INTERNAL LOG SCANNING: RESEARCH TO REALITY

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ABSTRACT

Improved log breakdown into lumber has been an active research topic since the 1960's. Demonstrated economic gains have driven the search for a cost-effective method to scan logs internally, from which it is assumed one can chose a better breakdown strategy. X-ray computed tomography (CT) has been widely accepted as the most promising internal imaging technique. Six design and operational constraints needed to be satisfied, however, for industrial CT of logs to become a viable reality. These are aperture size and reconstruction circle, scanning speed, scanner duty cycle, harsh industrial environments, radiation safety, and effective application software. Current airport security scanners have achieved those goals and have bridged the gap between medical CT applications and industrial CT. The log scanning application has numerous similarities with the explosive detection application, which points to a relatively straightforward transition. A recent mill test of CT log scanning validates the value gains that can be realized. In some cases, those gains may become more pronounced in later processing stages. However, upstream sorting and product allocation can also lead to better resource use and an improved bottom line.

INTRODUCTION

Hardwood log breakdown is currently limited by what can be seen on the outside surface of the log. Log shape and wood surface defects are the only log features accessible to most sawyers. Log buyers and graders gain additional information from bark characters. In some cases, visual information for sawyers is augmented by external "sheet of light" scanning for shape, and by breakdown "optimization" software. Because the type, size, and placement of defects on boards determine most lumber value, however, the lack of internal log information

drastically restricts log value improvements. Real advances for this critical sawmill operation are dependent on internal log scanning, which can markedly increase mill lumber value recovery by up to 20% or more (Table 1) merely by selecting different log orientation or breakdown strategies.

The value improvements reported in Table 1 are conservative in most cases. For example, Steele et al. (1989) examined live-sawing and grade-sawing methods with multiple orientations, finding that selecting a better log orientation can increase value 12% over standard sawyer methods. There was no attempt to fully utilize internal information. Similarly for Richards et al. (1969), live sawing was compared to 4 variants of grade sawing, incorporating 12 orientations for each method. Not surprisingly, the results are essentially identical. Except for Steele et al. (1989), most researchers have found percentage value increase differences between log grades, with lower grade logs exhibiting greater relative improvement. One possible explanation for this difference is that the bottom-line comparison used by Steele et al. (1989) was a standard sawyer log breakdown rather than the worst value recovery orientation, as the other investigators used.

Table 1. Numerous past research studies have examined log breakdown value improvements.

Year	Author	# of Logs	Species	% Improvement
1962	Peter	10	Southern Pine	3%
1967	Peter	50	Yellow Poplar	9%
1969	Tsolakides	6	Red Oak	21%
1975	Wagner and Taylor	10	Southern Pine	8%
1980	Richards *et al.*	320	Red Oak	11%
1989	Steele *et al.*	24	Red Oak	12%
1994	Steele *et al.*	6	Red Oak	10%
'94-'99	Chang and Guddanti	10	Red Oak	18% -28%

For about 20 years, research has been conducted to find technologies to scan logs for internal defects. X-ray technologies have been the most widely investigated, including computerized tomography (CT). CT was identified, along with nuclear magnetic resonance imaging, as the most promising technologies for internal scanning of logs (Hodges et al. 1990). Therefore, much of the past research has focused on CT technology or other tomographic methodologies.

While economic analyses indicate that lumber value gains can offset internal scanning (CT) costs (Chang 1989, Hodges et al. 1990) there are several technological hurdles that must be overcome for the application of internal log scanning in general, and CT scanning in particular. CT technology was first introduced for medical purposes in 1972. The vast majority of CT scanners produced are for this application. Until recently, CT scanning had not had any commercial success in applications outside medicine. The most attractive applications outside the medical field have been in industrial settings for non-destructive testing and evaluation, where quality control inspections are conducted on a small subset of product or where high-value items receive 100% inspections (e.g., rocket motors). These industrial uses are either time consuming or conducted off-line.

Additional hurdles include the following design and operational parameters: aperture size and reconstruction circle, scanning speed, duty cycle, durability/reliability in harsh industrial environments, radiation safety, and automatic inspection software. Each of these industrial concerns is examined below. First, however, some

background information on CT scanning is provided. We also describe a case-study application of a CT log-scanning prototype conducted at a sawmill, and present results from that test.

COMPUTED TOMOGRAPHY SCANNING

The initial description of the mathematical principle underlying computed tomography occurred in 1917 (Radon 1917). Basically, it is a method for calculating characteristics (e.g., density) of points in a 2-D plane by measuring an infinite number of ray-sums passing through the 2-D area that includes those points. A variety of energy sources have been used to produce ray-sums when scanning materials. These include ultrasound, x-rays, nuclear particles, and microwaves. X-rays have been the preferred sensing method because they are relatively easy to generate and their high energies make them attractive for penetrating large or dense specimens.

CT scanning produces images that lie in the same plane as the x-ray beam (Figure 1). By measuring many simultaneous ray-sums and continually rotating the specimen (or source-detector pair), a detailed 2-D, cross-sectional image or tomograph is generated. By taking successive 2-D images it is possible to determine the internal appearance of a 3-D object. Specimen features that differ in density by 1-2% are easily distinguished in tomographic images. An image consists of a rectangular array (often square) of picture elements (pixels), where each pixel represents the attenuation coefficient of a small volume. This volume is determined by the size of the image pixel and by the thickness of the x-ray beam.

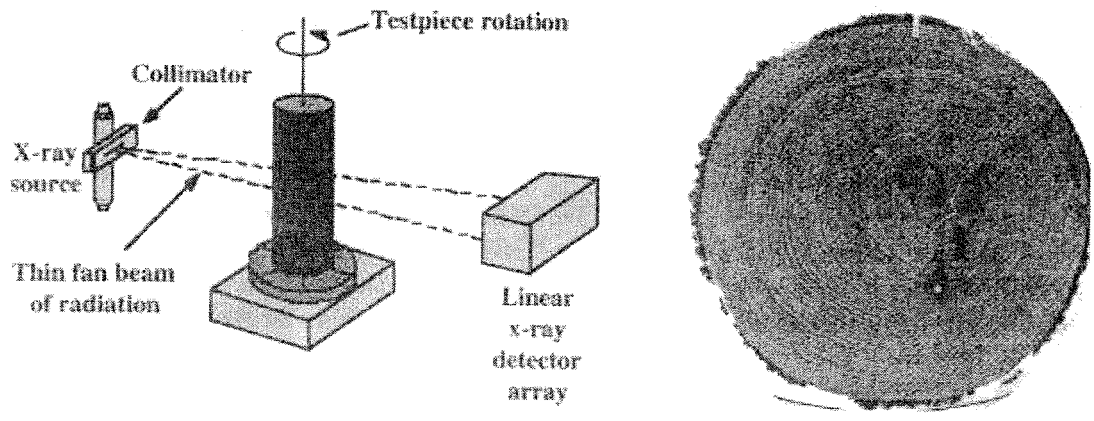

Figure 1. In computer tomography, the imaging plane is parallel to the x-ray beam and generates a cross-sectional image.

Log Scanning Research

Chemical similarities between human specimens and wood led researchers to consider CT scanning of wood objects. A number of investigations have examined the quality of CT images and their use for wood density and moisture content estimates and for the identification of internal structures (Benson-Cooper et al. 1982, Birkeland and Holoyen 1987, Burgess 1985, Cown and Clement 1983, Davis and Wells 1992, Miller 1988, Onoe et al. 1984, Shadbolt 1988). All of these investigators have found that CT images provide a large amount of information about the internal characteristics of wood. Even for large objects, such as logs, internal structures are readily visible in a tomograph.

Empirical evidence demonstrated that the relationship between attenuation and density is very linear in woody materials (Davis and Wells 1992, Shadbolt 1988). Therefore, CT numbers can be broadly interpreted as density measures. Because knots, bark, decay, sapwood, heartwood, voids, etc. have different densities, CT numbers on tomographs can distinguish these features. Pixel by pixel, CT numbers can be used in subsequent image processing steps to segment and identify relatively homogeneous regions.

There are several operational scenarios for incorporating internal log information into log sawing (Schmoldt 1996): 1) provide a 3-D image of the log as sawing occurs ("glass log") so that the sawyer can choose a best opening face using more complete (internal) log information, 2) couple computer rendering of the log and its orientation on the carriage to accurately control log positioning by manipulating the computer rendition, 3) have the computer suggest a best opening face to the sawyer and automatically position the log for that cut, or 4) have the computer suggest the next face to cut during grade sawing by tying log face rendering to computerized lumber grading software. Log breakdown assisted by 3-D rendering is "fully informed," where the sawyer has knowledge about internal feature size, type, and location.

To realize 3-D rendering of a log and its internal characterization requires automated feature labeling. Early work on automatically labeling of internal log defects established the feasibility of utilizing CT images for this purpose (Taylor et al. 1984; Funt and Bryant 1987; Zhu et al. 1991a, b, c; Som et al. 1992; Zhu et al. 1996). These researchers employed a variety of methods to segment different regions of a CT image and then to interpret, or label, those segmented regions. While these efforts have demonstrated feasibility, they lacked validated accuracy. More recent work (Li et al. 1996, Schmoldt et al. 1997, Schmoldt et al. 2000) has demonstrated highly accurate labeling of log defects in CT imagery. Accuracies of 91-98% (at the image pixel level) have been achieved for several hardwood species. This is sufficient for identifying all but the smallest log defects.

In a recent simulated sawing study, traditional sawing heuristics (Malcolm 1961) were compared to information-augmented heuristics that incorporate internal defect information (similar to what would be provided by CT imaging). The 18 red oak logs sawn (6 in each grade #1, #2, #3) contained only knot defects. While no attempt was made to optimize value recovery or to compare different orientations, 5% average value gains were achieved by information-augmented heuristics (grade #2 and #3 logs improved 10%) over comparable traditional heuristics. Certain heuristics performed better *on average,* but none did the best on all logs. This implies that the generalized log descriptors used in simple heuristics (e.g., best face, defects on edges) are far from optimal.

Trials using medical CT scanners (Figure 2) have historically been limited to small sample sizes (1-25 logs or log sections). Logs also needed to be cut into sections, scanned, and pieced back together electronically. Several researchers have developed software models to optimize logs based on the reconstructed log samples (e.g., Guddanti and Chang 1998, Occeña et al. 2000).

Industrial CT Scanning

The path to develop an industrial CT scanner started with medical scanners, where much early log scanning research was conducted. Unfortunately medical scanners could not simply be applied to sawmills. A number of limitations prevented ready application.

Low duty cycle

To operate in a sawmill a CT scanner must be able to operate up to 3 shifts, 5 days per week. It must operate continuously in many cases. Generally, medical scanners can only operate for short periods of time. They were designed for short duration use and for low radiation doses absorbed by the patient. Medical CT x-ray tubes require time to cool, while continuous operation causes the tube to fail. In a medical environment, there are long

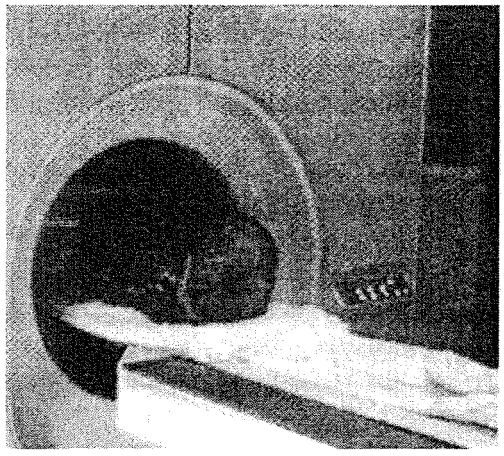

Figure 2. Medical scanners limit the size and weight of log sections that can be scanned.

periods of time between patients to allow for tube cooling. In a sawmill environment, there is no time between logs. Logs will be presented to a scanner in nearly a continuous stream throughout a shift. Sawmills will saw hundreds to thousands of logs per shift whereas a medical scanner will scan, at most, dozens of patients per shift.

Not self shielded - environmental conditioning

In most medical applications scanners are installed in specially designed rooms. The rooms are carefully controlled for temperature and humidity to protect the machine. Also, the rooms are lead-lined to prevent x-ray scatter from escaping. A luxury such as an environmentally controlled and x-ray-shielded room is not realistic in a sawmill environment. Machines will be exposed to extremes in temperature. Further, a specially designed shield room would add to the cost and complexity of a system installed at a sawmill. To get logs in and out of such a room would be a challenge.

Small reconstruction circle and aperture size

One important factor for CT scanning is that the object be entirely contained in the imaging or reconstruction circle. Medical scanners only need to image the human body. Therefore most have been designed with a maximum 40-50 cm reconstruction circle. Logs can be much bigger in diameter then this. Often the aperture of a medical scanner is larger than its reconstruction circle. In medical scanning this is acceptable because a patient can be carefully maneuvered into the scanner. Because of the high production rate of mills, scanner operators will not have time to carefully maneuver logs into a scanner. Therefore it is important that the aperture be a large as possible and the reconstruction circle match the aperture size. For the sawmill environment, an operator should only have to worry that a log fit through the aperture.

Just an imaging tool no auto inspection

For the most part, medical CT machines rely on an experienced doctor to interpret CT images. A doctor is afforded the time to properly examine each image. In a sawmill environment, a sawyer does not have the time to evaluate each image. Rather, images will have to be both quickly and automatically evaluated to determine the ideal method for sawing the log. To automatically evaluate a log and to meet production rates, a tremendous amount of computing power is necessary. CT machines produce a large volume of data regardless of the application. The amount of data collected in the sawmill application is no different, and in fact, may be

compounded by the need to acquire closely spaced (1-cm) slices over a 3-4 meter log. A single, 3-meter log produces upwards of 1.2 Gbytes of uncompressed data. Even when compressed, a single data set typically exceeds 15 Mbytes. Developing real time automatic evaluation software on such a large volume of data was not cost effective until very recently.

DEVELOPMENT OF A HIGH-SPEED INDUSTRIAL CT SCANNER

InVision Technologies, Inc. faced many of the same hurdles in the development of an industrial CT system for airport security that would be faced in developing a log scanning system for sawmills. These included all of the design and operational parameters described above. Side-by-side comparisons of the medical, baggage and log scanning applications with respect to those parameters are presented in Table 2.

To work in an airport environment, a CT scanner must be designed to accommodate standard baggage handling equipment. Baggage handling belts are up to 1 meter wide. Luggage is presented to the CT scanner very rapidly and in any orientation. Operators have no time to properly position a bag through a smaller reconstruction circle. Therefore, the aperture and reconstruction circle of a CT scanner in a baggage handling system must be more than 1 meter in diameter. This one-meter reconstruct circle and aperture size also happens to be very applicable to log scanning.

High speed is an essential requirement of CT scanners designed for airport security. Thousands of bags per day need to be scanned in a baggage handling system, with a throughput of 300 to 1200 bags/hr. Furthermore, airport security operates on a 24 hour, 7 day per week schedule. Once again, both the speed and duty cycle requirements of an airport are very similar to those of a sawmill.

Airport baggage handling environments can be dirty and dusty. Furthermore, they are characterized by high mechanical and electrical noise. CT scanners can be subject to extremes in temperature and humidity. Typically

Table 2. Medical, baggage, and log scanning application design requirements and operating criteria.

Criterion	Medical	Baggage	Logs
Aperture size and reconstruction circle	Human/animal 48 cm	Various sizes and orientation 1.1 m	Swept/crooked, longitudinal specimens 1 m (95%+)
Speed	15-30 min/study Minimize exposure	10 bags/min	8-16 ft/min
Duty cycle	Minutes (tube cooling time)	24/7 (continuous)	16-24/5 (2-3 shifts, 5 days)
Environment	Clean. quiet Temp. & humidity control	Mech. & Elec. Noise Dirty Temp & humidity variation	Mech. & Elec. Noise Dirty Temp & humidity variation
Radiation Safety	Shielded enclosure Supervised	Self-enclosed unit Unsupervised European safety standards	Self-enclosed unit Unsupervised
Application	Radiologist image interpretation	Automated detection	Automated detection Processing decision making

airports require equipment to operate in temperatures ranging from 20 °F (-7 °C) to 120 °F (49 °C) and up to 99% humidity. Airport CT scanners are subject to the most stringent cabinet x-ray standards to be licensed to operate unsupervised in a public environment. In terms of radiation safety, European standards dictate that an x-ray machine must be self-shielded and demonstrate less then 0.1 millirem/hr at the skin of the machine. Both the harsh environments of airports and the strict radiation safety requirements of airports are similar to those required in a sawmill.

To meet strict regulatory requirements, CT systems in airports must automatically analyze CT images of suitcases (Figure 3). Explosives need to be distinguished from a wide variety of "stuff" inside passenger luggage. Every object in a CT image will have a unique set of CT characteristics. The principle characteristic is CT number. CT numbers directly correlate to density. When automatically analyzing an image of a suitcase, every pixel is tested against a known database of explosives. If a pixel falls into the range of an explosive, neighboring pixels are tested. A region is grown consisting of adjacent pixels. If the area of that region exceeds an established threshold a 3-D object is built using adjacent CT images. If the volume of that object exceeds an established threshold the object is flagged as a possible explosive. This description is a simplification of the automatic inspection software used in explosive detection. In fact, hundreds of tests are applied to the pixels, the individual CT images, and 3-D volume to more accurately distinguish explosives from innocuous items in luggage. All of these tests are conducted in less than 10 seconds for a typical suitcase. Fast and accurate automatic inspection software is also a requirement of a log scanning system.

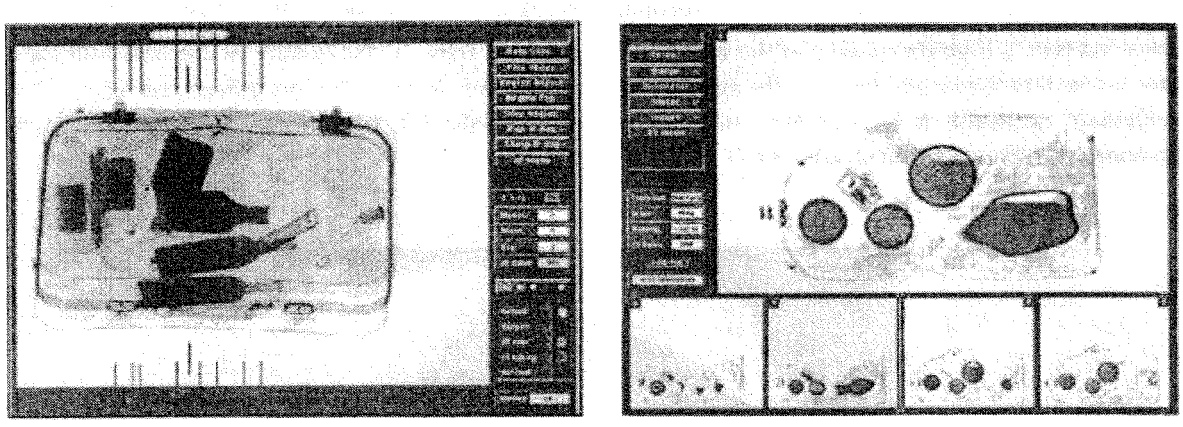

Figure 3. A radiographic image of a piece of luggage on the left shows that it is difficult to discern important features. The computer-processed image on the right depicts highly suspect objects automatically.

CASE STUDY

A prototype CT log scanner was taken to a medium-sized sawmill (~100,000 m^3/year) in Austria that produces window frames from spruce *(Picea abies)* and larch *(Larix decidua* [europea]). All logs, over 100 in this study, were processed using a band saw. All sizes and qualities of sawn products were chosen from the normal dimension and quality product lines of the mill. For value calculations, the mill provided current market prices for each product line.

Logs were randomly assigned to *scan* and *control* groups. For the *scan* group, logs were CT scanned, and reconstructed images were presented to the sawyers. Using a tool developed by InVision Technologies, sawyers

were able to see simulated board faces (virtual cuts) for different cutting positions. Selection of the cutting positions for log breakdown was done as usual, except that the sawyer could view deeper cuts without the risk of making expensive mistakes. Normally a thicker board has a higher value compared to thinner boards. But, without CT assistance there is also significant risk in cutting too deep into the log. The quality of the hidden face of a thick board may be worse then expected. In such cases, one or more high quality thin boards would produce more value. No additional computer-based optimizations were performed. Operators had no chance to become proficient with the CT system, because the tests were performed with several sawyers.

Depending on the overall quality of a log, varying amounts of sawing specifications were included in the sawing pattern. The inner (normally low quality) part of each log was never optimized and was processed normally. After complete optimization on the computer, the sawing pattern was transferred to the log end (Figure 4). Logs in the *control* group were processed according to normal mill operations.

After primary breakdown, mill experts graded all boards, without knowing which boards came from which group. Using lumber volumes and prices, the value of each log was calculated and summed for the groups. For a subgroup of 30 high-quality spruce logs with diameters of 51 cm and larger, the value increase per cubic meter was 6.3% (or 8.8%, if the best and worst logs in each group were removed). The data for this group appear in Figure 5. Other groups of logs showed increases from 0 to 18%.

Most of the high-quality boards of that mill are only an intermediate product for the window frame industry. They are processed into window slats in a secondary breakdown operation. If the classification of the primary board was correct, a high percentage of the board can be used for slats. If the quality of the board on the hidden side was worse then expected, many of the slats are lost and can only be used for low-priced products. Therefore, this secondary operation is an excellent indicator of how well the CT system can produce truly high-value boards compared to experienced sawyers.

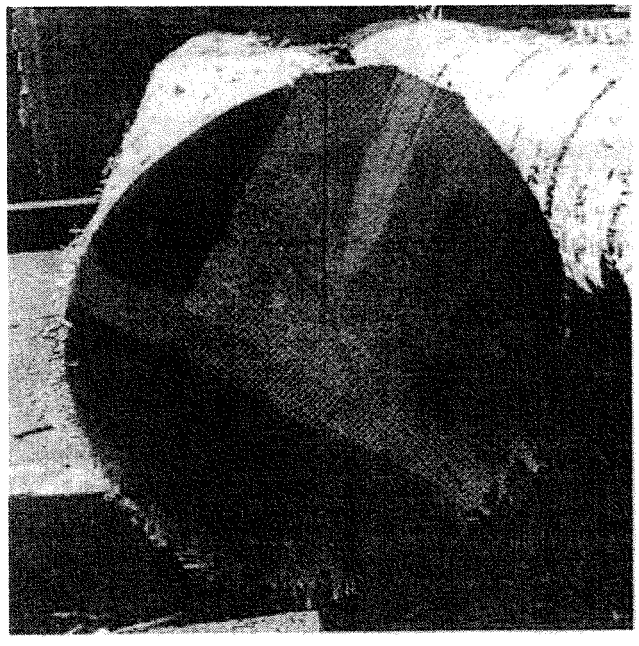

Figure 4. After examining virtual boards, the sawyer was able to mark the end of each log for later sawing.

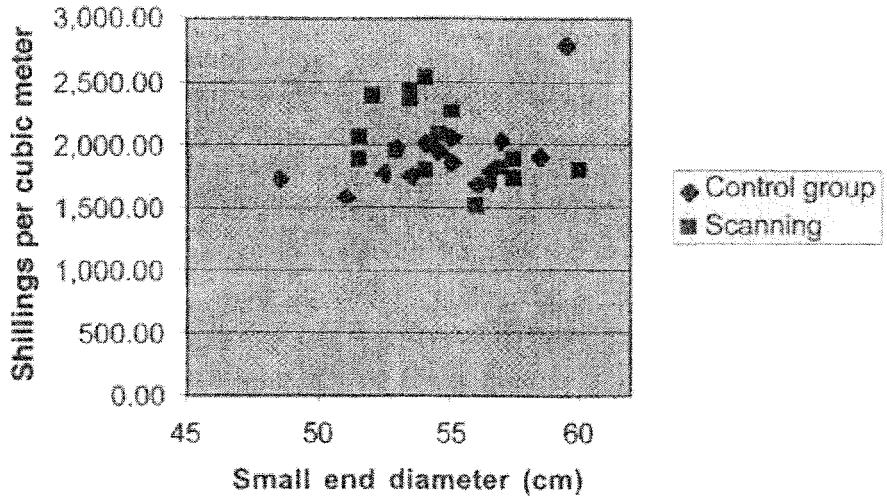

Figure 5. The values of sawn boards are plotted for *control* and *scan* groups by log diameter.

When slats are produced from boards with a thickness of 153 mm, it is very difficult to correctly estimate the quality of the board on the hidden face. After grading the slats, the control group produced slats that obtained 31% of their value in grade *a* (the most valuable grade). Most of the value appeared in class *b,* and 20% remained in classes *c* and *d,* which are low-quality/low-price classes. Bad sawing decisions affected the value distribution dramatically. On the other hand, CT-optimized boards obtained 71% of their value in class *a* slats, and only 1% in the low quality classes.

DISCUSSION

While these mill results show substantial gains from internal log scanning, there are several reasons for failing to achieve even higher value increases in this study. First, logs with very bad overall quality have too many defects. Human graders can not easily find a good cutting solution for very complex scenarios. Therefore, they refused to even try to find one for some logs. For the few logs they tried, a clear improvement could be demonstrated. Second, completely automated systems will be able to find better results even with high numbers of defects, if there are enough quality classes and sizes to use. Third, a limited number of possible quality classes and sizes reduced the possible improvements that were possible. This reduced complexity, however, and was easier for human graders to handle when viewing virtual boards. Human graders must learn to take advantage of the huge amount of additional information available. During the study, they mainly used the image of the reconstructed board faces for their decisions.

CONCLUSIONS

Our brief tour of past and recent log scanning research allows us to make a few observations. First, application of internal scanning information to improve log breakdown requires either (1) new sawing heuristics to achieve more than moderate value increases; (2) a fast, limited search of sawing orientations with a fixed heuristic; or (3) a new approach that combines different heuristics and log orientations. The latter possibility is relatively difficult owing to the nonlinear-time combinatorics of the search space. Second, lower quality logs seem to benefit most

(in terms of percentage improvement) by alternative sawing methods or log orientations. Third, airport baggage inspection has many design and operating parallels with the needs of industrial log scanning. This should facilitate a relatively easy engineering transition. Fourth, in some wood applications internal scanning value improvements may actually be realized in later processing steps, beyond initial breakdown. Finally, upstream sorting and product allocation (by the sawmill) can be improved by internal scanning. For example, marginal-quality logs in our case study could have been sorted out and removed from window-frame processing. This would have further increased the benefits of CT scanning in this mill study.

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