

Cooperative Use of Advanced Scanning Technology for Low-Volume Hardwood Processors

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Abstract— Of the several hundreds of hardwood lumber sawmills across the country, the majority are small- to medium-sized facilities operated as small businesses in rural communities. Trends of increased log costs and limited availability are forcing wood processors to become more efficient in their operations. Still, small mills are less able to adopt new, more efficient technologies due to initial cost, payback period, and modifications to operations. Based on the current marketing structure in the hardwood industry, the prevalent links between small- to medium-sized landowners and similar sawmills are log concentration yards. This paper examines the utility and logistics of locating industrial CT scanners in log concentration yards. If installed, logs can be scanned, automatically graded, and potentially optimized for sawmill breakdown (processing decisions) at the yard. By knowing the correct grade of each log, a mill can properly manage its log inventory. In addition, by knowing the internal structure of each log, a mill can optimize the sawing of that log. The advantage of this proposed system for the small mill is that it is affordable and, with little or no infrastructure changes, they can buy and utilize value-added logs that have been CT-scanned upstream.

INTRODUCTION

Wood Processors

With reduced timber harvesting on public lands, more pressure is being placed on individual landowners to supply an increasing demand for hardwood products. That pressure is also transferred to the sawmills that have to fill that demand with a relatively poor-quality log supply from cut-over lands. Historically, the highest value yields come from older trees, but current and future supplies of older trees, such as old-growth and long-rotation timber, are very limited (Luppold and Baumgras 2000). There are two approaches to this paradox. Either landowners must significantly change the way they manage their forests to produce more high-value logs (which is being done in some cases), or sawmills must turn to technology to better utilize existing, and anticipated, small-diameter, low-quality raw material.

Extracting high-grade lumber from diminishing timber resources has been an increasing challenge for most hardwood sawmills. Most large softwood mills and many large hardwood mills have implemented the latest sawing and optimization technology to increase lumber yield and value. Lumber yield over the past years has steadily increased with the advent of optimization technology. However, the capital cost of much of this advanced technology prohibits many

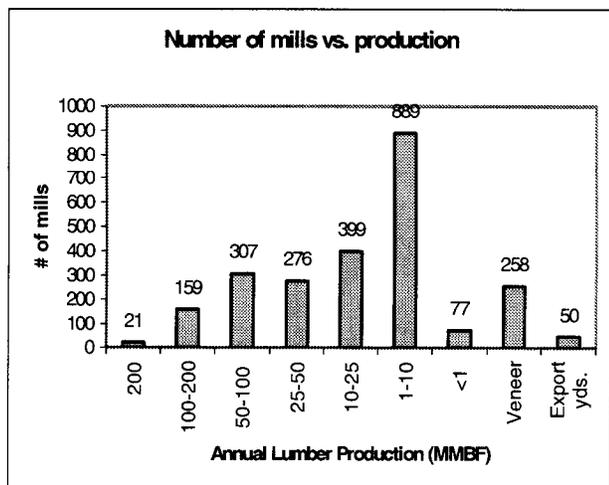
of the small- and medium-sized hardwood mills from participating in the propagation of technology. Small mills are under increasing financial pressure and face a difficult time ahead if they cannot access at least some of the advanced technology.

These small hardwood mills are numerous and important. Mills under 25 million board feet (MMBF) per year make up about 70% of hardwood mills (Figure 1). It is clear from the graph that small hardwood producers are a key contributor to the industry as they represent a significant share of the market. Nevertheless, fewer than 20% of the hardwood mills surveyed in 1997 by the newsletter *Hardwood Weekly Review* report the use of any new technology (Luppold and Baumgras 2000). In a recent survey of 424 sawmills, 63% reported no type of scanning or optimizing equipment in the sawmill operation (Bowe *et al.* 2001). The amount of under-utilization of advanced technology and the corresponding pressure on land use are significant.

Sawmill Operations

In contrast to softwood lumber, which is valued in terms of volume and mechanical strength, the value of hardwood lumber is based more heavily on appearance-related criteria. For this reason, hardwoods account for most wood used in the manufacture of high-value furniture, cabinets, flooring, millwork, and molding, along with hardwood exports

Figure 1. Hardwood lumber production is concentrated in small (<25 MMBF) mills.

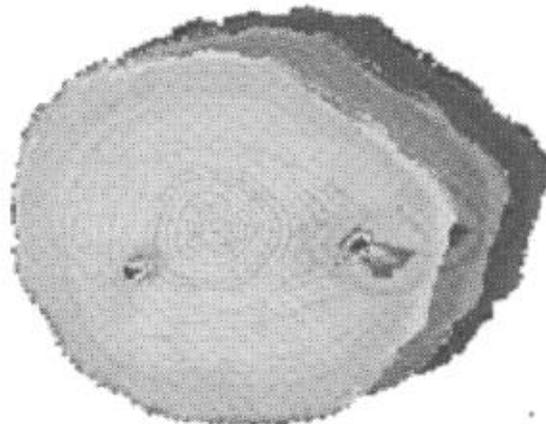


dependent on the quantity, type, and location of defects, thus each log must be sawn to minimize (subject to board sizing constraints) the number, size, and severity of defects in the resulting boards.

Conversion of hardwood logs into lumber involves a number of steps. While there are variations of twin line or twin-band headrigs, the following description is typical of a single-saw headrig. Logs entering the mill are debarked. Following this operation, they go to the headrig where a sawyer moves the log repeatedly past a saw to remove flitches (unedged and untrimmed boards) one at a time. The sawyer chooses a sawing strategy by visually examining the exterior of a log, and periodically picks a better grade face by rotating the sawing face as the log interior is exposed (Malcolm 1961). This type of sawing is *information-limited* in the sense that the sawyer only has knowledge of external indicators of internal features (e.g. knots) (Occeña *et al.* 1997). Flitches go through subsequent operations of edging and trimming, where defects and bark at the edges and ends are removed to increase the board's grade, and consequently its commercial value. The cant may either enter a resaw operation where additional boards are sawn, or may be sold intact for use in low-value products, such as railroad ties or pallet parts. During initial log breakdown, profit-critical decisions are made by the sawyer that can significantly affect downstream processing operations. This observation suggests that targeting sawlog breakdown improvements can drastically increase lumber value recovery, as well as volume recovery, for downstream operations.

The sawyer uses log shape, external indicators of internal defects, and knowledge of lumber grades to make sawing decisions. While sawyers are highly skilled in this task, studies (Tsolakides 1969, Richards *et al.* 1980, Wagner *et al.* 1990, Steele *et al.* 1994) have shown that the lumber value of logs can be improved anywhere from 10% to 21% by carefully selecting the proper sawing strategy. However, the current level of information available to sawyers during the log breakdown operation is inadequate for enhancing the

Figure 2. Tomography produces cross-sectional “slices” of a log that capture density-related internal features.



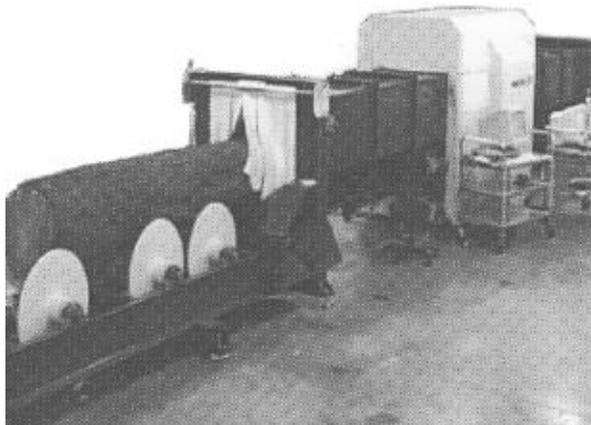
sawyer's capability to produce high-value boards. Developing nondestructive sensing and analysis methods that can accurately detect and characterize interior defects is critical to future efficiency improvements for sawmills (Occeña 1991). This type of sawing would be *information-augmented* in the sense that internal defect information is leveraged to obtain better value and volume yields from the log (Occeña *et al.* 1997). Increased information from scanning removes much of the guess-work that hinders sawyers' skill, and it also enables log sorting/processing decisions prior to breakdown.

Internal Log Scanning

Because most defects of interest are internal, a nondestructive sensing technique is needed that can provide a 3-D view of a log's interior. Several different sensing methods have been tried, including nuclear magnetic resonance (Chang *et al.* 1987), ultrasound (Han and Birkeland 1992), and x-rays (Benson-Cooper *et al.* 1982, McMillin 1982, Cown and Clement 1983, Onoe *et al.* 1984, Taylor *et al.* 1984, Burgess 1985). Due to its efficiency, resolution, and widespread application in medicine, x-ray computed tomography (CT) has received extensive testing for roundwood applications (McMillin 1982, Taylor *et al.* 1984, Funt and Bryant 1987, Roder 1989, Zhu *et al.* 1991a, Som *et al.* 1992). An x-ray CT scanner produces image “slices” that capture many details of a log's internal structure (Figure 2). Because x-ray attenuation is linearly related to wood density (Shadbolt 1988) and many wood features (including defects) exhibit density differences (Hopkins *et al.* 1982), many lumber-quality defects (e.g., knots, voids, and decay) are visible in CT images.

CT technology is quite capable of providing sawmills with valuable log processing information. The critical issue is how to introduce internal log scanning into an industry whose members have valid concerns about initial cost, payback period, and integrating new technology into existing mill

Figure 3. The current prototype log scanner includes specialized conveyors to move logs through the scanning ring.



operations. The next section introduces industrial CT, describes preliminary prototype tests conducted in a softwood mill, and covers CT data handling issues. Then, we present our vision of how private landowners and small processors can share CT technology, and we lay out a series of steps to accomplish this goal. Finally, we offer some observations on why this approach to technology transfer is particularly beneficial.

INDUSTRIAL COMPUTED TOMOGRAPHY

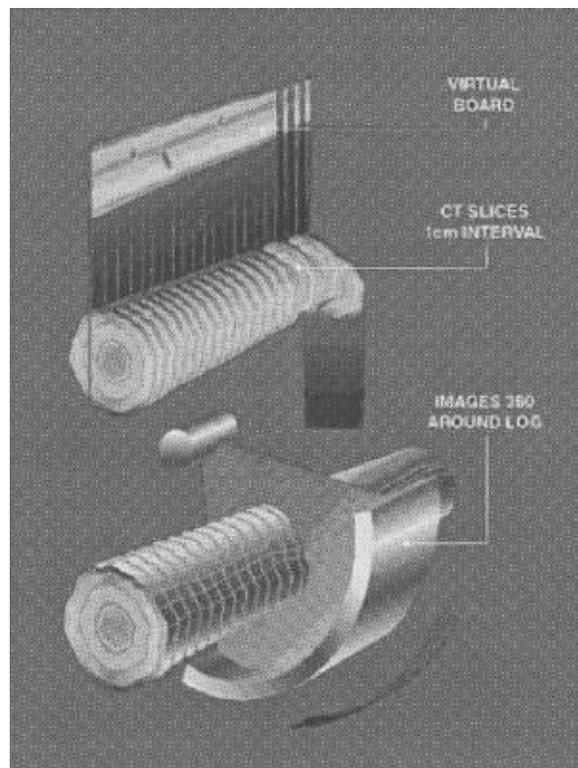
Background

CT scanning entails rotating an X-ray source around an object. X-ray scans are collected from 360 degrees around an object to produce a tomographic slice of that object. The slice is a detailed density map of the object's internal structure. CT was introduced in 1972 for medical imaging. Since that time, CT has become a cornerstone diagnostic tool for hospitals. Although medical CT systems would appear to be easy to adapt to such applications, it is, unfortunately, the case that current medical CT systems have been engineered for infrequent, short duration use. This is incompatible with industrial sawmill needs (Schmoldt *et al.* 2000b). In 1994, InVision Technologies, Inc. produced the CTX 5000 scanner that became the first industrial CT scanner for the detection of small amounts of explosives in passenger luggage for aviation security. CTX machines can now be found at airports throughout the world. Due to similarities in application environments (Schmoldt *et al.* 2000b), the industrial CT engine from the aviation security application can be translated to log scanning for sawmills. InVision has developed and tested a log-scanning prototype (Figure 3).

Log Scanning Mill Test

The first long duration study of a CT scanner in a sawmill was performed in a medium-sized softwood mill (~ 100,000

Figure 4. After all CT "slices" are generated, longitudinal "virtual" boards can be created.

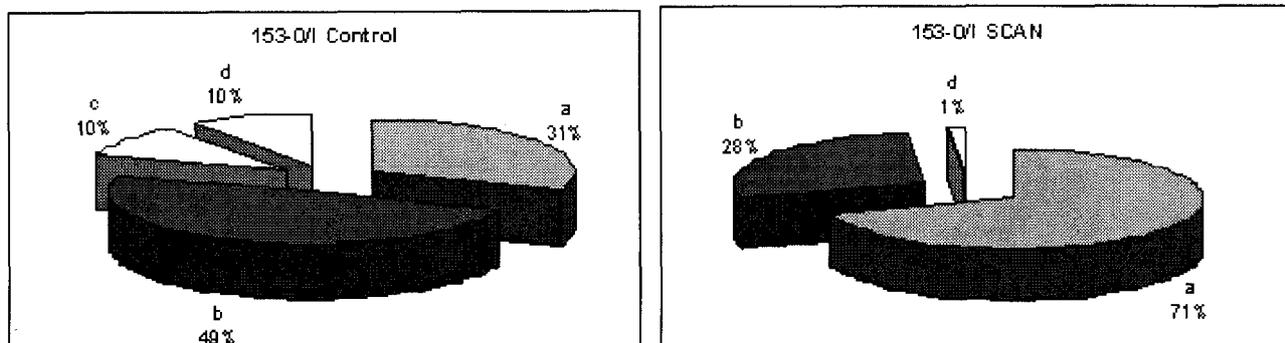


m³/year) in Austria (Schmoldt *et al.* 2000b). The sawmill specializes in producing window frames from alpine softwood species, mainly Norway spruce (*Picea abies*, L.). Some tests were also performed for European larch (*Larix decidua*, Miller), another common species of this region. All dimensions and qualities were chosen from the normal dimension and quality product lines of the mill.

Two sets of logs (over 100 logs total in this study) with comparable diameters were randomly placed into a *scan* group and a *control* group. 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 (Figure 4). 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. For this application, a thicker board has a higher value compared to several thinner boards. But, without CT assistance there is significant risk in cutting too deep into the log to capture a thicker board. The quality of the hidden face of a thick board may be worse than expected. In such a case, one or more high quality thin boards would have been a better choice. No additional computer-based optimizations were performed. Sawing patterns were then manually marked on the log ends to serve as a guide for the physical sawing of the logs at the headrig.

The *control* group was processed according to the normal operation of the mill. After the primary breakdown, all boards from both groups were blind-graded by expert grad-

Figure 5. Slat yields by grade illustrate a shift to higher quality slats between the control and scan groups of logs.



ers (without knowing to which group boards belonged). Using volumes and prices, the value yield for each log was calculated. As one example out of the study, the results of grading 30 high quality spruce logs with diameters of 51 cm and larger showed an increase in value per m^3 of 6.3% for the scanned group (8.8% if the best and worst logs in each group were removed).

Normally, most of the high quality boards in that mill are cut as intermediate products for the window frame industry. They are processed further to produce slats in a secondary breakdown. If the classification of the primary board was correct, a high percentage of the board can be used for slats. So this secondary stage of processing is an excellent indicator of classification accuracy for the CT system compared to experienced sawyers, and might be a better demonstration of yield improvements by the CT system.

Slats were produced from boards with a thickness of 153 mm. With this dimension, it is very difficult to correctly estimate the quality of the board on the back face. After grading the slats, the control-group slats yielded 31% (in value) for grade A (the highest value grade), 49% for grade B, and 20% in grades C and D (the lowest value grades). On the other hand, the CT optimized boards resulted in 71% grade A and only 1% in grades C and D (Figure 5). This improvement cannot normally be achieved without knowing the quality of the board in advance.

CT Data Application

While the previous mill test illustrates the potential value gains that internal scanning can achieve, it relied on sawyers carefully examining full CT imagery. In viewing 2-D “virtual” boards, they were able to accurately determine how thick boards should be without risking much-reduced slat quality. In general, however, this interactive use of CT imagery is frequently incompatible with mill operations and not the most effective for log breakdown. In most hardwood mill operations, log breakdown decisions must be made quickly, and sawyers benefit greatly from a complete 3-D view of a log, where both log shape and internal defects are clearly visible, i.e. a “glass log” view. This cannot be achieved

by viewing a sequence of 2-D CT images, or even “virtual” boards. Furthermore, generating CT images produces tremendous amounts of data. For example, depending on resolution and frequency of scans, scanning a single 4 m log may result in 20-800MB or more of image data. Storing and handling that amount of data between scanning and processing for many logs would be cumbersome at best. Fortunately, CT data contain a large amount of redundancy, which can be exploited to condense the data into a form that is more manageable and usable.

Only those internal features of a log that are important for subsequent processing need to be identified (log shape comes free as tomographs are captured). These features are the defect areas within a log. Each density-related defect is relatively contiguous and each such defect type is fairly homogeneous with respect to density. Consequently, over the past 20 years researchers have begun to develop automated methods to interpret CT imagery (Hopkins *et al.* 1982, McMillin 1982, Funt and Bryant 1987, Zhu *et al.* 1991b, Schmoldt *et al.* 1993, Li *et al.* 1996, Zhu *et al.* 1996, Schmoldt *et al.* 1997, Schmoldt *et al.* 1998). Once different internal log defects can be automatically detected, then those views can be integrated into a 3-D rendering of the log. Defect information can also be used in generating automated log breakdown decisions. One defect detection algorithm using artificial neural networks (Schmoldt *et al.* 2000a) achieved accuracy above 96% for single-species classifiers, 90-97% for two-species classifiers, and 91-92% for three-species classifiers. It is able to label an entire CT image (containing 64K pixels) in 1-2 seconds (depending on processor speed).

Eventually, CT data will be used to automatically arrive at log breakdown decisions. One early computer model designed to deal with this defect specific approach was PDIM (Pattern Directed Inference Model), which generates a log breakdown pattern specific to the internal defect configuration found inside the log (Occeña 1992). It accomplishes this by enveloping defects in a defect hull and analyzing a composite end view that represents an aggregation of the defects' distribution through the log. Automated decision making was driven by the shape of the hull, and density numbers that reflected the defect concentration

along the length of the log. Designed to be a generative process-planning model, PDIM generated sawing instructions that could be used to direct a numerically controlled sawing headrig and log carriage. This and other similar models have the potential for effectively automating log breakdown decisions.

CONCENTRATION YARD SCANNING

Log Yards

Log brokering operations (concentration yards) provide a convenient intermediary between loggers/land owners and sawmills/log buyers. In particular, these yards form an important link between the small- to medium-sized landowners and similar sawmills. Harvested logs are brought to these concentration yards either by independent loggers or by broker-contracted crews. In most instances, logs are bucked, i.e., log lengths of 2.5-5m (8-16 ft) are produced from tree-length stems on the log deck at the harvest site. This greatly simplifies transport, but leaves an important processing decision to variably trained—and incorrectly rewarded—logging operators. Most of these bucking operators have a volume, but no value, incentive for their bucking efforts (Pickens 1996). From concentration yards, logs are then merchandised to various client sawmills based on a bill of materials (Bush *et al.* 1992). Prior to sale, the merchandiser grades each log (based on external characteristics) and estimates board-foot volume. Logs are then sold in batches to appropriate mills based on species and anticipated product. The highest quality logs go to veneer mills, or are exported. Lower quality logs go to various sawmills for lumber production.

Valued-Added Scanning

Locating a log scanner at a concentration yard possesses several theoretical advantages. First, it allows many members of the hardwood industry to take advantage of advanced technology. Second, it generates important log information early in the processing stream, so that it can be used throughout mill operations. Third, it greatly increases the objectivity of log valuation; less guesswork is involved in log pricing. Precise pricing can be reflected in prices paid to landowners, can provide incentives for loggers to buck for log value (not volume), and can ensure mills that they are getting the log quality that their operations need. The information generated adds value to each log—value that is retained in the local economy. While the price of the log might increase by the cost of the scanning operation, it will be more than offset by the benefits mentioned above accruing from the information (Hodges *et al.* 1990).

With a concentration yard log scanner, logs can be scanned, automatically graded, and optimized for sawmill breakdown. Current hardwood log grading rules estimate clear wood volume by examining external characters of the log faces. Detailed internal information should provide better estimates of log grade and even permit development of an alternative set of log grades based on internal informa-

tion. Because scan information will allow simulated breakdown of the log into lumber (which can be computer graded), it should also be possible to generate a lumber grade distribution and lumber value for each log. When a sawmill takes delivery of a log, it could have an accurate log grade, a description of the lumber contained in the log, and information about the internal structure of the log. Sawmills can purchase whatever level of detailed information they wish to use, and feasibly could do so on an individual log basis. The nature of the internal information can be manifested in one of two ways:

- Saw line markings on the log ends can indicate the location of the best opening face, or the location of maximal clear wood content.
- A computer file can contain reconstructed 3D images, and/or log breakdown optimization data with lumber yield.

Information about log grade and lumber content for each log can help a mill properly manage its log inventory. By knowing the internal structure of each log, in addition, a mill can optimize the sawing of that log and also improve downstream edging and trimming operations.

Another immediate advantage of such a system for the small mill is that with little or no infrastructure changes, they can buy and utilize logs that have been CT-scanned upstream at the concentration yard. If a sawmill chooses to use the grade and the location of the best opening face or clear wood (as marked on the log ends), then there will be no setup cost. On the other hand, if a sawmill would like to customize certain logs—e.g., the intermediate grade logs which value varies greatly depending on breakdown pattern—by also procuring the prescribed log breakdown optimization, then it will require a small setup investment in a PC-based computer system, a barcode reader, and a visualization/imaging system. The latter investment will be required to register the log with the stored scan data and download the breakdown optimization. Furthermore, it should be possible in the future to tailor optimization patterns to individual mill operations and product lines.

Implementation

A CT engine for log scanning already exists in the form of InVision's baggage scanner. It has already been prototyped as a log scanner and tested successfully in two sawmills (one hardwood mill in the western U.S. and one softwood mill in Austria). Considerable additional work needs to be done, however, before it is ready to scan hardwood logs in an industrial setting, and before it can operate as envisioned above. Four of the important next steps are outlined in the following sections.

Optimization and Defect Identification Software

The goal of this step is to develop and optimize defect

identification software based on CT-derived volumetric images. Log breakdown software already exists that uses external dimension information, from commercial log shape scanners for example. It needs to be extended to optimize log breakdown based on full 3-D internal information derived from CT. This development will rely on the defect identification software reported earlier, as well as CT image processing and explosives/narcotic detection experience gained in baggage inspection. Because breakdown optimization requires knowledge of lumber value (which includes lumber grade), existing lumber grading software will be included (Klinkhachorn *et al.* 1988). Optimal edging/trimming software will also be added to the set of software tools, so that this important downstream process can be integrated into upstream decision making. These tasks, and several others, are listed below:

- Task 1. Modify existing external dimension log optimization software to utilize internal CT information.
- Task 2. Develop defect identification software based on CT images.
- Task 3. Develop software to map defect size and type onto a wire frame representation of a board.
- Task 4. Develop protocols to send the board representation to board edging/trimming software.
- Task 5. Develop a user interface to allow users to modify optimization parameters.

Increase Acquisition Speed of CT Engine

Increased log throughput requires improved software and hardware for continuous scanning. Continuous scanning of logs will require the use of a fast data streaming and storage system, as the current InVision CT prototypes' computer architecture cannot handle the vast amount of data generated by volume scanning. To scan a log using the current computer architecture the scanner must stop acquiring data for a short period of time (a few hundred milliseconds), move the acquired data from one memory location to another, then start scanning again. This data acquisition stopping and starting causes small gaps (0.5-1 cm) during continuous data collection. To ensure that all defects are fully imaged, these gaps must be eliminated. Continuous scanning and data storage should be possible after completion of the following tasks.

- Task 1. Specify a high-speed data buffer and computer system capable of streaming a continuous flow of CT log images and storing them prior to processing.
- Task 2. Convert the present discrete slice CT system to incorporate the high-speed buffer and computer system.
- Task 3. Develop the software necessary to acquire continuous CT log images.

Integration with Log Handling

Access to, and use of, internal log defect information will require the design and development of an automated log and scan-data tracking system. This system will tag the log, mark the opening face on the log ends, store the scan-data and/or optimized breakdown instructions, associate the log with the scan-data/optimized breakdown instructions, and transmit or enable the retrieval of stored scan-data/breakdown instructions at the client's sawmill. A log/data tracking scheme, a database architecture that can store scan data, as well as traditional data formats, and efficient data communications (including business-to-business data exchange) are necessary for easy access to the scan-data/breakdown instructions associated with each log at the concentration yard. These tasks can be summarized as follows.

- Task 1. Develop a barcode or radio frequency tagging system to identify and track each log.
- Task 2. Develop an automated system to mark log ends with opening face positions and to optically read those markings.
- Task 3. Design and develop database and data warehousing systems to store and retrieve associated scan-data and/or optimized breakdown instructions.
- Task 4. Test, implement, and maintain above-mentioned data and log handling systems.

Data Collection and In-House Testing

In-house data collection can be used to thoroughly test the system prior to field-testing. These in-house tests can serve as a final proofing of the system prior to field deployment where any software and hardware bugs can be worked out efficiently and quickly. To perform meaningful tests, several hardwood log specimens from the eastern U.S. should be used. Given their importance to the eastern hardwood industry, the species red oak (*Quercus rubra*, L.), yellow-poplar (*Liriodendron tulipifera*, L.), black cherry (*Prunus serotina*, Ehrh.), and sugar maple (*Acer saccharum*, L.) are preferred. For each species, several logs would be selected in each of the three log grades. These samples would provide examples covering a variety of wood densities, wood structure, and wood quality. This variability will aid testing both the scanning engine (hardware/software) and the application software (sawing optimization, edging/trimming).

- Task 1. Obtain a representative sample of different hardwood logs that will be used for the in-house data collection.
- Task 2. Setup CT system ready for log screening together with full data collection and storage.
- Task 3. Test and record data from each log.

DISCUSSION

Unlike most softwood sawmills, hardwood sawmills are not completely automated at the headrig. Because most hardwood sawmills produce appearance grade lumber, they require a sawyer to evaluate the outside of the log to predict the best opening face and the optimum sawing pattern. Small sawmills have been able to stay competitive in this environment because log breakdown is a learned skill that can be developed over years of training and experience. A good sawyer specializing in a specific species or product mix can be responsible for significant value increases in that sawmill, whatever the size of the mill might be.

The last frontier in automated hardwood sawmill optimization is the ability to see inside a log before sawing, which would reduce the sawyer's role in determining value yield from a log. The ability to see inside a log is on the horizon. Unfortunately for small sawmills, they will face the same problem as they have historically, i.e., a CT scanner is a capital-intensive product in which small sawmills will likely not be able to invest.

Small mills are in further danger because one of their key competitive advantages will be removed with the introduction of CT, in that the sawyer's learned skills and experience will become less important. Sawmills using CT technology will be able to predict product mix, product grade, and product value more accurately before ever sawing a log. Using CT technology has already been established in several studies to be more accurate than the sawyer. CT brings a wide range of benefits, from reduced log inventories at the front end of a mill, to edging and trimming based on grade at the back end of the mill.

Our approach to technology transfer will allow mills to share the cost of technology and to also avoid mill layout changes. Therefore, small- and medium-size sawmills can benefit from the advantages of internal log scanning at little cost and without negative operational impact on their mills. By including small mills in the benefit stream of CT, the 70% of hardwood mills that are not currently impacted by technology will have equal opportunity. This will lead to far more logs being optimized. Better optimization and inventory control will allow more trees to stay in the forest longer, and allow landowners more flexibility when it comes to land management.

Technology can either alienate people/groups or it can democratize them, leveling the playing field for all. The keys to enabling the latter are *access* and *acceptance*. Installing internal log scanning operations in log concentration yards will provide technology access for a wider clientele, while the economic benefits will hopefully engender their acceptance. Many hardwood mills are located in rural areas. By providing those mills access to technology that would otherwise be beyond their reach, rural economic stability will be enhanced. The information attached to each log at scanning will add value to that log and will allow rural areas to benefit from that value addition. Furthermore, with many, small mills located close to the raw material—

rather than a few, large mills—transportation costs can be kept lower and not add to the increasing cost of hardwood lumber. In this scenario, log concentration yards will no longer be just marketing points for raw material, but will act as technology distribution centers for the industry.

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