Investigation of the Effect of Reducing Scan Resolution on Simulated Information-Augmented Sawing

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Abstract

In the past few years, computed tomography (CT) scanning technology has been applied to the detection of internal defects in hardwood logs for the purpose of obtaining *a priori* information that can be used to arrive at better log breakdown or sawing decisions. Since today sawyers cannot even see the inside of the log until the log faces are revealed by sawing, there is no perceived need to obtain scan images as fine and as high a resolution as those obtained in medical CT imaging. The resolution in which the CT scan data is collected is a factor of physical pixel size, thickness, and pitch. A 2^3 factorial experiment with two levels for each of the three factors was designed. Three hypothetical logs corresponding to the three hardwood log grades were simulation-scanned and studied. The results showed that the effect of reducing CT resolution factors (doubling pitch, thickness, and pixel size) in a simulated log processing experiment did not significantly reduce the lumber values produced from the logs.

Keywords: CT scan resolution, primary hardwood processing, sawing simulation

Introduction

Non-invasive scanning technologies have been applied to the detection of internal defects in hardwood logs for the purpose of obtaining a priori information that can be used to arrive at better log breakdown or sawing decisions. A major challenge in the eventual implementation of non-invasive scanning technology such as CT (computed tomography) is the development of a rugged, wide-diameter, high-speed industrial CT scanner that can collect CT data in a hardwood sawmill. Scanning can be performed either on-line which will require pacing with the sawing operations, or off-line prior to sawing which will require data storage and log tagging/tracking (Occeña et al., 1996).

One of the determinants of speed is the resolution in which the CT scan data is collected. Conventional CT scanning is performed by transmitting a collimated x-ray beam through the log to a detector array at a particular location, in specific intervals along the length of the log. The resulting image is a cross-sectional slice through the log at that location. Each slice has a cross-sectional area represented in terms of picture elements (pixels) and a thickness which together compose the volume of the scan. Consecutive CT scans are taken along the length of the log at a specific incremental distance or pitch. The resolution in which the CT scan data is collected is thus a function of physical pixel size, thickness, and pitch.

In principle, CT scanning speed can be increased by reducing the resolution of the CT scan data collected. Besides speed, there will be energy cost savings from using fewer x-ray emissions. Since today sawyers cannot even see the inside of the log until the log faces are subsequently revealed by sawing, there is no perceived need to obtain scan images as fine and as high a resolution as those obtained in medical CT imaging. The question is how coarse can the resolution be and still allow us to improve sawing decisions? The goal of this study is to conduct an investigation of the effect of CT resolution on the value of lumber produced from a log. The specific objective is to simulate the impact of CT resolution on value by varying the determinants of resolution — physical pixel size, thickness, and pitch.

Background Information

Current log grading and sawing methods are limited by the invisibility of internal log defects. The development of nondestructive sensing and analysis methods that can accurately detect and characterize interior defects is critical to future efficiency improvements for sawmills (Occeña, 1991). Technology has been developed to the point that wood defects can be seen in the interior of logs by using nondestructive imaging techniques.

The log scanning ability to differentiate internal defects in logs has been successfully demonstrated. Log scanning methods using sophisticated technologies, such as computed tomography (CT) (Zhu et al., 1996), nuclear magnetic resonance (NMR) (Chang et al., 1989), ultrasonic (Berndt et al., 1999), laser (King, 1979), optical (Lee et al., 1991), and microwave (Martin et al., 1987) imaging, have been studied and tested in laboratory experiments. Of these methods, CT is the imaging modality that has been most often tested for the possibility of industrial application to log inspection because of its high penetrating power, efficiency and resolution (Som et al., 1992). In 1999, InVision, a leader in aviation security, developed and tested a log scanning prototype based on its explosives detection CT scanning engine and is now working to make this technology available for hardwood sawmills (Schmoldt et al., 2000). The research described in this paper refers to CT-based imaging.

In 1961, a study of log breakdown heuristics was conducted using a large number of logs that were physically sawn into lumber (Malcolm 1961). Current computer software, however, has the ability to generate hypothetical logs (Chen and Occeña, 1996) and to simulate their breakdown by computer (Occeña and Schmoldt, 1996). Computer simulation is used in this research to evaluate the impact of varying the CT sawing parameters.

Methodology

Study Data

Three hypothetical red oak log with internal defect representations, representing the three log grades were used in this study (Thawornwong et al., 2000). These logs are shown in Figure 1 after log scaling according to Forest Service grading rules.

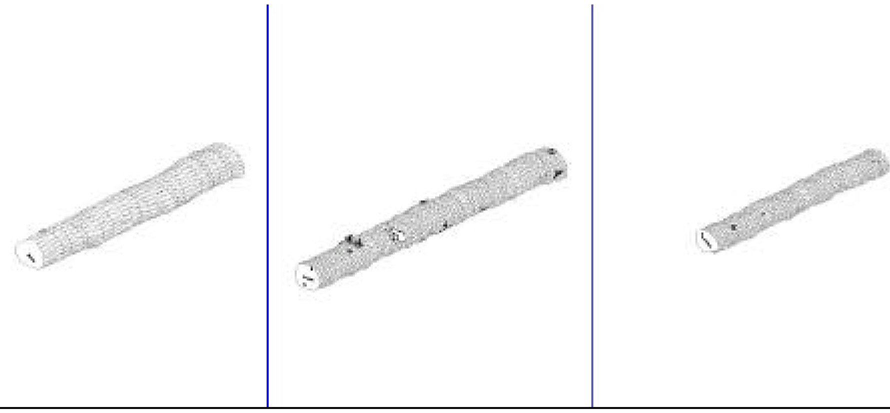

Figure 1. *Log Specimens (L to R: Grade 1 log, Grade 2 log, Grade 3 log).*

The 23 factorial experimental design with two levels for each of the three factors, namely, physical pixel size, thickness, and pitch was simulated through the computer-aided processing of collected profile data. In previous studies (Schmoldt et al., 1999), CT images were collected with 256x256 resolution. Each image pixel was 2.5 mm square and successive tomographs were imaged every 8 mm on the center with a thickness of 2.5 mm. A more recent study reported scanning with 1.55 mm pixel size, 5 mm thickness, and no scan interval. Following these parameters, the two levels in this study consisted of the current original "simulated CT factor value" and a doubled factor value (i.e., double the pixel size, double the thickness, double the pitch) as can be seen in Table 1.

Table 1. ***Two Levels of CT Factor Value.***

Parameter	**Original CT Factor Value**	Doubled Factor Value
Pitch (P)	0 mm	5 mm
Scan Thickness (T)	5 mm	10 mm
Pixel Size (S)	1.55 mm	3.1 mm

The original logs were simulated-sawn cross-sectionally in regions where defects existed along the length of the log at specific increments of 1.25 mm using the GRASP (Occeña and Schmoldt 1996). These slice data were used to represent the different combinations of the three parameters (scan thickness T, scan pitch P, scan pixel size S) in Table 1, resulting in eight new "scanned logs" in each log grade, or a total of 24 new "scanned logs". We refer to the original three logs as the "true log set", and the 24 logs generated from the parametric combinations as the "reduced resolution set". A sample knot defect reconstruction for the 23 factorial design is shown in Figure 2.

Simulated Sawing

27 sawing experiments, consisting of the three logs in the true log set and the 24 logs in the reduced resolution set, were performed using an information-augmented heuristic with defects on the center of faces, best quadrant sawn first, and full taper setting. This heuristic was selected from a previous simulated sawing study because it gave the highest value improvement (Occeña et al., 2000).

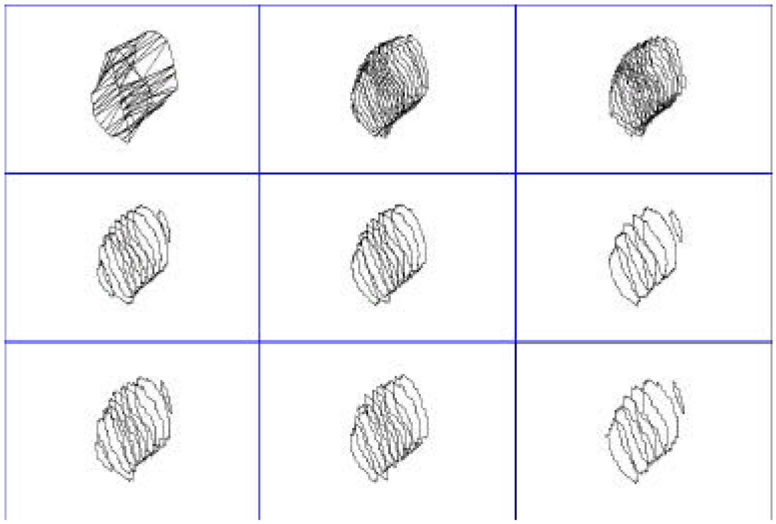

Figure 2. *Example 23 factorial CT image (LT: original defect, MT: P=0 T=5 S=1.55, RT: P=0 T=5 S=3.1, LM: P=0 T=10 S=1.55, MM: P=5 T=5 S=1.55, RM: P=5 T=10 S=1.55, LB: P=0 T=10 S=3.1, MB: P=5 T=5 S=3.1, RB: P=5 T=10 S=3.1).*

Information-augmented refers log sawing where the sawyer has knowledge of the internal defect features inside the log, including their types, size, and location, from noninvasive scanning. A full description of the sawing technique is described in the following paragraph.

The logs were positioned so that major surface defects were oriented to the center of the sawing face. The best quadrant, which was determined by selecting the least-defected quadrant of the four quadrants from orthogonal sawing, was set out the full taper and sawn first. The full taper setting represented the total angular displacement required so that the opening face was parallel to the saw line. By using the small-end of the log as the pivot with respect to an axis perpendicular to the longitudinal axis, the log was set out so that the unopened face became parallel to the saw line. The second-best, third-best, and least-best quadrants, respectively, will be full taper sawn if a full taper maximizes the board value. Log turning was not done unless it was perceived to result in boards with the highest grade possible. This determination was made from GRASP images, and no hidden line removal algorithm was activated for all sawing experiments in order to view all possible internal defects. Interactive sawing simulation is no different from real log sawing, other than the log is a 3-dimensional representation on a computer screen. The resulting flitches were edged, trimmed, and graded after the whole log had been completely sawn. For comparison purposes, logs were sawn completely, leaving no cant.

Sawing decisions and experimental setup

To arrive at the impact of a “reduced CT resolution”, the breakdown pattern for the 24 logs in the reduced data set were prescribed from a visual examination of the reduced data set, but were then actually applied to their corresponding “original” log in the true data set. In the GRASP simulator, there is a capability to precisely indicate the sawing pattern using line markers without actually sawing yet. These line markers were then used as a template to perform simulated sawing of the corresponding "original log" in the true log set. The above procedure is based on the premise that a "reduced CT resolution" image will lead to a misperception of the "true log" condition, e.g., sawing a clear face where in reality there are defects hidden from view by the reduced resolution. Sawing the corresponding log from the true log set realizes the impact of the misperception.

To prevent bias from the comparable logs in the reduced data set, the following five steps were employed in the sawing experiments. First, 15 additional logs, five logs in each of the three log grades, were randomly included during the prescription of the line markers, giving a total population of 42 logs. Interleaving these logs serves to break any perceivable log and defect patterns. Second, the order of these 42 logs — 27 logs from the reduced resolution and the true log sets, plus the 15 additional logs — was randomized, and the logs were renamed to hide their identities. This was done without the sawyer's involvement. Third, the sawyer then prescribed sawing patterns for the renamed 42 logs using line markers and the information-augmented heuristic described earlier. Fourth, the sawing patterns for the 27 logs from the reduced resolution and true log sets were extracted from the total population, and simulated-

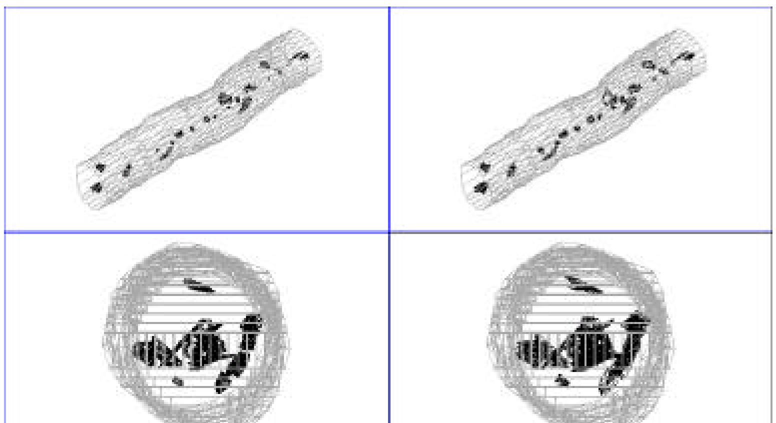

Figure 3. *Sample Results of Grade 1 Log. LT: Reduced-Resolution (P=5 T=10 S=3.1), RT: True Defect Information, LB: Perceived Sawing Decision, RB: Sawing Pattern on True Grade 1 Log.*

sawn on their corresponding original logs in the true log set. Only after the simulated sawing were the true identities of the logs divulged to the sawyer. This was the final step.

Samples results for Grade 1, 2 and 3 logs, are presented in Figures 3, 4, and 5, respectively. The left side shows the perceived CT resolution and sawing pattern, and the right side shows the corresponding true log resolution and impressed sawing pattern (from the reduced resolution set). The bottom-left side presents the prescribed sawing patterns based on the perceived defect information from the reduced resolution set. The bottom-right side presents the application of this prescribed sawing pattern to the corresponding true log. The top images in Figures 4 and 5 show sample perceived defects from the reduced data set compared to the actual defects in the corresponding logs in the true log set.

Results and Discussion

Results

After performing all 27 sawing simulations — for the 3 logs in the true log set and the 24 logs in the reduced resolution set — the value yield was obtained as shown in Table 2. The highest dollar values of lumber produced for Grades #1, #2, and #3 came from the P=0 T=5 S=3.1 reduced-resolution, true, and P=0 T=10 S=3.1 reduced-resolution logs, respectively. The total value of lumber produced from the three

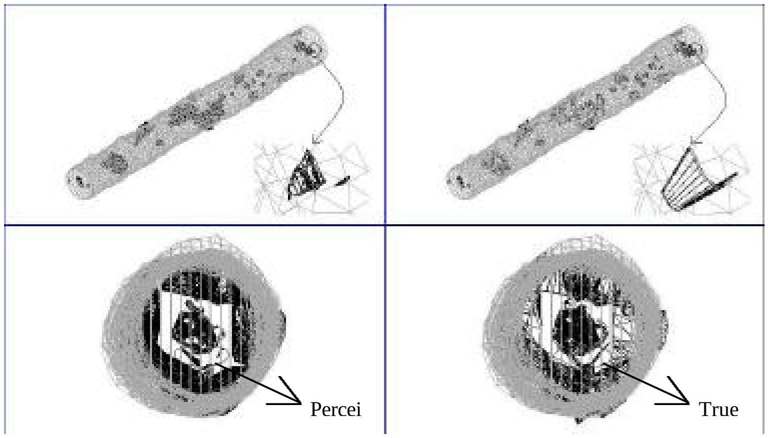

Figure 4. *Sample Results of Grade 2 Log. LT: Reduced-Resolution (P=5 T=10 S=3.1), RT: True Defect Information, LB: Perceived Sawing Decision, RB: Sawing Pattern on True Grade 2 Log).*

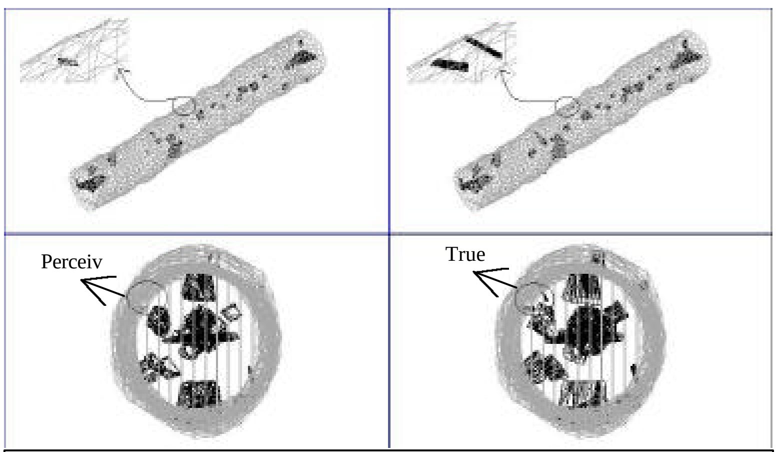

Figure 5. *Sample Results of Grade 3 Log. LT: Reduced-Resolution (P=5 T=10 S=3.1), RT: True Defect Information, LB: Perceived Sawing Decision, RB: Sawing Pattern on True Grade 3 Log.*

grades is shown in the last column. According to Table 2, the true log set obtained the highest total dollar value. The P=0 T=5 S=3.1 reduced-resolution log provided the highest total dollar value from the reduced data set. In contrast, the P=0 T=10 S=1.55 reduced-resolution set produced the lowest total dollar value.

The average, range, and standard deviation of the dollar values for each grade are also provided in Table 2. It shows that Grade #1 logs had the highest range ($9.62) and standard deviation ($3.57). In contrast, Grade #3 logs had the lowest range ($3.24) and standard deviation ($1.08). This suggests that the CT resolution factors may have an effect on the dollar-value improvement, especially for Grade #1 logs. The relationships ($\sigma_{grade\#1\&\#2}$= 0.49, $\sigma_{grade\#1\&\#3}$= -0.50, $\sigma_{grade\#2\&\#3}$= -0.68) among the log grades were also calculated. This indicates the positive relationship of dollar values obtained between Grades #1 and #2 logs. On the other hand, the dollar values obtained from Grade #3 were negatively correlated to those of Grades #1 and #2. This may suggest that the dollar values obtained from Grade #3 logs were generally below the average, while the dollar values obtained from Grades #1 and #2 logs were above the average or vice versa.

Table 2. *Dollar Values Obtained for Each Sawing Decision and Each Grade Log.*

Reduced Resolution Sets: CT Factor Value (mm)			Dollar Value			
Pitch (P)	Thickness (T)	Pixel (S)	Grade #1	Grade #2	Grade #3	Total
0	5	1.55	132.06	98.09	65.30	295.45
0	5	3.1	133.94	98.09	64.46	296.49
0	10	1.55	124.32	93.54	66.00	283.86
0	10	3.1	128.30	94.89	67.70	290.89
5	5	1.55	131.22	93.54	67.56	292.32
5	5	3.1	128.19	95.22	66.60	290.01
5	10	1.55	125.49	97.25	66.60	289.34
5	10	3.1	126.00	97.25	66.60	289.85
True Log Set			133.39	99.24	65.30	297.93
Average			129.21	96.35	66.24	291.79
Range			9.62	5.70	3.24	14.07
Standard Deviation			3.57	2.10	1.08	4.33

The distribution of lumber grades — FAS, F1F, Selects, #1 Common, #2 Common, and Below Grade — was also examined. The volume distribution for the three grades in each sawing decision is provided in Table 3. According to Table 3, the true log set also obtained the highest total board foot volume. The P=5 T=5 S=3.1 reduced-resolution set provided the highest total board foot volume from the reduced data set. On the other hand, the P=5 T=10 S=1.55 reduced-resolution set gained the lowest total board foot volume.

Table 3. *Total Board Foot Volume of the Three Grades.*

Reduced Resolution Sets			Results of the Three Lumber Grades						
P	T	S	FAS	F1F	Selects	#1 Common	#2 Common	Below Grade	Total
0	5	1.55	12.83	47.93	6.92	238.43	36.00	26.03	368.13
0	5	3.1	0	65.98	6.92	227.78	32.10	33.34	366.13
0	10	1.55	0	57.27	0	228.50	55.47	25.55	366.78
0	10	3.1	0	62.72	1.63	224.27	56.03	24.23	368.88
5	5	1.55	0	75.08	6.92	207.21	52.03	26.13	367.37
5	5	3.1	0	65.20	0	227.06	52.02	24.82	369.09
5	10	1.55	0	62.25	0	239.39	37.27	23.26	362.17
5	10	3.1	0	62.28	0	238.33	38.73	25.60	364.95
True Log Set			12.92	21.27	6.88	270.60	36.38	23.19	371.23

The true log set was examined more closely to figure out why the total dollar value and board foot volume were higher than those of the reduced resolution set. It was noted that the true log set produced the lowest board foot volume of below grade boards. That is, the increase in value of the true log set is due to both an increase in volume and a shift to higher value board grades. The result is consistent with the assumption that the value increases can be obtained by using higher CT resolutions.

Because this research was limited to one log in each grade and each factorial defect information, there are few other variables that can be analyzed statistically. The dollar values of the sawing results also did not exhibit a particular distribution. In addition, the logs used in the sawing experiments were not identical in terms of their grades and sizes. Thus, an Analysis of Variance (ANOVA) associated with the real dollar values can not be examined. Their percentage dollar yields, however, could be used as a pseudo measure for the real dollar values of the three grade logs. Therefore, the highest dollar values of the sawing experiments from each grade were used as the maximum dollar values (100 percentage yields) of the lumber produced, as shown in Table 4.

Table 4. *Percentage Dollar Yields Compared With the Highest Dollar Values.*

Reduced Resolution Sets: CT Factor Value (mm)			Percentage Dollar Yield		
Pitch (P)	Thickness (T)	Pixel (S)	Grade #1	Grade #2	Grade #3
0	5	1.55	98.60	98.84	96.45
0	5	3.1	100	98.84	95.21
0	10	1.55	92.82	94.26	97.49
0	10	3.1	95.79	95.62	100
5	5	1.55	97.97	94.26	99.79
5	5	3.1	95.71	95.95	98.38
5	10	1.55	93.69	97.99	98.38
5	10	3.1	94.07	97.99	98.38
True Log Set			99.59	100	96.45

The summary of the one-way ANOVA results indicates that the differences among percentage dollar yields for different log sets (reduced resolutions set and true log set) are not statistically significant at the 95% level of confidence (0.703<2.51). It can be further concluded from the two-way ANOVA that there are no significant differences (0.804<3.634) among dollar yields of different log grades. Therefore, these results indicate that the average dollar yields of the reduced resolution sets are not significantly different from the average dollar yield of the true log set.

The impact of each factor value was also examined by combining the data for each factor value, as shown in Table 5. Again, the average dollar yields for different log sets do not demonstrate the significant differences (0.636<2.235) among pixel size, pitch, and thickness. This suggests that the P=5 T=10 S=3.1 reduced-resolution set may be used to detect the defect information inside the logs with no significant reduction in the resulting lumber values. However, it should be noted in Table 5 (also supported by Table 2) that the combination of 5 mm thickness (97.5%), 3.11 mm pixel size (97.16%), and 0 mm pitch (96.99%) were the factor values that produced the highest dollar value possible.

Table 5. *Percentage Dollar Yields Combined for Each Factor Value (Averages appear in the last row).*

True	s=1.55	s=3.1	p=0	p=5	t=5	t=10
99.59	98.60	100	98.60	97.97	98.60	92.82
100	98.84	98.84	98.84	94.26	98.84	94.26
96.45	96.45	95.21	96.45	99.79	96.45	97.49
	92.82	95.79	100	95.71	100	95.79
	94.26	95.62	98.84	95.95	98.84	95.62
	97.49	100	95.21	98.38	95.21	100
	97.97	95.71	92.82	93.69	97.97	93.69
	94.26	95.95	94.26	97.99	94.26	97.99
	99.79	98.38	97.49	98.38	99.79	98.38
	93.69	94.07	95.79	94.07	95.71	94.07
	97.99	97.99	95.62	97.99	95.95	97.99
	98.38	98.38	100	98.38	98.38	98.38
98.68	96.71	97.16	96.99	96.88	97.50	96.37

Discussion

After all the simulated sawing experiments had been completed, the defect resolutions and sawing patterns in the reduced resolution set were investigated. This was done primarily to compare the resulting images created from different defect resolutions. No post-process data reduction procedures were performed during the reconstruction of the CT process to fully display all the shape information the CT scan could provide. As a result, the data sizes of the reconstructed defects in the reduced resolution set were larger than the data sizes in the true log set. This explains why the resulting images in the reduced data set look busier that in the true log set.

Also, it was observed from the experiments that the resulting defect images from the reduced resolution set created appeared to be shrunken from the original defect images in the true log set. This can be explained by the phenomenon called *volume averaging*, where the defect images were diluted by the wood. The smaller the defects are, the greater the likelihood for missing defects. For example, one heart-check in a Grade #2 log and two sound knots in a Grade #3 log were poorly detected at a factor value of 3.1mm. pixel size, which in turn drastically reduced and changed the shapes of these three defects. The circles inscribed at the top of Figures 4 and 5 demonstrate sample differences between perceived and actual CT images of these defects resulting from reduced CT resolution. However, all major defects were adequately detected in the 2^3 factorial combinations of resolution factors. It may be for this reason that, in spite of the random ordering and seeding of logs, the sawing decisions for the same log grade provided almost identical sawing patterns.

In addition, a live-sawing pattern resulted for logs in Grades #2 and #3. This may be due to the abundance of defects. Turning to the other quadrants would not have ensured that maximization of board value would occur. Furthermore, it was found in the sawing experiments that the edging operations frequently varied although the sawing patterns were almost identical. These secondary operations may be among the factors affecting the lumber values produced from the logs.

The lumber values produced from the logs by using the true log set were presupposed to provide the highest dollar value for each grade. However, there were several sawing experiments employing the reduced resolution sets, especially in Grade #3, which produced higher dollar values than the true log set. This may be due to the fact that Grade #3 logs contained an abundance of scattered defects. Therefore, finding an appropriate opening quadrant may be difficult. Consequently, the sawing experiment using the true log set showed no value improvement for this grade. On the other hand, when a log contained fewer scattered defects (e.g. Grades #1 and #2), it was relatively easy to find a quadrant that relegated the defects onto fewer boards, and thereby creating a greater lumber value. If this trend proves correct, i.e., there is little impact on the improvement of value from internal information for Grade #3 logs, then fewer scanning resolutions will be required to effectively attain similar lumber values for Grade #3 logs.

In addition, the lumber values produced from the logs by using the P=0 T=5 S=1.55 reduced-resolution set were expected to provide the highest total dollar values that can be obtained from the use of internal defect information. However, the lumber values produced from the logs by using the P=0 T=5 S=3.1 reduced-resolution set were higher instead. In fact, 75% of the sawing experiments using a 3.1mm pixel size provided total dollar values higher than those using a 1.55 mm pixel size for the same values of pitch and thickness factors. This suggests that the ability of a 1.55 mm pixel size (fine) to improve lumber value compared to that of 3.1 mm pixel size (coarse) is not significantly different. It may be due to the fact that the sawyer paid more attention to the gross image than the detailed image of the defects when making sawing decisions. This is the same premise proposed by the PDIM approach to automated hardwood log breakdown (Occeña, 1992). Undoubtedly, more log samples should be included in the experiments to arrive at meaningful conclusions.

Summary

Conclusions

The ability of information-augmented heuristics to improve lumber value over information-limited heuristics has been previously demonstrated. Non-invasive scanning technologies, such as CT scanning, however, are necessary for the detection of internal defects in hardwood logs. The resulting internal defect information can then be used to arrive at better log breakdown or sawing decisions.

Industrial scanning of large-volume hardwood logs in an on-line operation used in hardwood sawmills demands high-speed CT scanning technologies. As demonstrated in this simulation study, CT scanning speed can be increased by reducing the resolution factors — pitch, thickness, and pixel size — of the CT scan data collected. Besides the shorter scanning time when the resolution factors are reduced, there will be energy cost savings from using fewer x-ray emissions (e.g., less tube wear, and use of less film), and reduced data storage.

It can be concluded from the study that the effect of reducing CT resolution factors (doubling the pitch, thickness, and pixel size) on the simulated information-augmented sawing did not significantly reduce the lumber values produced from the logs. In the future, sawing experiments from additional log samples will have to be included and analyzed in order to draw meaningful conclusions. At this point, however, it implies that there is room to further reduce the CT resolution factors, which can be effectively used to improve the sawing decisions through information augmentation while maintaining the lumber value yield.

Further Studies

As already mentioned, the sawing experiment with a 2^3 factorial design did not significantly affect the outcome. It would be of interest to setup a 3^3 factorial experimental design with three levels for each of the three factors: physical pixel size, thickness, and pitch. The 3^3 factorial design will create the equivalent of 27 new CT scanning results from each log sample. With 81 (27×3) sawing decisions received from the different CT resolution factors, the lumber values of the experiments from sawing the original logs would benefit from the increased sample size.

Because the test sample was limited to one log for each log grade, very few variables could be statistically analyzed according to log grade. More log samples in each grade will allow analysis according to log grade.

The sawing technique used was one of several information-augmented heuristics that have been tested for future efficiency improvements in the sawmills. The Pattern Directed Inference Model (PDIM) that treats defects as an aggregation or cluster (projected onto the log end) with a dominant axis may be a good candidate to evaluate automated sawing decisions for different CT resolution factors. The sensitivity of reducing scan resolution to different information-augmented heuristics could be further studied.

The simulated sawing experiments were performed by one sawyer. The results of the sawing decisions and experiments could change if different sawyers were to conduct the simulated sawing. The sensitivity of sawing results to different sawyers could be further investigated.

The secondary edging and trimming operations were observed to be a potential source of recovery improvement. Even though the resulting flitches were consistently edged and trimmed in the simulated sawing experiments by one operator, these manual operations could adversely affect the lumber values produced from the logs. Thus, an edging and trimming optimizer should be employed to effectively control the operating conditions.

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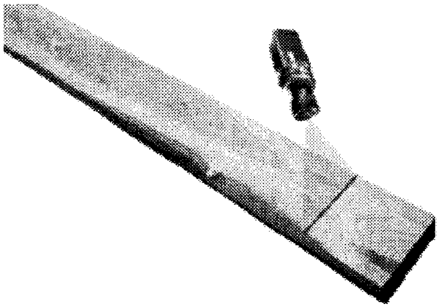

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