without a convincing log database, either simulated or manually generated (log digitising), sawing simulation results are unlikely to find acceptance by industry.

Chang thus decided to collect "real log" data by using X-ray CT scanners. The advantage of this method over log simulation is that every log is "diagnosed", not "designed". Its advantage over log digitising is that the data acquisition is highly automated and far less time consuming.

Researchers all over the world in the internal log scanning field know about each others' work through conferences or direct personal contact. Chang has given a brief description of what the other groups have done[2] (see the following text), but hardly made any comments, which is understandable.

The Department of Wood Technology of Luleå University in Sweden has an extensive CT log database of scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). A Siemens X-ray CT scanner was used.

McMillan Bloedel (Canada) have been interested in searching and defining the size of defect core of Douglas-fir. The company has built an X-ray projection machine for this purpose (3 X-ray tubes are set at 120 degrees to each other).

Chang questioned about the practicality of ultrasonic scanning methods being investigated by Birkeland's group of Norwegian Institute of Technology. Since water is the media to enable ultrasonic waves to travel between transducers and log, the log needs to be fully submerged. Each time a log is loaded in the water tank, one has to wait for the water to completely settle down before log scanning. No mills can wait for this long in real life. In addition, ultrasonic waves have longer wave length which yields lower image contrast than X-rays. But this method may suit the softwood species in Norway.

The LSU group are aware of the log spinning attempt of Davis' group in Australia[3]. However, they consider spinning log may not be a practical and better approach in

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[1] It took 2 person years about 6 years ago to gather internal and external data of 24 red oak logs and to assemble the data into 3-D computer log representation (pers. comm. Steele).

[2] Details about scanning equipment may be obtained by contacting Dr. John Davis of Monash University, Australia.

[3] Costs of log splinning will not be excessive, at least for a prototype facility, according to Davis' group.

comparison to spinning the X-ray source. It is very difficult to spin full-length logs from an engineering aspect. In addition, to spin logs could cost just as much or even more. For poor form logs, larger scanner aperture will be needed and an XY charger has to be used to search for the geometric centre of these logs, which is a costly process. If a scanner cannot handle poor form logs, it misses a considerable portion of the log resource. This opinion of the LSU group, from the author's point of view, may not apply to commercially important Australian eucalypts which are overall far straighter than American hardwood logs.

Software development for utilising log CT data

Only "real log" data (X-ray CT data) were used in LSU' R&D.

The major outcome of their computer software development is the *TOPSAW-HW*: Tainting and Optimisation system for Sawing Hardwoods.

There are two purposes for developing *TOPSAW-HW*. The first is to demonstrate to industry that real log data can be practically obtained by using an X-ray CT scanner, optimal log sawing sequences can be found by processing real log data, and that it is advantageous to the industry to develop X-ray CT-scanning technology. Sawing optimisation can be achieved through two stages: primary log breakdown and secondary re-sawing (edging and trimming). However, the LSU group have not attempted to build the component of optimal edging and trimming into *TOPSAW-HW* at this stage. They decide not to do too many things at one time to overwhelm the industry or go too far above the level the industry can practically absorb. The second purpose is to create an opportunity to test and improve *TOPSAW-HW* before industrial internal log scanners become commercially available. Successful development of decision-making software like *TOPSAW-HW* prior to the birth of log scanners not only provides confidence to software developer themselves, but more importantly, assures the builder of log scanners.

TOPSAW-HW is written in C language, and runs on IBM compatible machines under DOS operating system. A fast computer with minimal 32 MB RAM is needed.

Figure 3 schematically depicts how sawing optimisation technology can be integrated into mills and how optimal sawing solutions are generated. *TOPSAW-HW* deals with the procedures from 3-D log model reconstruction to generating optimal sawing sequence. Each of these procedures is explained below.

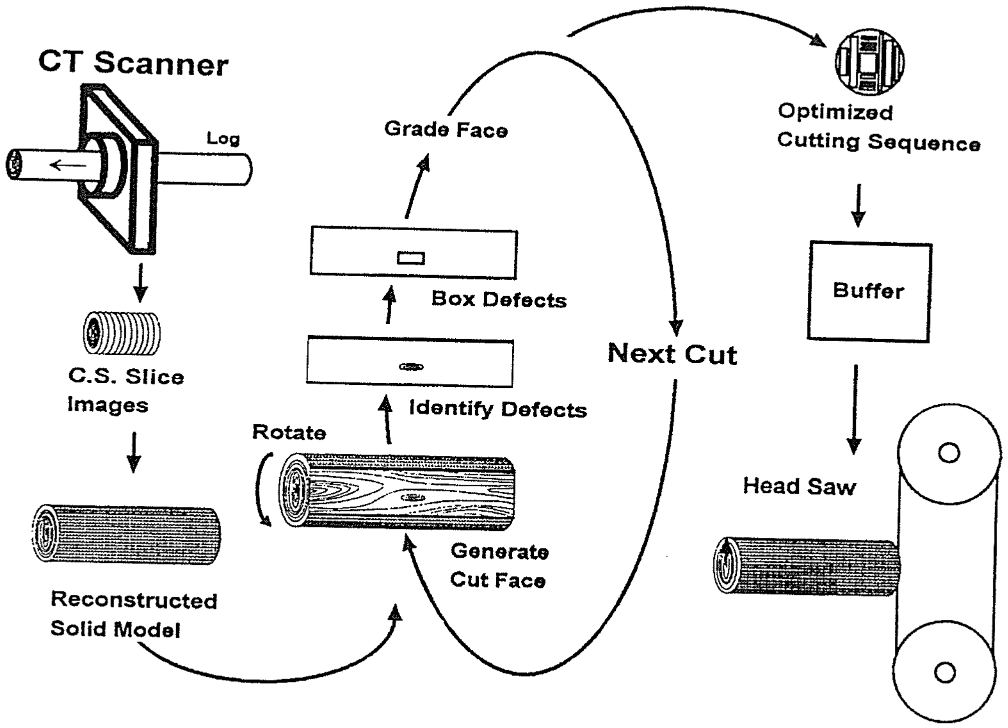


Figure 3. Schematic illustration of a log breakdown procedure involving a CT internal log scanner and *TOPSAW-HW* sawing optimisation. Reproduced from, and permitted by, Chang and Guddanti (1995).

Reconstruct solid log model	A 3-D solid log model is reconstructed from a series of CT images of a log using a computer program developed in-house.
Generate cut surface	A saw cut can be made by placing the vertical saw line anywhere on the image of the log end (presumably the small log end). The image of the sawn surface is generated and displayed on computer screen in real time, revealing defects, boarder profile, and wood grain (Figure 4). The log can be rotated at every 15 degrees. The operator interacts with *TOPSAW-HW* through the key board. Joystick might be incorporated in the future to improve interaction.

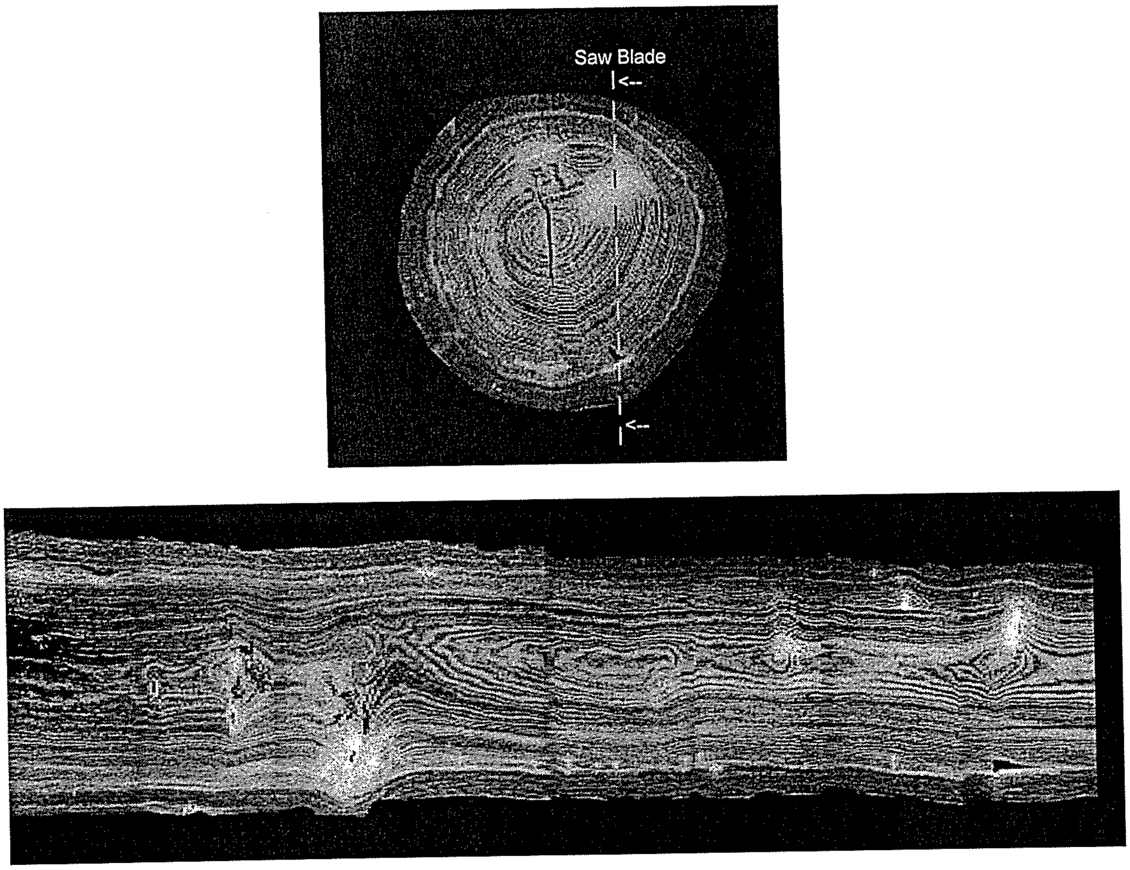
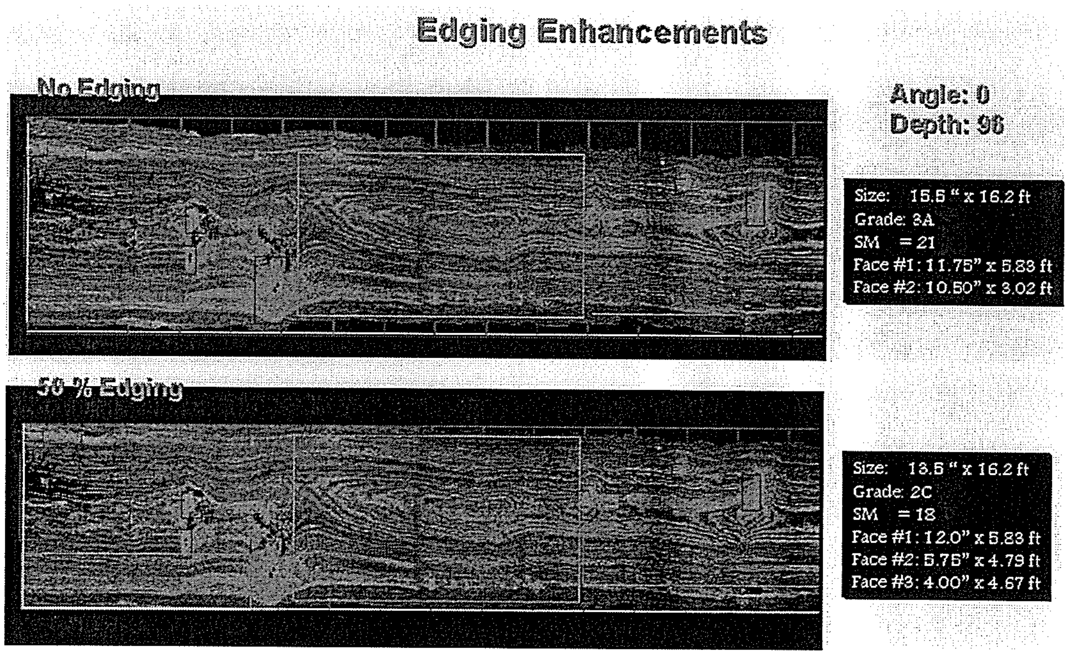


Figure 4. Illustration of computer sawing. A full-length sawn surface is generated in real time by putting the vertical saw line anywhere over the CT image of the log. Reproduced from, and permitted by, Chang and Guddanti (1995).

Identify defects	Various defects on the sawn surface are detected and identified using computer techniques developed in-house.
Box defects	Defects are boxed. By boxing the defects, their maximum dimension along and across wood grain is quantified. The zone of clear wood in between the defects is also boxed and its size is determined.
Grade face	The sawn surface is graded by using National Hardwood Lumber Association hardwood lumber grading rules (NHLA, 1986). According to these rules, the grade of a hardwood board is determined by the size of the board, the quality (clear face or sound), number, size, and proportion of cuttings that can be cut from the board. As shown in Figure 5, the grade of the board, the total surface dimension and the surface dimension of each clear cutting (clear faces) are measured. The grading program was developed in-house.

A board is generated when two saw lines are put on the log end, at a specified thickness (4, or 5, or 6 quarters of an inch). Both faces of this board are then graded. The poorer face determines the grade of the board. It takes less than a second to generate and grade a board on a Pentium 90 MHz computer (Guddanti and Chang, 1995).

The operator at this stage can manually try various degree of edging (taking off various amount of wane from the board). The board is re-graded after each attempt of edging. The grade and surface dimension of the newly-edged board are displayed on the screen. Figure 5 shows that the grade of the board is improved from 3A to 2C after 50% of edging (50% of wane is removed). However, edging does not always improve grade. Figure 6 shows that the grade of a board remains unimproved after 50% of edging. Sawmills are recommended to refrain from edging if it does not improve the grade (Chang and Guddanti, 1995).

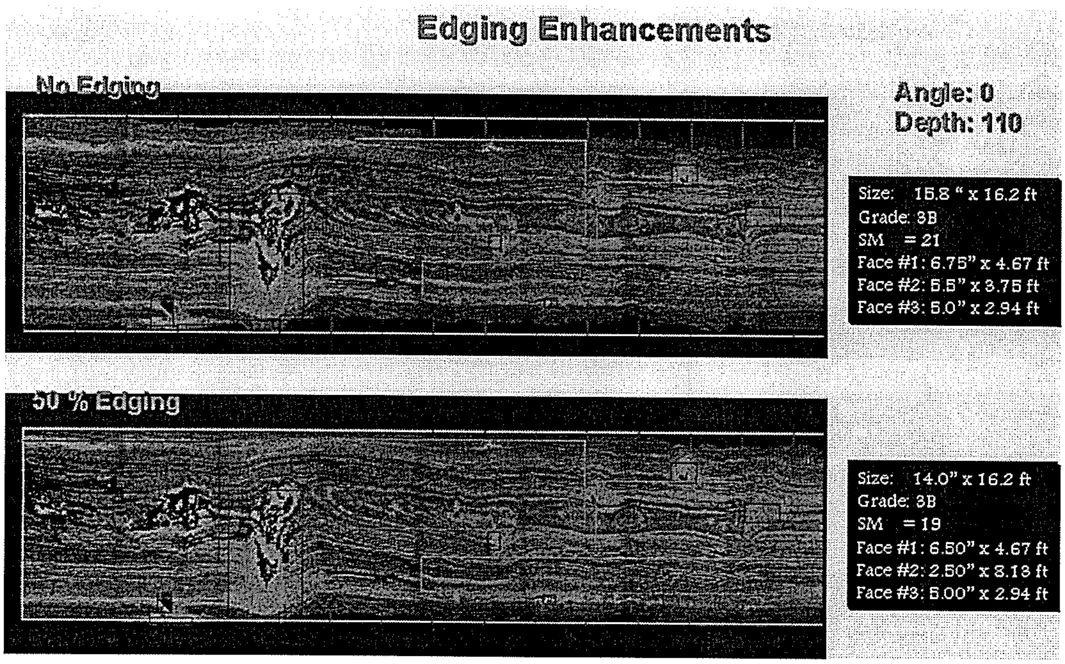


Angle: 0
Depth: 96

Size: 15.5 " x 16.2 ft
Grade: 3A
SM = 21
Face #1: 11.75" x 5.83 ft
Face #2: 10.50" x 3.02 ft

Size: 13.5 " x 16.2 ft
Grade: 2C
SM = 18
Face #1: 12.0" x 5.83 ft
Face #2: 5.75" x 4.79 ft
Face #3: 4.00" x 4.67 ft

Figure 5. Illustration of the effect of edging on the grade of a sawn board. On this occasion, 50% of edging raised the board grade from 3A to 2C. The board surface area is reduced from 21 to 18 square feet after edging. Reproduced from, and permitted by, Chang and Guddanti (1995).



Size: 15.8 " x 16.2 ft
Grade: 3B
SM = 21
Face #1: 6.75" x 4.67 ft
Face #2: 5.5" x 3.75 ft
Face #3: 5.0" x 2.94 ft

Size: 14.0" x 16.2 ft
Grade: 3B
SM = 19
Face #1: 6.50" x 4.67 ft
Face #2: 2.50" x 8.13 ft
Face #3: 5.00" x 2.94 ft

Figure 6. Illustration of edging having no effect on the grade of a sawn board. In this occasion, the board grade remains as 3B after 50% edging. The board surface area is reduced from 21 to 19 square feet after edging. Reproduced from, and permitted by, Chang and Guddanti (1995).

Next cut

For training purpose, the operator can use the training version of *TOPSAW-HW* to repeat above processes by choosing a new log rotation and placing the saw line at a new position on the log end. He/she can find out the board grade and the effect of edging at this new cut. By exploring various sawing decisions on the same log, *TOPSAW-HW* helps sawyers to learn and sharpen their sawing skills.

Optimised sawing sequence

The optimisation version of *TOPSAW-HW* can search for optimal sawing solution for a log. In doing so, it examines both live sawing and grade sawing processes, and carries out previously described sawing and grading process automatically. For live sawing, the thickness of boards can change within the same log. The grade and value of each board, and the total value yield at each log orientation are determined and recorded. The log is automatically rotated every 15 degrees for the next sawing orientation. *TOPSAW-HW* also does various degree of edging and trimming automatically if board value can be improved. It takes less than 10 seconds to saw one log at one rotation and to demonstrate the sawing results. At the end, the sawing solution (combination of rotation and sawing pattern) that yields the highest total board value is found and displayed.

The biggest difference in value yield between best and worst log orientation in grading sawing one of their study logs is 50% (pers. comm. Guddanti). The group will work on more logs before they can compare value increase between grade sawing and live sawing methods (pers. comm. Chang).

TOPSAW-HW is proprietary software. Details of its optimisation procedures are withheld.

Chang believes that *TOPSAW-HW* should be able to work on X-ray CT log data of any species. The only change to make when used in another country is to incorporate a grading module which describes that country's timber grading rules. The group have expressed interest in working with Australian Glass Log Project in the future: one party builds X-ray CT log scanner, the other provides log processing software tools.

TOPSAW-HW and the Users Manual have been supplied to the sponsoring companies, at $6,000 a copy, to go through the QAQC process (quality assurance and quality control). The final product of *TOPSAW-HW* will be commercialised. The sponsoring companies will have 18 months lead time.

Their short and long term goals

The short term goal	Develop and fine tune *TOPSAW-HW* training system for sawyers to practice sawing on a PC based computer and sharpen their sawing skills. Use *TOPSAW-HW* to encourage the industry and others to build an X-ray CT-scanner for hardwood logs.
The long term goal	Develop and fine tune *TOPSAW-HW* sawing optimisation system. Use this system to automate hardwood log processing under the CAM/CIM production environment once an industrial scanner becomes available.

USDA Forest Service Southern Research Station

The resource

This research station has a *Primary Hardwood Processing and Products Research Unit*. There are 4 staff at the unit at the present. The X-ray CT log scanning research is undertaken mainly by Dr. Daniel L. Schmoldt and postgraduate students of the Bradley Department of Electrical Engineering of Virginia Tech. I understood that these postgraduates were funded, at least partially, by this research unit. This unit has spent arrpoximately US$100,000 in the past 6 years for extramural log scanning research. This figure does not include salaries and travel within the unit. The project leader Mr. P. Araman travels extensively in order to generate research funds.

Log scanning

The X-ray CT log scanning with this group started in 1990. The group wish to have a better access to X-ray CT scanners to generate enough data. So far, they have scanned some short log sections and obtained over 2,000 CT images. Principal species on their investigation list include oak and yellow poplar. Various scanners have been tried.

According to Schmoldt, there are 2 factors driving the development of industrial log scanners. Firstly, wood industry needs internal log information. Mills are under increasing need to get more value out of limited and low quality raw material. Secondly, the market for medical scanners is very depressed. Scanner manufacturers are looking for other markets.

Development of computer integrated hardwood processing software

They have, jointly with Virginia Tech, made a considerable effort in developing CT image analysis techniques to detect internal log defects (Li et al., 1996; Schmoldt et al. 1993, 1996b; Zhu, 1993; Zhu et. al., 1991; 1996). By the number of publications, detection of internal log defects appears to be amongst their major activities in the last few years. Quite an effort has also been made towards using CT data for improved hardwood log processing. The results include a recently developed CT based simulator for veneer slicing. Apart from Virginia Tech, this group have collaborated with West Virginia University and University of Missouri in computer integrated hardwood log processing research.

In addition to X-ray CT-scanning work, they have also developed graphical and interactive computer training programs for edging and trimming of hardwood boards, and for manual grading hardwood pallets. The industry currently does not grade pallets although there are grading rules to follow. Since an automated pallet grading system has not been developed, manual grading is an intermediate step between no grading and automated grading.

Their new approach to defect detection (neural-net based) and their veneer simulator are described in the following sections.

Neural-net based technique for defect detection

Neural network approach “offers the potential of being very fast and also capable of handling the tremendous variety of defect manifestations found in logs” (Schmoldt, 1992).

A neural-net based classification technique has been investigated by Li et al. (1996) and Schmoldt et al. (1996b). The purpose was to improve the accuracy and speed of internal defects detection. This technique consists of 3 procedures: preprocessing of images, primary classification, and postprocessing of images.

In the preprocessing procedure, the background and internal voids were separated from wood. Also, CT values of different species were normalised in order to accommodate various species in the following primary classification procedure. The preprocessing is accomplished by means of thresholding methods and histogram normalisation procedures.

In the primary classification procedure, image segmentation and defect labelling tasks were combined into a single classification step by taking a multilayer feed-forward artificial neural network, contrary to global approaches by which these two tasks are dealt separately.

In the postprocessing procedure, inaccurately classified areas were removed by using grey-scale operations of erosion followed by dilation.

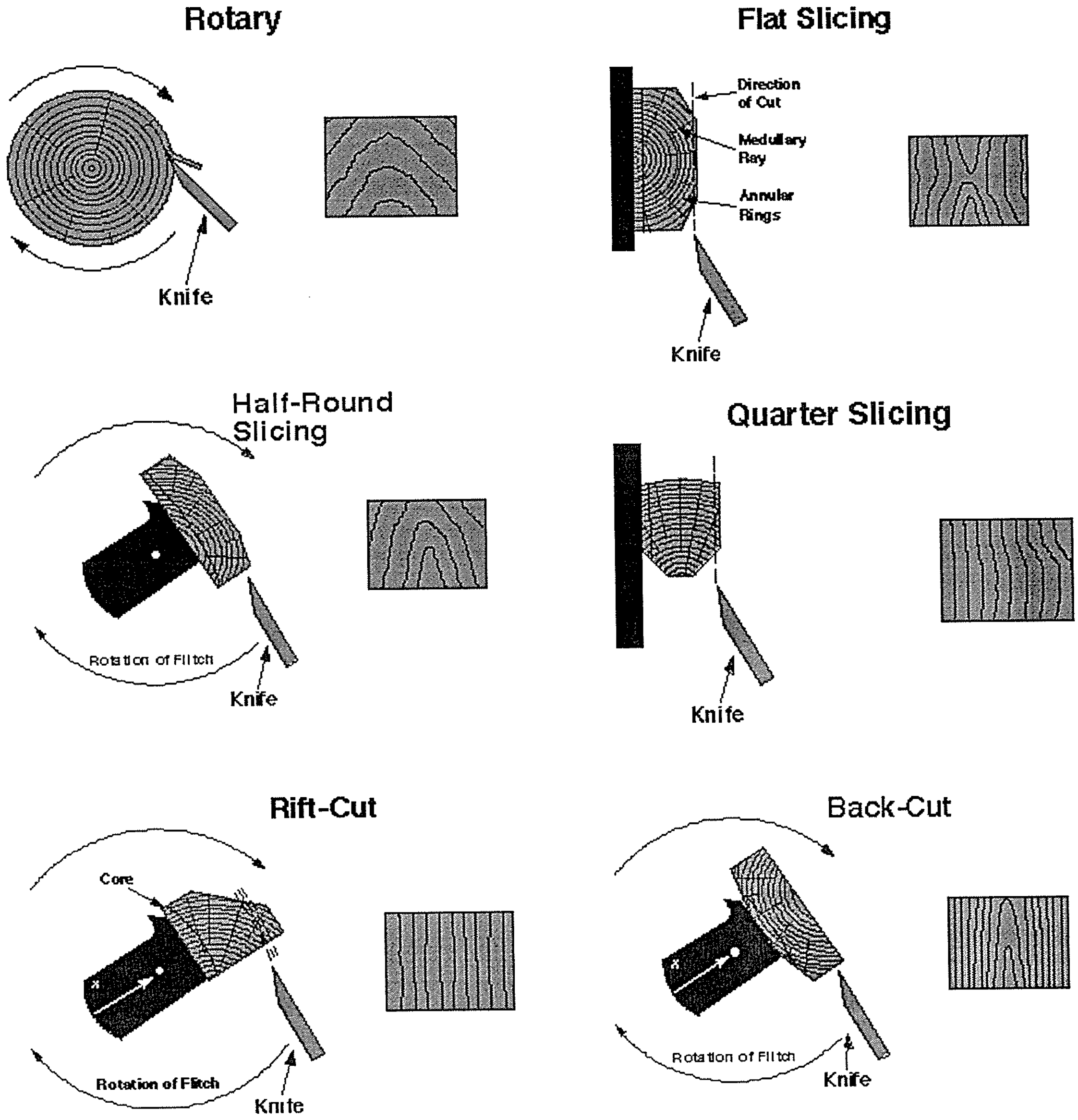
According to Schmoldt et al. (1996b), this image interpretation system works fast and with an accuracy above 95%. It took 25 seconds to analyse a single 256x256 CT image on a desktop computer containing a 33 MHz processor. Previous approaches required 9 minutes on a VAX 11/785 computer, as quoted by Schmoldt et al. (1996b, 1996c). The processing speed of the current approach could be considerably increased by using hardware more suited to this type of work.

CT-based simulator for veneer slicing

Schmoldt et al. (1995, 1996a) made the first attempt to develop a simulator for veneer slicing using CT data of logs. Prior to this, there was no research, for several reasons, to investigate the ways in which veneer logs can be best flitched and sliced for increased value. Firstly, it is time and cost prohibitive to generate a real log model which has growth ring information. Without growth ring information, researchers are unable to determine grain patterns in veneer and to assess veneer value accordingly. Secondly, there are no standard veneer grading rules, like those for timber grading, in the USA, to allow straight comparisons of veneer value without considering other non-technical factors. Rather, the veneer value is determined in practice by its size and patterns, and buyer preferences (Schmoldt et al., 1995, 1996a).

This simulator is coded in C language as a stand-alone Macintosh application. For demonstration purposes, it currently runs on a log model reconstructed from X-ray CT images of a water oak log with 256x256 pixels resolution. These images were generated under ultrafast mode in which case 34 cross-sectional log scans can be acquired per second (Wagner et al., 1989).

This simulator currently allows the user to perform 6 different slicing operations. They are rotary-cut, half-round cut, flat-cut (equivalent to crown-cut in Australia), quarter-cut, back-cut, and rift-cut, as illustrated in Figure 7. These methods represent most of the common slicing operations. Back-cut (also called cathedral cut), flat-cut, and half-round cut are more popular than other cuts in the USA.


Rotary

Flat Slicing

Half-Round Slicing

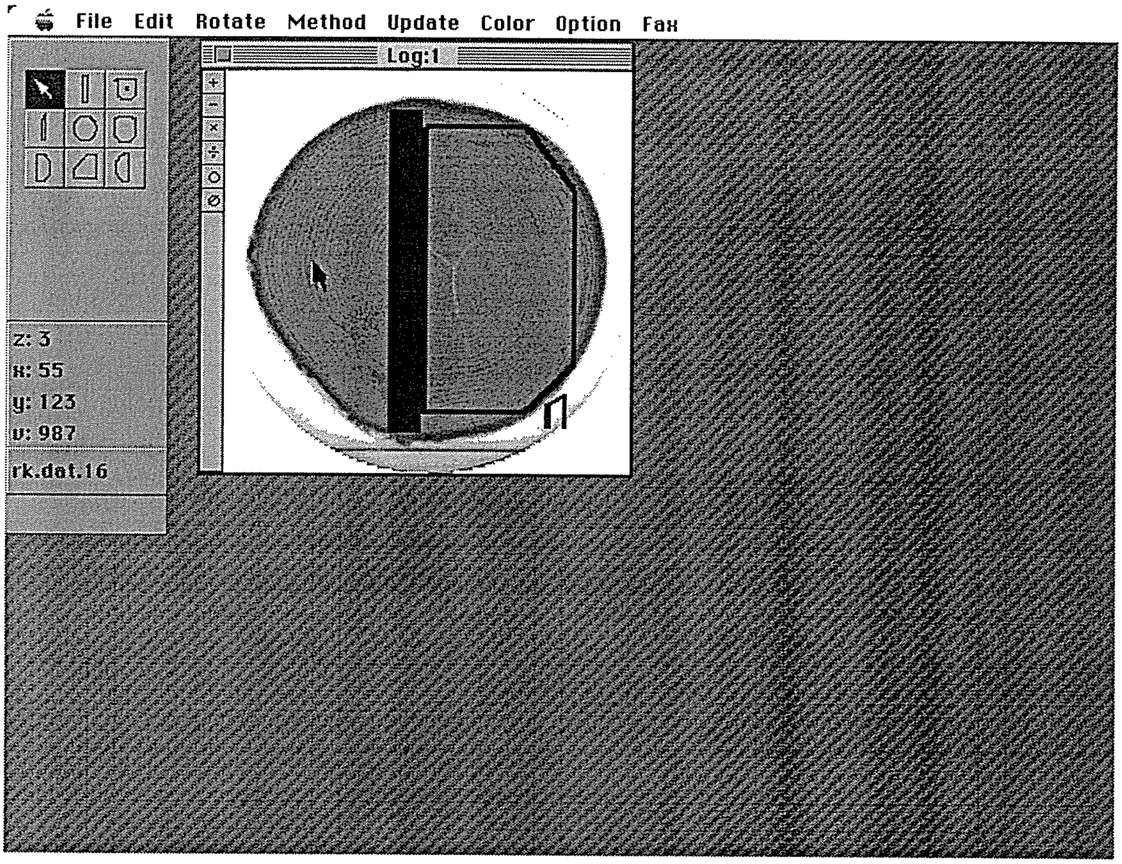
Quarter Slicing

Rift-Cut

Back-Cut

Figure 7. Six different veneer slicing options that represent most of the common slicing methods. Reproduced from, and permitted by, Schmoldt et al. (1996a).

The simulator contains a tool palette and various menus. Figure 8 is a screen snapshot of the simulator, which shows the CT image window, the tool pallet, the main menu, a flitch table, a flitch, and the knife. The user can use the tool palette to draw, over the CT image in the CT image window, a flitch table, a flitch of varying shape, the knife, and graphically arrange these objects. For rotary-cut, only the log and the knife need to be specified. According to the type of flitch table and flitch specified, the simulator only permits the appropriate slicing method. At this stage, this simulator is limited to allowing the flitch table to be rotated at 90^0 increments.



z: 3
x: 55
y: 123
v: 987
rk.dat.16

Figure 8. A screen snapshot of the simulator shows the flitch table, a flitch, and the cutting knife, over the CT image in the CT image window. The tool palette is at the upper left corner of the screen. Below the tool palette, slice number (z), x and y coordinates of the pointer and CT number (v) at where the pointer is, and data file name, are displayed. Reproduced from, and permitted by, Schmoldt et al. (1996a).

The CT number (v) and X,Y coordinates of the pointer (mouse) at any location within the CT image are shown below the tool palette. These numbers change when the pointer moves within the image.

Veneer can be individually "sliced" by manually positioning the knife at any location over the CT image in the CT image window for one cut. The knife can be positioned anywhere within the CT image by dragging it with the pointer. Veneer can also be "sliced" in multiple-quantity by running the "Multiple-Path-Veneering" option in the "Method" menu. Under this option, slices are taken every 10 pixels up to the size of the flitch. The locations of all these veneer slices are displayed on the CT image, and information about them is stored at once. These veneer slices can be retrieved quickly for later display.

A veneer already sliced can be selected and viewed in the veneer window, as demonstrated in Figure 9. In the veneer window, the user can move a vertical marker line (see the line near the left edge of the veneer image in Figure 9) and dynamically view the closest corresponding CT image of the log in the CT image window. This vertical line can be positioned anywhere within the veneer image by dragging it with the pointer. This simulator also enables direct visual comparison of veneers produced with different slicing methods or settings, as illustrated in Figure 10.

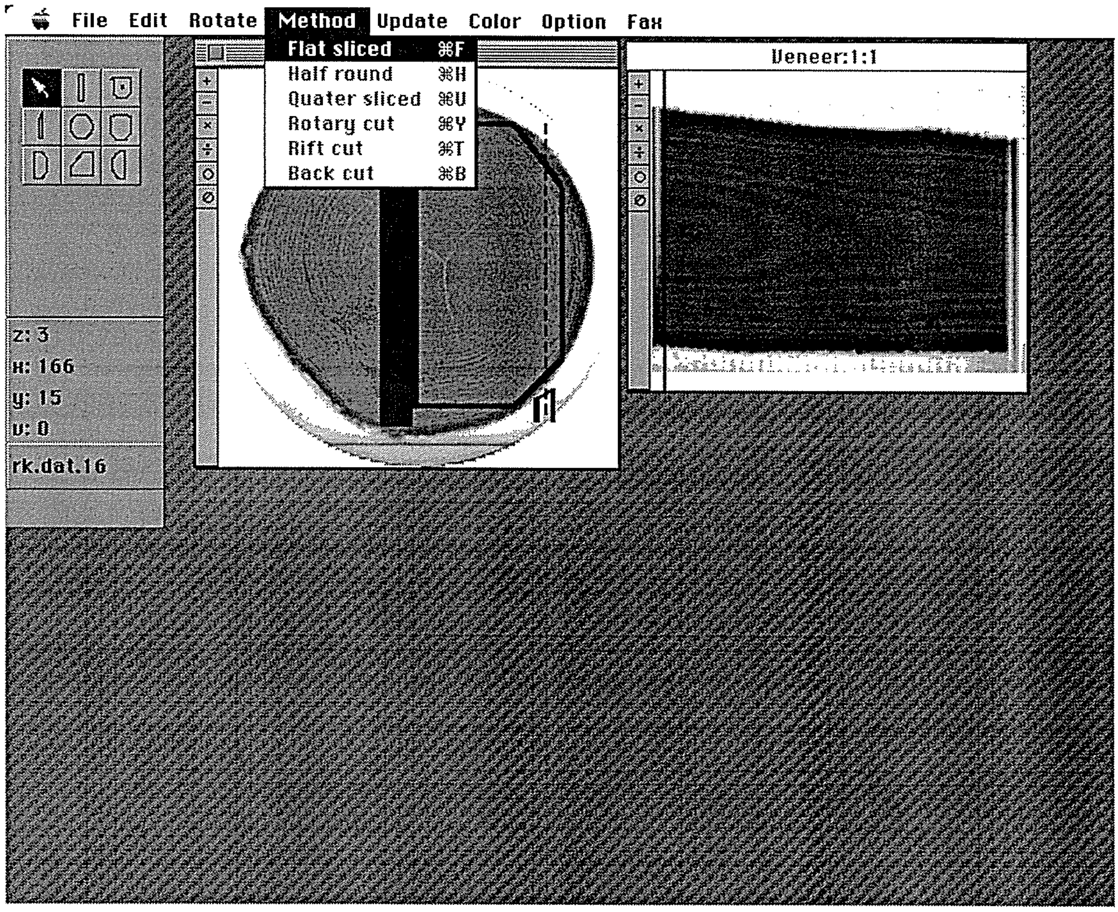


Figure 9. The dashed line on the log CT image marks the location of the veneer slice that has been generated and is displayed in the veneer window to the right. The vertical marker line near the left edge of the veneer image can be moved left or right to view the corresponding CT image. Reproduced from, and permitted by, Schmoldt et al. (1996a).

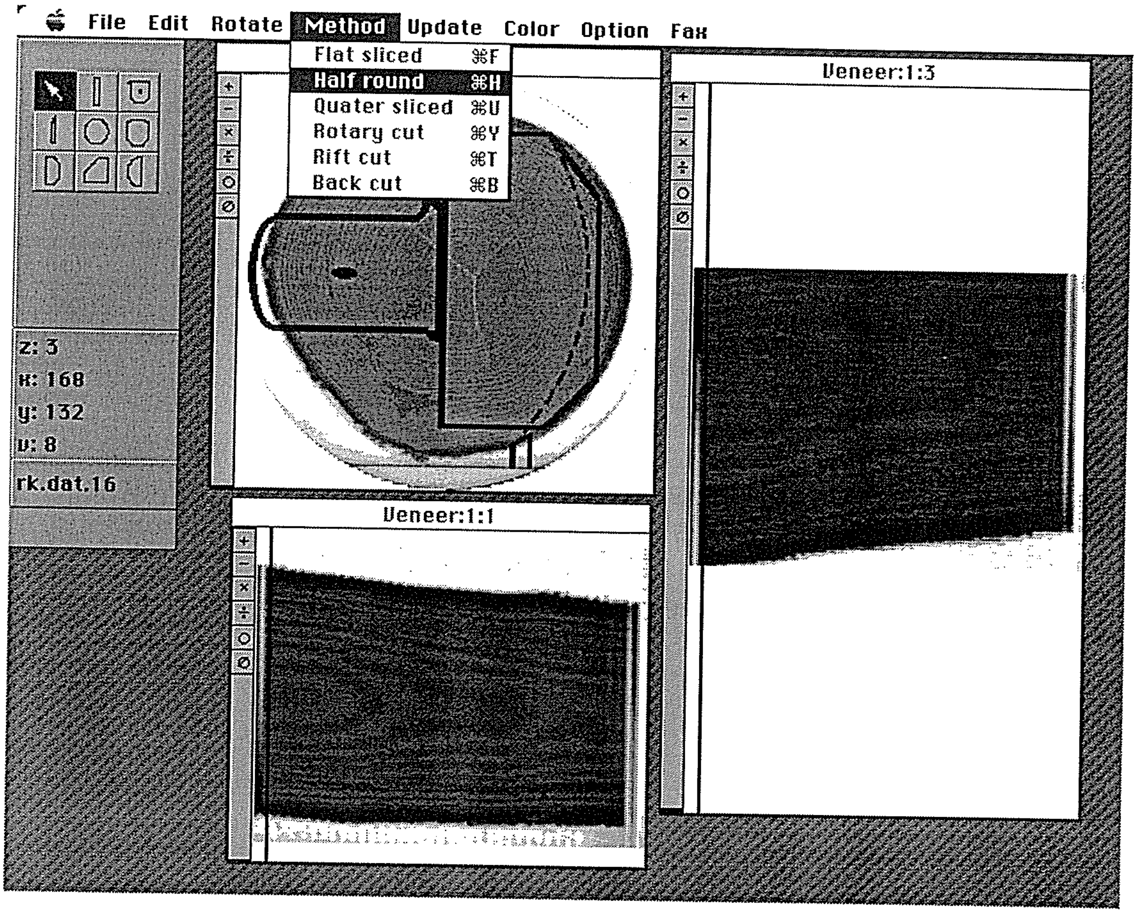


Figure 10. The flitch table, a flitch for half-round slicing, and the trace of the knife movement (dashed line) are shown over the CT image. The veneer slice corresponding to the dashed line is shown in the veneer window to the right. The user can compare this veneer with a flat-sliced veneer in another veneer window (lower image). Reproduced from, and permitted by, Schmoldt et al. (1996a).

Graphical simulators can help veneer producers to eliminate guesswork about the internal characteristics of each log, and to quickly evaluate different flitching and slicing options. Simulators like this will not only bring increased value yield for high quality veneer logs, but also considerably improve the value yield of marginal quality veneer logs (Schmoldt et al., 1996a). The economical implication of the veneer simulator with the second aspect is probably more significant. In the meantime, this simulator has been used as a demonstration tool to help veneer manufacturers and other industry innovators better understand the value of internal log information and its utilisation.

This simulator is currently under improvement and more functions are to be incorporated (pers. comm. Schmoldt).

Their short and long term goals

The short term goal	Conduct the research necessary to pave the way for future implementation of CT scanning in mills. This involves developing the software application tools that allow mills to utilise CT data. To get log scanning technology implemented in a mill and demonstrate its economic and manufacturing usefulness.
The long term goal	It is possible for them to work with X-ray CT-scanner manufacturers to build a log scanner if there is enough financial support. Different scanners may have to be built to suit different species and customers. Specification of the technical design of these scanners requires a lot of research. This group are quite a distance from being technically ready to build an X-ray CT log scanner. They do not know yet what spatial resolution and energy level are required for their species. Due to greater resolution and scanning intensity required for veneer logs, hence greater complexity and higher cost involved, earlier scanners may be designed for satisfactory scanning of sawlogs rather than for veneer logs (pers. comm. Schmoldt).

University of Missouri-Columbia

The resource

There is no forestry related department at the University of Missouri-Columbia. The hardwood processing research group is located within the Department of Industrial Engineering, and led by Dr. Luis G. Occeña. Currently the group has 5 postgraduate students including 3 Ph.D students. The research of group members directly or indirectly relates to *Computer Integrated Hardwood Manufacturing*. The funding situation looks quite healthy. They had obtained a US$45,000[1] grant from National Science Foundation in year 1994-95 for research on Computer-generated optimum hardwood log sawing. Some funding also came from the USDA Forest Service Southern Research Station at Blacksburg, Virginia.

The R&D

The research of this group addresses the issue of how internal log information can be best put to use. The group does not deal with non-destructive log scanning, nor internal log defect recognition, which have been large tasks of the LSU group and the USDA Forest Service group. The objective of their research is to develop a computer integrated hardwood processing system that uses intelligent computer tools to integrate all the log processing stages from log breakdown to furniture components extraction. In other words, hardwood processing is optimised as a whole, rather than individual processes improved unconnectedly with one another.

Occeña uses the *Computer Integrated Manufacturing* (CIM) concept as the approach to achieve these objectives. "Computer integrated manufacturing (CIM) is neither a type of technology, nor a set of techniques". It is a way of thinking, an approach to interrelate individual procedures and not to make decisions separately in isolation. Technology itself can improve an area of specialisation hence increase the efficiency of an individual step of production. However, technology is not the key to streamlined production if different stages of a production are not coordinated. The central role of CIM is to establish communication and information flow between processes at different stages (Occeña, 1991). The result is reduced waste and efficient whole production. Occeña is able to take this research approach owing to his Industrial Engineering background. This group's work along this line has had about 10 years of history.

This group has developed various computing methods and software to carry out individual processes encompassed within the integrated automation system. These methods and software include[2]:

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[1] A figure published in the Annual Report of College of Engineering, University of Missouri-Columbia. The author does not know the amount of funding in that year, or before and after that year, from other sources.

[2] Information presented here is based on that available to the author.

A graphic log sawing simulator

This simulator was developed in late 1980's as a supporting analytical tool for a larger automated hardwood log breakdown planning system (Occeña and Tanchoco, 1988). It later became the core engine of an interactive graphic sawing program that is described in the following text. It has 3 modular components: the main control program, the polyhedral solid modeller, and a lumber grading program. These 3 components can be replaced by other programs of similar capacity. The log data input can be that obtained by physical sawing, or by using X-ray CT or NMR methods. The log model is boundary representation (BRep) based. The log and its defects are represented as polyhedra. The polyhedral model approximates the true log shape and the internal defects more closely than using truncated cones and cylinders to represent the log shape, and rectangular boxes to represent internal defects. The simulated sawing is performed using a Boolean operation between closed solids.

Methods of constructing solid log model

This group has developed a method to construct a log model from data obtained by physical log sawing. Yellow poplar logs were physically sawn and 3-D log representations were generated from the measured data (Occeña and Tanchoco, 1988). The advantages of solid models over non-solid models are their precision and flexibility in representing the log and internal defects.

Methods to reduce the size of solid log model

Solid log models often contain massive data. Large data input considerably slows down data analysis. Large data files can be condensed by taking out repetitive information. This group has developed a method to heavily reduce the size of a solid log model, in particular, a model reconstructed from CT log data (Occeña, Chen and Schmoldt, 1995). The basic idea of this method was to remove log cross-sectional profile information that does not have significant influence on the overall log external profile variation. A CT log was used in developing and testing this method. The number of slices of the solid model representing this CT log was reduced by 59% but the volume of the resultant log was reduced by only 0.03%. The integrity of the solid log model was not sacrificed. The data size was reduced from 10 MB to 600 K. To retain internal defect information, only the cross-sectional log slices that neither contain defect information nor have significant influence on overall log geometry will be dispensed in reality.

A hardwood automatic edging system	This group has developed a fast hardwood edging automatic decision-maker (Occeña and Wang, 1992). It is logic-based and consists of 4 parts: wane edge projection, surface edge calculation, edging position, and edging decision generation. As a part of this automated edging system, the group has also developed a hardwood lumber grading program, that is presently undergoing test. The major operational difference between this program and the grading programs developed elsewhere earlier is speed. This program can grade a piece of lumber in less than a minute, often within a few seconds. The other grading programs such as that developed at West Virginia University could take 30 minutes to grade a piece of highly defected lumber (pers. comm. Occeña).
An interactive GRAphic Sawing Program (GRASP)	This group, jointly with the USDA Forest Service group, have developed a prototype interactive GRAphic Sawing Program, *GRASP* (Occeña and Schmoldt, 1995). This program can be used as an analytical and training tool for modelling various operations of hardwood processing from log bucking, log breakdown, board edging and trimming, extracting furniture components, to flitching and veneering. Based on solid modelling principles, *GRASP* has a robust foundation in geometry and topology. Running on a microcomputer platform makes the program more affordable and accessible to users. *GRASP* is an improved and enriched version of the graphic sawing simulation program developed earlier by Occeña and Tanchoco (1988). It has incorporated a number of graphics-orientated programs, such as rendering an object as a see-through wire-frame image, viewing an object from various angles, and magnifying or reducing the scaling of an image.

Response to Internal Log Scanning Research and Funding

The USDA group have a more or less recent intention towards building an X-ray CT pilot log scanner. However, they seem to have a less ambitious or less “involved” approach towards this aim. They have not tried to pursue a large special government grant for their X-ray CT log scanning research. Being a part of the government, they have been limited in the past in seeking large grants from other government programs. This situation might have changed for better with a new program in place now, which requires collaboration from industrial partners (pers. comm. Schmoldt). This group did have tried to examine feasibility questions with wood processors and CT manufacturers, which is part of their effort in getting industry support. However, no one has committed to build a scanner to date because of the feasibility concern (pers. comm. Schmoldt).

The overall effort towards building an X-ray CT pilot log scanner and the progress accomplished so far in the USA are not comparable to those in Australia. This may well be explained by the situation that hardwood sawmilling research in the USA has not attracted much attention. According to Steele (pers. comm.), sawmilling research appears to be applied research in many people's mind. Consequently there has been a lack of funding for this research in general. One evidence is the absence of sawmilling research at the Forest Products Laboratory of USDA Forest Service. X-ray CT log scanning research therefore has little chance to attract much funding and no one in the USA is too surprised about it (pers. comm. Steele). The attitude toward sawmilling research is much more supportive in New Zealand.

The author has heard quite different statements regarding the industry's response to internal log scanning technology. According to Guddanti of the LSU group, the industry's reaction is quite warm. At least 5 hardwood mills in the USA will buy the scanners when they are available, and one mill will probably buy two. The cost is not a concern. One scanning system (scanner and optimisation computer software) will probably cost US$3 million. Guddanti's account of the industry's response is substantiated by the financial support their group has received from the sponsoring sawmilling companies.

According to another source (pers. comm. Schmoldt), however, the hardwood timber industry appreciates the x-ray CT-scanning idea, but is concerned about the high capital cost, high maintenance, and low scanning speed. One academic gave me a "realistic" or "pessimistic" analysis as follows. One US X-ray CT-scanner manufacturer claims that it is able to build an X-ray CT log scanner for US$6 million, and it will build these scanners if mills promise to buy them. However, no mills are prepared to buy a scanner at this stage, because the investment does not stop at the cost of the scanner itself. Other equipment will have to be integrated when implementing the scanner, costing probably more than the scanner itself.

The author tends to agree with X-ray CT log scanning researchers that some of the feasibility concerns are almost impossible to resolve without having a scanner built and run first. It will only be at that time, a full assessment or investigations can be made on aspects such as the actual technical capabilities and performance of the scanning system, areas for future improvement, technical and economical feasibility for such an improvement, and "real" cost and benefit analysis.

As a log scanning researcher, Guddanti holds a positive outlook of the future. According to him, external scanners for log geometry were regarded as very expensive 10 years ago and few mills were prepared to install them at that time. Now many softwood mills in the USA have installed external scanners, which cost about US$500,000 each. His view is that the X-ray CT-scanning technology is going through the same process. He believes that it is just a matter of time, and it may actually not take too long, for an industrial X-ray CT log scanner to become reality and be gradually taken up by the industry. His view is shared by Steele of Mississippi State University.

Mr. Bogue of Weyerhaeuser also has an optimistic outlook on the future of internal log scan technology (pers. comm). According to him, sawing optimisation based on external log geometry has been well accomplished for quite some years; it is the past in a sense. Identifying internal defects and using this information to raise optimal log processing to a higher level should be the focus of the current and future R&D.

Where is the potential application?

Sliced-veneer industry

X-ray CT-scanning has two great potentials for sliced-veneer production. One is to help mills to choose flitching options and slicing methods that will yield desired grain patterns (Schmoldt, 1996a). The other is to use internal log information to segregate marginal and better veneer logs from logs unsuitable for veneer production (pers comm. Schmoldt).

According to Guddanti, sliced-veneer mills have not given warm response to internal log scanning technology because they think their logs are clean thus there is no need to scan them. The LSU group have had a difficult time to get veneer mills involved. On the other hand, even if veneer mills wish to look for internal log defects, they might be more concerned about the cost than sawmills. The accuracy of defect detection is more critical for veneer logs. Scanners providing higher resolution and greater image contrast are therefore needed for veneer log scanning. Consequently, veneer log scanning could be 3 times as costly compared to sawlog scanning (pers. comm. Schmoldt). More work will be needed to improve the defect detection ability of the computer programs as well.

Hardwood sawmills

The LSU group believe that hardwood sawmills producing 20 million BF (47,200 m^3) per annum and above are in a viable position to benefit from this technology. This judgement is based on an assumption of a 13.5% increase in total product value and US$3 million for the scanning and optimisation system (Chang and Guddanti, 1995). The actual amount of profitability depends on the size of the mill, the size of the mortgage, and any other cost associated with installing and keeping this system running (Chang and Guddanti, 1995). The author considers that wood species, the quality of logs, market price, etc. are also important factors. Smaller mills may also benefit from this technology if other factors are favourable.

The log scanning system may be integrated into sawmill production at one of two different stages (pers. comm. Guddanti):

On-line before the headrig. Potential problems with this arrangement are disruption of log breakdown if the scanning system malfunctions.

In a yard. Logs are scanned, tagged, and stored in a buffer. The disadvantages with this arrangement are the time and effort required to keep track of the tags and to search for the information matching each tag at a later stage. The CT data are massive. Astronomical space is needed to store the information of hundreds of scanned logs.

A number of researchers believe that only mid-quality logs (accounting for about 60% of total log resource), in particular *the grade 2 logs*, can benefit substantially from internal log information. Sawing optimisation will not make much difference to value increase for high quality and highly defective logs. Even though visual grading fails to identify or "unintentionally creates" internal log defects from time to time, grading errors are generally very small for top quality logs. In addition, no particular log orientation and sawing sequence are perceived to be significantly better than others for top quality logs. It is therefore not economically justifiable to scan every top quality log to make sure that every small defect is correctly identified. Similarly, no particular log orientation and sawing sequence are perceived to be significantly better than others for highly defective logs. However, these views have been questioned by Steele. One of their recent studies (Steele, et al., 1994) shows that a higher value increase from optimum sawing orientation was achieved with better grade logs, although the difference was not statistically significant due to a large variance between the value yields at each orientation. Except for this study, no one has actually examined the relationship between log grades and the outcome of sawing optimisation for hardwoods (pers. comm. Steele).

Softwood sawmills

Everyone visited by the author thinks that X-ray CT-scanning technology does not fit into softwood sawmilling production at this stage because of the high speed of softwood sawlog conversion, which is about 10 times higher than hardwood sawlog conversion. Softwood sawlogs have been live sawn and the production is volume driven. The cutting pattern therefore has been dictated by the external shape of logs. The sawn boards are cut to standard thickness, width, and length. Most softwood boards are for structural application and there is plenty of log supply presently. The softwood sawmilling industry may have to consider improving grade recovery if log prices keep rising in the future, and when log scanning and data processing become considerably faster.

Summary of Major Observations

Hardwood resources and hardwood sawmilling industry

There are approximately 79 million hectares of commercial hardwood forests in the USA. Ninety percent of hardwood forests are grown in the Eastern regions. Hardwood forests are almost all naturally regenerated because natural-look hardwood forests are preferred and the forests naturally regenerate well themselves. There are very few hardwood plantations in the USA.

Approximately 70% of the hardwood forest resources are privately owned, accounting for 67% of the volume of hardwood harvest. Because of this, log harvesting and log merchandising are more or less a matter determined by the private owners.

In the USA, hardwood log grading rules are rarely used by industry as these rules are considered complicated, and also there is a lack of training.

There are approximately 4,500 -5,000 hardwood sawmills in the USA with most distributed in the Eastern states. Most hardwood sawmills are small, producing below 10 million BF (23,600 m^3) of sawn timber products per annum. Only about 20-25 individual hardwood sawmills have output larger than 10 million BF (23,600 m^3). Mills producing more than 20 million BF (47,200 m^3) per annum are rare.

The hardwood sawmills in the USA share quite a few similarities with Australian hardwood sawmills. The mills are run in the old traditional manner, and are often reluctant or not ready to make relatively large capital investments to improve their operational efficiency and product yields.

Views on the economical feasibility of X-ray CT-scan technology

The incentive for developing X-ray CT log scanning technology is to improve log value yield. This incentive is likely to become stronger as log prices rise. In both the scientific community and wood industry, there are few doubts about the usefulness of internal log information.

Most researchers agree that X-ray CT-scanning is at present the best method for detecting internal log defects and growth ring features. In terms of resolution and feature contrast, X-ray CT compares favourably with other methods such as microwave, ultrasonic, and NMR[1]. The drawback, however, is its high cost.

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[1] Microwave and ultrasonic are not applicable to log scanning; NMR not suitable for industrial scanning (pers. comm. Davis).

There are split views on the economical feasibility of X-ray CT-scan technology among both researchers and mills. Two economical feasibility studies were completed a few years ago, and there still remains some concerns. Evidence indicative of these concerns is that the industry does not have 100% confidence to commit large amounts of funds to expedite internal log scan research. Not helpful to this situation, hardwood sawmilling research itself has not been in a good position to attract large grants, and there has been overall cuts in the scientific research budget in the USA which have placed serious constraints on all funding.

Additionally, one academic raised a concern about other investment costs that possibly have to come following the installation of a log scanner, involving purchasing new equipment and changing exiting mill set-up.

X-ray CT log scan research

Each group either has a combination of required expertise in hardwood processing, CT data processing and analysis, and computer software development within the group (eg. the LSU group and the USDA Forest Service group) or are able to gain this combination by collaborating with people in other disciplines (eg. the University of Missouri-Columbia group). X-ray CT log scanning research requires strong skills in CT data processing, image processing and analysis, and normally is beyond the scope forest product researchers can handle by themselves. The combination of expertise or collaboration has made it possible for American forest product researchers to initiate and undertake complicated projects such as X-ray CT log scanning.

CT data processing and analysis are not in the author's field of expertise. Thus the author is not in a good position to judge American researchers' accomplishments in defect detection and to compare it against the achievements made by others. Nevertheless, the author's overall impression is that more people have been working on defect detection in the USA, resulting in an appreciable number of publications as compared to the field worldwide. On the other hand, commercial confidentiality could be a major reason for a less publicity on similar research by other overseas groups.

It is not clear how precise the existing defect detection techniques are. A Neural-net based technique has been recently explored. Considerable work still seems needed in order to improve the speed and accuracy of defect detection, which is a challenging part of CT data analysis.

Since the log scanning research was initiated and mainly carried out by forest product researchers, strong emphasis has been put into developing CT-based decision-making computer software tools. Remarkable progress has been made in this area in the USA. The examples are *TOPSAW-HW*, the CT-based simulator for veneer slicing, and *GRASP*.

There is a long history in sawing simulation, sawing optimisation, and sawing automation research in the USA for hardwood and softwood log conversion. It is the author's impression that expertise in these areas are concentrated in the USA, Canada, and New Zealand. Achievements in these areas provide the very necessary knowledge base and framework for incorporating log internal information into sawing automation software tools. The USA is in an advantageous position to keep a lead in developing the CT-based decision-making software tools, and will probably maintain this position for some time.

X-ray CT log scanning research is costly. The research has not been on a large scale in the USA because of limited research funds and lack of large industry financial support. The work has continued up till now largely because of the commitment, dedication and strong belief the researchers have had towards this technology.

Most researchers believe that internal log scanning and subsequent optimal sawing solutions will enable mills to benefit substantially only from mid-quality logs. However, this view has been questioned and further research is required to clarify the picture. The correct answer is crucial because it helps to develop appropriate log scanning schemes. Unnecessary scanning costs can be avoided by segregating out logs that have no reason to be scanned.

The overall effort towards building an X-ray CT pilot log scanner and the progress accomplished so far in the USA are not comparable to those in Australia.

Thoughts of the Author

Using X-ray CT log scanning technology on the right raw material

Scanning costs probably do not vary too much between hardwood species when the same scanning system is used. With similar scanning costs, a "promising" species will bring back far more profit than a "low-pay-back" species. Two aspects decide whether a species is "promising". Firstly, the species is already or will be able to catch a high market value. Politically, it is sound and correct to use X-ray CT-scanning technology to recover some good wood from residual logs. In economical terms, using this technology on "low-pay-back" logs will only result in an alarming loss to the mills. Secondly, the species is something that mills already know how to successfully process through most, if not all, value-adding stages. In other words, the mills already have sound techniques to make the wood perform from the beginning to the end of the processing.

Economically sensible sawing solution

One measure of efficient log conversion is high log value yield. Internal log information and subsequent optimal log conversions enable mills to obtain the highest value yield from logs. However, it must be realised that high log value yield is not necessarily the only driving force for log processing. It could be risky to push for the highest value yield without bringing other factors into balance. Mills need to know what is the production cost when pushing for a higher log value yield. Mills also need to know how big the market is for the sawn products resulting from various promising sawing solutions. The final factor that decides the use of one particular sawing solution is the overall mill profit, NOT necessarily the highest log value yield. Mills can be greatly aided by computer integrated simulation software to look for an economically sensible combination of product grades and dimensions as well as an economically sensible conversion process.

Hardwood boards should appear as trimmed slabs rather than standard-size boards?

Australian hardwood logs have historically been sawn to produce structural timber of standard sizes like softwoods. Value-adding the hardwood resource has started and will be the future trend for the Australian hardwood industry. Wood manufacturers are keen to utilise every possible piece of useable wood, especially in countries where log prices are high and clear wood catches high prices. Small-size wood is no longer regarded as useless. Gluelaminated products are finding their way into the Australian furniture market. Facing these changes, will it be sensible in the future to remove the resizing process from hardwood sawmills so that the products of primary hardwood log conversion are trimmed slabs in "free" width (preferably large width?) and less restricted length? There is no sound reason to size slabs to standard widths during primary conversion as in current practice if the slabs will be resawn at a later stage to yield product components for final use where dimensions are highly variable. Wider slabs will offer more resizing options and result in higher recovery of dimension products.

Investigate the level of value increase when sawing eucalypts

Sawing eucalypts can be more complicated than sawing most American hardwoods. Due to the presence of residual growth stresses in eucalypt logs, certain combinations of sawing patterns and sequences must be followed in order to minimise board and/or flitch distortion. As a result, it is impossible to always position the saw blade at a would-be-ideal location to minimise the down-grading effect of internal log defects. It would be of great interest and importance to find out what value increase we can get from optimal log orientation and sawing patterns with eucalypts, and compare these figures with those found with American hardwoods.

New approach to assess log value

When mills purchase logs, they wish to know what and how much they can get out of the logs. Should log "grading" move towards supplying mills with information on the product potential of logs in the future? Is there still a need in the future to put logs into concrete grades in the same fashion as present? Should optimal log grading and allocation be driven by product potential of logs? With external and internal log information, a prediction can be made for individual logs on their product potential (either veneer or sawn boards) and the production cost. Product potential of logs is measured by the market demand for what the logs can best offer and the production cost. Thoughts and views similar to the author's have been expressed by Steele and Chang.

Real time CT data processing crucial?

Real time defect recognition may not need to be as critical as considered by some researchers as a precondition for successful implementation of CT scanning systems. This is especially so for log merchandising and segregation. Logs can be scanned and tagged. A few, rather than one computer system can be set up to process and analyse CT data, and work out optimal sawing or veneering solutions. Following is a possible operational model for a sawmill. A sawmill has piles of scanned and tagged logs. The data files are stored in their data processing system. The mill knows what grade and dimension they need to produce. They can go through their log data inventory prior to log processing (even quite a few days in advance) to decide which logs to use and how to process each of them. In this case, real time data processing is unnecessary, although a faster data processing system is preferable.

Recommendations

Feasibility study needed

We could make a safe assumption, that if mills know for sure they can get a good profit by implementing a technology, they will go ahead and invest. A case in point is that Bunnings Forest Products Pty Ltd has invested in excess of 26 million dollars into researching and developing the state-of-the-art predriers and high temperature kilns for jarrah timber (*E. maginata*). They have accordingly installed 5 predriers and 1 high temperature kiln, costing multi-million dollars each. The result is a significant reduction of drying time, which then enables the company to value-add 80% of their jarrah by drying the timber and making high quality furniture grades and mouldings.

Sawmills know the value of internal log information, although not quantitatively in exact terms. They seldom need others to convince them of this point nowadays. X-ray CT log scanning systems can be successfully built in the future. The cost of this system itself does not appear to be a determinant factor in mills' decision in taking up or rejecting it. Mills know they can get something out of this scanning system. What they do not know with enough certainty is how much profit they can get and the pay-back time. They are probably also not clear of the level of "hidden" or unforeseen investment that is tied to implementing and running this scanning system. These doubts, or answers to these doubts, will determine the investment decisions of various sources on log scanning R&D, to either shield away or support it.

A sound and complete economical feasibility study is needed to clear the existing doubts. The outcome of this study will help everyone understand the correct conditions, the associated cost, the profit margin, etc. when implementing this technology. Mills should then be able to make a well founded judgement on whether they are in the right position to implement the scanning technology.

Support log scanning research

There is an increasing need to get more efficient use out of logs. There has been a continuing effort in Australia, Europe, and North America, to develop a non-destructive log scanning technology for the forest products industry. The benefit from such a technology through various applications was briefly discussed in the *Introduction* of this report. Industrial log scanners will most likely become more affordable with time as the manufacturing cost drops and more mills start to use them.

While economic doubts exist over the near-term feasibility of X-ray CT log scan technology, the potential advantages in the long term are enormous. Industry is typically wary of committing itself to a long-term investment without confidence in a positive cost-benefit. Government and corporate planners need to be able to project costs on a long-term basis as major research and development undertakings commonly take several years of effort.

The Australian effort in developing the X-ray CT log scan technology should be actively encouraged.

Determine relationship between log grades and sawing optimisation

Further research is required to clarify the relationship between defectiveness of logs and sensitivity of sawing optimisation. The correct answer is crucial because it helps develop appropriate log scanning schemes. Unnecessary scanning cost can be avoided by segregating out logs that have no good reason to be scanned.

Develop CT-based decision-making software tools

It is obviously too much of a task for the human brain to process external and internal log information and work out optimal log processing solutions. Decision-making computer software must be developed for fast evaluation of all possible sawing solutions. Sawing simulation and optimisation research for hardwood has been on a limited scale in Australia. One option for Australia is to watch for expertise in other countries to develop these software tools and customise the software after they are commercialised. There are drawbacks to this option. Firstly, Australia is not giving itself a chance to develop the expertise in this field, thus it would always depend on others. Secondly, customising the off-shelf software tools may take as long and cost as much as to self-develop the decision-making software. A better approach is to bring Australian expertise and industry together, and if necessary to recruit overseas expertise, to help developmental work in Australia. The developmental work for CT-data utilisation is not simply to write decision-making software. It requires substantial sawing research to pave the ground and propel the needed breakthroughs. Because of this, the developmental work should take place in the near future, especially if the Australian effort of building an X-ray CT log scanner gets the next-phase funding to proceed.

Develop a computer simulator for veneer slicing	Develop a computer simulator for veneer slicing. This simulator will enable learners to flitch a log and slice a flitch on a computer in any way they want. By providing cost/benefit analyses, the learners will be able to identify better flitching and slicing options. This simulator can also be used to determine the profit yield of veneer logs, thus to segregate veneer logs from sawlogs. When veneer mills have to process smaller logs in the future, which they have little experience with, this simulator can assist them to better understand and handle that new resource. The potential of this simulator will be fully realised when internal log information becomes available in the future. In Australia, defect and colour variation are the only two factors determining the value of sliced veneer from local hardwood species. Because of this, using CT log data to decide flitching and slicing scheme for various wood grain patterns in the veneer does not have an immediate application in Australia (per. comm. B. McCombe).
Optimise hardwood log cross-cutting (bucking)	A saying, if not too exaggerative, has been heard over again and again: the man who cross-cuts bushlogs into sawlogs at a sawmill can either enrich or break the mill. Optimal log cross-cutting has been a satisfactory commercial practice for softwoods, which does not require direct measure of internal log information. For hardwoods, internal log information is essential in optimising log cross-cutting, and full optimisation can not be achieved without an "inside-out" diagnosis of the logs. Nevertheless, there must be a room for improvement on the present bushlog cross-cutting practice, which does not require direct measure of internal log information.
Develop computer training programs for grading hardwood logs and hardwood sawn boards	Develop computer training packages for grading hardwood logs and sawn timber. By using an interactive training package on a PC, the learner can learn by himself/herself. The training package teaches step by step how to grade a log or a board. It informs the learner whether a log or a board is graded correctly, and more importantly, where and why there is a mistake. Computers nowadays are reaching every aspect of life at an amazing speed. The old attitude and methods of learning should be examined, and changed if new methods do a better job. Experiences in developing these training packages could also serve as a good exercise for future development of decision-making software tools.

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Itinerary and Major Contacts

Week 1	Louisiana State University Baton Rouge, Louisiana	Professor S. Joseph Chang Dr. Suresh Guddanti
	Mississippi State University Starkville, Mississippi	Professor Fred W. Taylor Professor Philip H. Steele Professor R. Daniel Seale
Week 2	USDA Forest Service Southern Research Station Blacksburg, Virginia	Dr. Daniel L. Schmoldt
	Virginia Tech Blacksburg, Virginia	Dr. Earl Kline
	University of Missouri-Columbia, Missouri	Dr. Luis G. Occeña
	Missouri Pacific Lumbers Pty Ltd Missouri	via Dr. Luis G. Occeña, University of Missouri
	Stanton Manufacturing Company INC. Missouri	via Dr. Luis G. Occeña, University of Missouri
Week 3	Minneapolis Minnesota	Forest Products Society 1996 Annual Meeting
Week 4	USDA Forest Service Forest Products Laboratory Madison, Wisconsin	Mr. Theodore L. Laufenberg Mr. Kent A. McDonald Mr. John "Rusty" Dramm
	Walnut Hollow Farms Pty Ltd Wisconsin	via Mr. Theodore L. Laufenberg of USDA Forest Products Laboratory
	University of Wisconsin Madison, Wisconsin	Mr. Gene Wengert
Week 5	Weyerhaeuser Tacoma, Washington	Mr. Gilbert L. Comstock Mr. Doug Hay Mr. David N. Bogue
	University of Washington Seattle, Washington	Professor David Briggs