Effect of small changes in sawpattern on lumber value in pruned Douglas fir logs : Steps towards greater value from pruned logs

[1]Christine Todoroki and [2]Eini Lowell

[1]NZ Forest Research Institute Ltd, Rotorua, New Zealand
[2]Pacific Northwest Research Station, Portland, OR, United States of America

ABSTRACT

The silvicultural practice of pruning juvenile stems is a value-adding operation due to the formation of knot-free wood after the pruned branch stubs have healed. However it is not until after the log has been processed that the added value is realized. The motivation for this paper stems from wanting to extract as much of that added value as possible while minimizing scanning costs and data requirements.

In this paper we test the hypothesis that increased value can be attained when the cutting strategy is based on a measure of the defect core (DC) size as opposed to a measure of log size. We consider both simplified and intensive methods for determining DC and make small changes in cutting strategies through selecting the cant size from one of five predetermined sizes, according to:

1) Small-end diameter: with the cant positioned to maximize lumber volume ("Best Volume")
2) Defect core size: with the cant positioned to maximize lumber volume ("Best Core")
3) Allocation of both cant size and position according to optimal lumber value ("Best Value").

The relationship with log small-end diameter and defect core size to value recovery is also demonstrated.

Two geographically disparate samples of pruned Douglas fir logs were sourced : one sample, comprising 97 logs, from the US Pacific Northwest, and the other with 61 logs, from plantations within New Zealand. All logs were measured lengthwise and crosswise in 2 planes (elliptical cross-sections) and, for the NZ sample, deviations of each cross-section from a central string line was recorded (irregular log shapes). The US sample was processed through a sawmill into primarily structural lumber while the latter samples were cross-cut into discs at 20 cm intervals, clearwood cut away with an axe to expose the branch stubs, and the extent of the DC measured at each cross-section ("Intensive DC"). For the US sample, DC measurements were made at the log ends only ("Simplified DC") and were based on ring counts to year of pruning. Each log's external geometry and internal knotty core (generated by computer for the US sample) was reconstructed into digital formats and the digital logs sawn according to the three cutting strategies using the AUTOSAW sawing simulator. The resultant boards were graded into four categories: a) knot-free; b) knots on one face; c) knotty both faces; and d) knotty both faces with pith. Board value was calculated relative to that of the highest valued lumber using weights: 1.0 knot-free grade, 0.85 knotty one face, 0.30 knotty both faces, and 0.25 knotty with pith.

significant increases in yield were noted with the intensively measured DC, not only for the optimal value solution but also for the Best Core strategy. The yield increases averaged 11 % and 5 % respectively, equivalent to \$24/MBF (\$10/m^3) and \$11/MBF (\$5/m^3) based on a price of US\$840/MBF (US\$356/m^3) for knot-free lumber.

Based on our research findings of value yield we conclude that:

1) Small changes in sawpattern have a significant effect on lumber value
2) Selection of the cant size and position is critical to optimizing value yield
3) Volume maximization is not a good strategy when it comes to sawing pruned logs
4) Increased value can be extracted from a pruned log when the DC is derived from intensive measures of the internal knotty core structure

Thus a system that includes a non-destructive evaluation tool that scans the log for the internal knotty core, determines the DC, selects the appropriate cant size, and applies an optimization procedure to position the cant lwould yield significant benefits in terms of increased value..

To realize the full potential of pruned logs and achieve optimal value, a complete knowledge of internal defects coupled with optimization capability is required ("Best Value"). However, simplified optimization procedures (aka heuristics) together with some knowledge of the internal defect core can enhance value extraction from pruned logs. This was demonstrated by the "Best Core" strategy in association with the intensively measured DC. Although there was not a significant increase in value with the simplified DC, more work is required to establish whether or not this result holds in the presence of complex knotty cores. Because of the commercial importance of determining the minimal set of requirements for increasing value this will be addressed in future work.

INTRODUCTION

Many years or even decades can pass between the time a stem is pruned in the final lift and when it is processed. The longer the lapse the greater the clearwood sheath and hence the lesser the ability to accurately locate pruned branch stubs within the defect core (DC). The DC can be defined as the diameter of a hypothetical cylinder containing pith, branch stubs, and occlusion scars and includes any widening effects due to stem sinuosity at the time of pruning (Maclaren, 2000). This, in turn, makes the allocation of the best sawpattern that optimizes value more difficult.

Sawpatterns are generally allocated using sawing systems that provide external shape scanning capability and are coupled with log breakdown optimization software. These systems optimize lumber volume, rather than value. To optimize value, internal scanning capability that captures internal defects is required. Various nondestructive evaluation (NDE) methods have been investigated over the past two decades. In the early 1980s X-ray computed tomography (CT) was applied to artificially pruned radiata pine (*Pinus radiata* D. Don) logs (Benson-Cooper et al. 1982). Since then there have been significant advances in detection accuracy and processing speed (Funt and Bryant 1987, Wagner et al. 1989, Schmoldt et al 1997, Schmoldt et al. 1999, Thawornwong et al. 2000). Other NDE techniques have been evaluated, including sound wave transmission and impulse radar (Schad et al. 1996). Although losses in image recognition and defect location accuracy are associated with sound wave and short-wave tools, they are still worthy of consideration due to being substantially cheaper, and safer than CT scanners.

Determining best cutting solutions based on external shape, i.e. volume optimization on the one hand, and value optimization on the other, represent two extremes: one for which knowledge of internal data is neither known nor required in developing the optimal breakdown strategy, the other for which detailed data is a prerequisite.

A comparison of simulated value yields from pruned radiata pine logs (Todoroki 2001) showed an average increase in value yield of 18% (range 3 to 45%) when the value optimized solution was compared to a global volume optimized solution (best opening face, BOF). When value optimization was enabled at the secondary breakdown stage (i.e. primary breakdown based on BOF followed by grade-optimization at the edger) the average increase in yield was 3% with a range of 0 to 7%. Although the study was limited in terms of sample size (12 logs) and sawpattern (through-and-through sawing was employed, thus all flitches had to be processed at the edger) the study did highlight trade-offs between volume and value optimization

Between the two extremes of volume and value optimization, there are intermediary levels for which some, be it limited, internal data is known or can be extracted. The intermediary position is of interest because it represents a trade-off between technological costs and added value. Recent simulation studies (Todoroki 2003) on pruned *Pinus radiata* models developed from actual log measurements (both external and internal) have demonstrated potential for NDE tools with lower resolution or imprecise detection capabilities. In a study with 80 logs, processed using the more widely used cant sawing patterns, an average increase in value of 13% relative to that obtained with no knowledge of internal defects was recorded and an average increase of 18% was obtained with precise knowledge.

The practice of pruning is not restricted solely to radiata pine, the predominant species in New Zealand, representing 89.2% (NZFOA 2004/2005) of the plantation forest area. The secondary species Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) that comprises 6.0% of the planted forest area has also been subjected to pruning. Pruning was extensive in the 1950s (Fenton 1967) but has reduced dramatically in recent times mainly due to the ability to control branch size within the limits defined (35 to 40 mm) before the lumber is downgraded (Knowles and Ledgard 2004) and the current lack of premium for pruned Douglas-fir lumber that also acts as a disincentive to prune. This state of affairs is now not dissimilar to that in North America. “For whatever reason, pruning is rarely a management practice in North America” (Cahill et al 1988). Similarly, “Pruning has not been adopted as an operational practice in the management of coast Douglas-fir on any significant acreage in the Pacific Northwest” (Fight et al 1988). However “In the United States, primarily in Washington and Oregon, there has been a new level of interest in pruning Douglas-fir stands because clearwood from old-growth stands is no longer available” (Potts et al 1997).

Fight et al (1992) developed a Lotus 1-2-3®-based spreadsheet, DFPRUNE, for estimating the expected financial return from pruning coast Douglas-fir. The software estimates the return to pruning by comparing the value of the butt log of a pruned tree to the value of the same log had the tree not been pruned.

In this study, rather than examining differences between pruned and unpruned log counterparts, we focus on within-log lumber variation caused by industrial rather than physiological processes. We examine differences created through small changes in sawpattern and test the hypothesis that increased value can be extracted from a pruned log when the cutting strategy is based on a measure of defect core size.

DATA

The pruned Douglas-fir logs that formed the basis for this study were grown in two geographically disparate locations in the Northern and Southern Hemispheres. The northern sample, comprising 97 logs, was sourced from the US Pacific Northwest (Washington state, west side of the Cascade Mountains) from a site for which the 100-year site index averaged 145 feet (Reukema 1972). Trees, selected based on DBH at time of pruning and subsequent growth, were from all crown classes and had been pruned when the stand age was 38 years. Because of this, there were few or no live branches removed during pruning. At time of harvest the stand was 75 years old. Annual ring count to year of pruning was used to locate the defect core. The southern sample, comprising 61 logs, was sourced from plantations within the North and South Islands of New Zealand (Golden Downs, Longwood, Mamaku, Reefton, Waimihia, and Waiotapu). Although with similar diameters to the US sample (see below), the NZ logs ranged in age from 27 to 51 years and had been pruned when aged about 10 years

The US logs were straight, and uniformly tapered while the NZ logs were swept and irregularly shaped. The US logs ranged in small-end diameter (SED) from 20 to 57 cm, length from 5.0 to 5.5 m, and in defect core size DC from 18 to 53 cm. The NZ sample ranged in SED from 24 to 65 cm, length from 3.6 to 7.2 m, DC from 17 to 41 cm, and sweep from 2 to 19 mm/m. These statistics along with the mean and standard deviation are provided in Table 1.

Table 1: Sample statistics of the pruned Douglas-fir logs.

	Length (m)	SED (cm)	LED (cm)	Sweep (mm/m)	Volume (m^3)	DC (cm)
US sample of 97 logs						
Mean	5.1	39	51	0	0.9	36
Std deviation	0.1	9	12	0	0.4	8
Minimum	5.0	20	24	0	0.2	18
Maximum	5.5	57	73	0	1.7	53
NZ sample of 61 logs						
Mean	5.3	39	51	7	0.8	27
Std deviation	0.9	8	10	3	0.3	5
Minimum	3.6	24	31	2	0.2	17
Maximum	7.2	65	84	19	2.0	41

All logs were measured prior to processing and the DC subsequently determined after exposing branch stubs. The US sample was processed through a conventional sawmill and branch stubs measured at the log ends only ("Simplified DC"). An allowance was added for occlusion using the Petruncio ROO equation (Petruncio et al 1997). On the other hand, the NZ logs were cross-cut into discs every 20 cm along the length of the log. Each cross-cut disc was then measured, the cross-section and pith mapped, and the clearwood cut away with an axe to expose the branch stubs which were in turn measured and mapped ("Intensive DC").

Due to the method used for locating the DC in the US sample and the assumption of straightness, DC of the US logs was equivalent to that at the large end DC measurement. This follows from the definition of DC as the diameter of a hypothetical cylinder containing pith, branch stubs, and occlusion scars and includes any widening effects due to stem sinuosity at the time of pruning (Maclaren, 2000). In cases where little growth occurred after pruning, DC exceeded SED. This occurred for 28 of the US logs and one NZ log and caused SED–DC, a measure of the clearwood sheath, to be negative in these instances.

The external geometry and internal knotty core of each log was reconstructed into digital formats. To remove the void and give some form of normality to the internal knotty core of the US logs, branch stub measurements between the large and small end were generated by computer and scaled proportionately along the length of the log in both x- and y-planes. They were generated at intervals such that the Factory Lumber Grading Rules (WWPA 1998) would find no clearwood. Hence the internal knotty core of the US logs was uniform and regular, whereas that of the NZ logs was irregular.

SAWING STRATEGIES

The digital logs were sawn according to the three cutting strategies ("Best Volume", "Best Core", "Best Value") using the AUTOSAW sawing simulation system (Todoroki 1990). The sawpatterns were similar for each strategy but could differ in the size and position of the cant.

For "Best Volume" cant size was allocated according to SED and positioned to maximize lumber volume; for "Best Core" cant size was allocated according to DC and also positioned to maximize lumber volume; while for "Best Value" both cant size and position were determined to obtain optimal lumber value. The five allowable cant sizes (widths) were: 100, 150, 197, 251, and 302 mm.

Threshold values to assign cant size according to SED were as follows:

SED > 425 mm, cant 302 mm
375 < SED ≤ 425 mm, cant 251 mm
325 < SED ≤ 375 mm, cant 197 mm
275 < SED ≤ 325 mm, cant 150 mm
SED ≤ 275 mm, cant 100 mm.

Cant size was set at 100 mm when DC was less than 185 mm, thereafter, for each successive 50 mm increment in DC size, cant size was increased to the next size available (150, 197, 251, or 302 mm).

A schematic representation of the sawing strategies (Figure 1) shows "Best Volume" with a cant whose size was determined according to SED and placed to maximize volume, "Best Core" with cant size determined according to DC and placed to maximize volume, and "Best Value" with cant size determined and placed such that value is maximized.

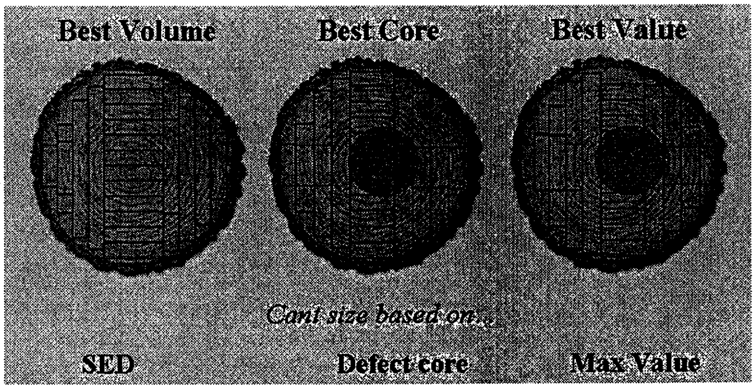

Figure 1 : Schematic representation of the three sawing strategies.

Boards of 44 mm and 24 mm thickness were cut with a 3.7 mm sawkerf. The resultant lumber was graded into four categories: a) knot-free; b) knots on one face only; c) knotty both faces; and d) knotty both faces with pith. Lumber value was calculated using relative prices, i.e. weights, rather than lumber prices, to compensate for price volatility. The weights reflected the higher value of the knot-free lumber: 1.0 knot-free grade, 0.85 knotty one face, 0.30 knotty both faces, and 0.25 knotty with pith. As an illustration of the weights, if $600 per thousand board feet is assumed for Douglas-fir lumber of the highest quality, then other products commanding premium prices would be valued at $510 and the two lower categories would be $180 and $120 per thousand board feet respectively. During the 10-year period from 1993-2002, prices (dollars per thousand board feet) for D Select category ranged from $583 to $900, and for Economy from $108 to $195 (Haynes and Fight, 2004) while the price of Economy relative to D Select ranged from 0.18 to 0.23.

Note that the cant, rather than entirely enclosing the DC, was positioned within the DC, thus defects would be exposed on either side. This was chosen to allow knotty-one-face boards to be cut from either side of the cant due to their relatively high value. Total lumber value was calculated using this method for each log.

STATISTICAL ANALYSIS

Statistical significance of the difference or bias in value between "Best Core" and "Best Volume", "Best Value" and "Best Volume", and "Best Core" and "Best Value" was tested using Students t-Test with a 95% confidence interval, CI. Relationships between SED and DC with value derived from "Best Volume", "Best Core", and with "Best Value" were also explored.

RESULTS

The difference in value of the "Best Value" and "Best Core" strategies relative to that obtained for the Best Volume strategy is shown in Figure 2, and plotted against SED. A small positive bias is evident for the Best Value strategy with US logs, and a greater positive bias with the NZ logs for both the Best Core and Best Value solutions. The statistical significance of the bias is discussed below and impressed through the pair-wise comparisons statistics in Table (2).

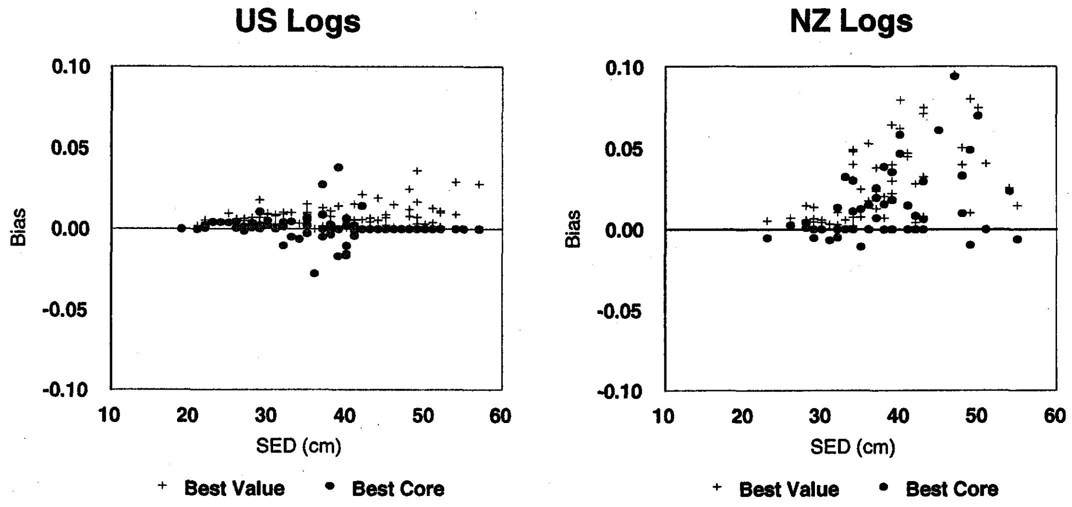

Figure 2 : Value bias relative to weighted value of Best Volume strategy..

"Best Core" / "Best Volume" Comparison

The "Best Core" and "Best Volume" sawing strategies resulted in the same cant size, and hence identical cutting pattern and lumber production for 42 of the 97 US logs, and for 24 of the 61 NZ logs. For this reason pair-wise comparisons were repeated for the sub-samples that did not contain duplicate results. For the US 97-log sample and 55 log sub-sample, the pair-wise comparisons between "Best Core" and "Best Volume" were not significantly different, however the NZ sample and sub-sample recorded significant differences ($p < 0.0001$). The mean value for "Best Core" with the 61-log sample was about 5% greater than that obtained for "Best Volume" (with weighted values of 0.273 and 0.260 respectively) and about 7% greater for the 37-log sub-sample (0.312 and 0.291 respectively).

"Best Value" / "Best Volume" Comparison

"Best Value" was significantly different to "Best Volume" for both US and NZ samples ($p < 0.0001$). In the US sample cutting patterns were identical in 14 cases so a further pair-wise analysis was performed on the sub-sample comprising 83 logs. This too showed a significant difference between the two strategies. The mean value for "Best Value" US sample was about 3% greater than that obtained for "Best Volume" (weighted values of 0.234 and 0.227 respectively) and about 4% greater for the 83-log sub-sample (0.223 and 0.215 respectively). Within the NZ sample all but two pairs of cutting patterns were unique. The statistically significant increase in value was nearly 11% for the sample (0.288 and 0.260 respectively) and sub-sample (0.293, 0.264).

"Best Value" / "Best Core" Comparison

"Best Value" was also significantly different to "Best Core" for both US and NZ samples ($p < 0.0001$). Sample cutting patterns were identical in 18 logs of the US sample and 7 of the NZ sample. The mean value for the US "Best Value" sample was about 3% greater than that obtained for "Best Core" (weighted values of 0.234 and 0.227 respectively) and with the sub-sample about 4% (0.230, 0.222). Within the NZ sample the increase in value was nearly 6% (0.288 and 0.273 respectively) and nearly 7% for the sub-sample (0.276, 0.259).

Table 2 : Paired t-Test comparison of lumber value from 3 cutting strategies with US and NZ pruned log samples.

Sample	Comparison	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_1 - \bar{x}_2$	95% CI for $\mu_1 - \mu_2$	*t-Value*	$Pr > \lvert t \rvert$
US, 97	Best Core, Best Volume	0.227	0.227	0.000	[-0.001, 0.002]	0.84	0.4006
US, 55		0.138	0.137	0.001	[-0.001, 0.004]	0.84	0.4027
NZ, 61		0.273	0.260	0.013	[0.007, 0.018]	4.63	<.0001
NZ, 37		0.312	0.291	0.021	[0.013, 0.029]	5.25	<.0001
US, 97	Best Value, Best Volume	0.234	0.227	0.008	[0.006, 0.009]	9.53	<.0001
US, 83		0.223	0.215	0.009	[0.007, 0.010]	10.38	<.0001
NZ, 61		0.288	0.260	0.028	[0.022, 0.034]	8.89	<.0001
NZ, 59		0.293	0.264	0.029	[0.023, 0.035]	9.09	<.0001
US, 97	Best Value, Best Core	0.234	0.227	0.007	[0.005, 0.008]	8.77	<.0001
US, 79		0.230	0.222	0.008	[0.007, 0.010]	9.69	<.0001
NZ, 61		0.288	0.273	0.015	[0.011, 0.020]	7.48	<.0001
NZ, 54		0.276	0.259	0.017	[0.013, 0.022]	7.97	<.0001

Relationship with SED to value recovery

In general, weighted value increased with increasing SED for both US and NZ logs (Figure 3). Curvature in the trend was apparent for small US logs (SED less than 35 cm) and the data fit well to an exponential function. However the NZ sample was better approximated with a linear regression. Regression statistics for both linear and non-linear (exponential) fits are given in Table 3.

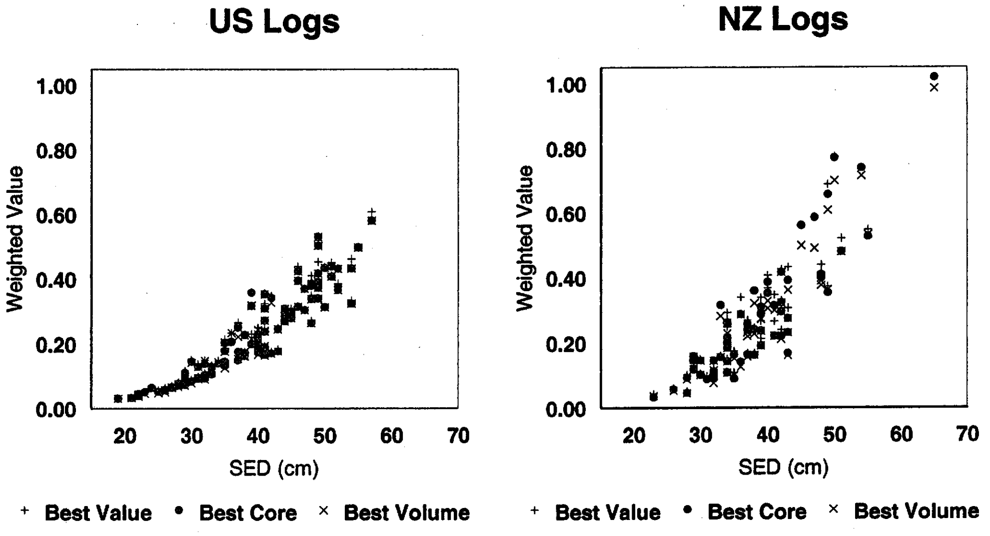

Figure 3: Relationship between SED and value.

Table 3 : Regression coefficients and statistics relating weighted value (y) to log Small-end Diameter (x) for the US and NZ samples.

	Linear: $y = mx + c$			Exponential: $y = ae^{bx}$		
	R^2	m	c	R^2	a	b
			US Sample: Simplified DC			
Best Volume	.86	.014	-.295	.91	.009	.076
Best Core	.85	.013	-.292	.91	.010	.075
Best Value	.85	.014	-.294	.91	.011	.074
			NZ Sample: Intensive DC			
Best Volume	.81	.020	-.515	.77	.126	.074
Best Core	.78	.021	-.544	.75	.012	.076
Best Value	.80	.022	-.544	.75	.014	.074

Relationship with SED – DC to value recovery

SED – DC (clearwood sheath) was positively correlated and, for both US and NZ samples, was represented by a linear relationship (Table 4). In comparisons with lumber value obtained from the "Best Volume" strategy, a positive bias was evident for the NZ intensive DC logs under both "Best Core" and "Best Value" strategies, and for the simplified DC of the US logs under the "Best Value" strategy (Figure 4). The gap between these two strategies (Core/Value) is clearly evident in the figure and illustrates the value-adding potential.

Table 4: Regression coefficients and statistics relating value (y) to SED– DC (x) for the US and NZ samples

	Linear: $y = mx + c$			Exponential: $y = ae^{bx}$		
	R^2	m	c	R^2	a	b
			US Sample: Simplified DC			
Best Volume	.57	.019	.169	.53	.133	.100
Best Core	.58	.019	.169	.53	.135	.099
Best Value	.59	.020	.175	.54	.140	.098
			NZ Sample: Intensive DC			
Best Volume	.76	.023	-.016	.68	.080	.081
Best Core	.79	.025	-.028	.70	.079	.085
Best Value	.78	.025	-.014	.69	.087	.082

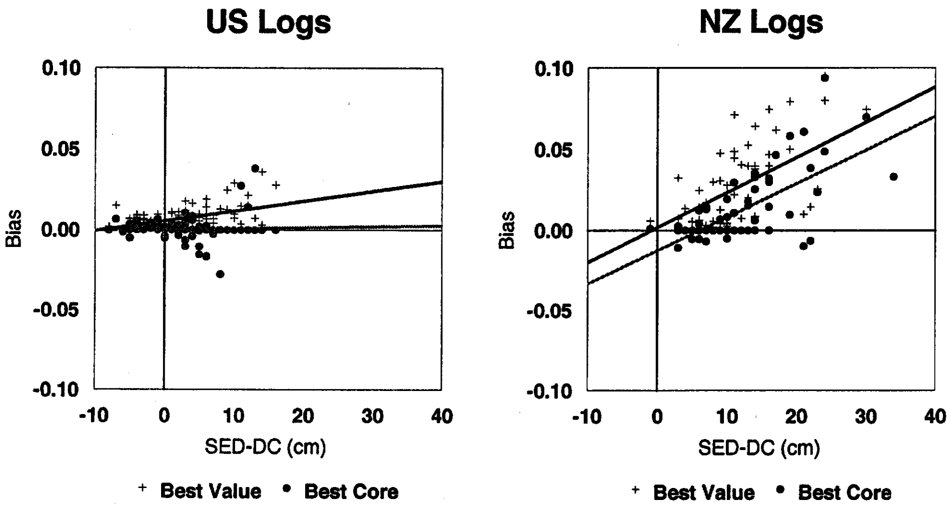

Figure 4: Relationship between SED – DC and value

Relationship with SED and DC to value recovery

Multiple linear regression models with the two variables, SED and DC were strongly positively correlated with value recovery, and both variables significant. The standard errors for the US logs were .001 on SED and DC and .02 on the constant and, for the NZ logs, .001 on SED and .002 on DC, and .5 on the constant (Table 5). The coefficients for SED and DC of the US sample approached those of the NZ sample when those logs with a negative clearwood sheath (i.e. DC exceeded SED) were removed from the analysis (with m_1 = .022, .023, .023 and m_2 = -.010, -.011, -0.11 and c = -.27, -.27, -.27 for Best Volume, Best Core, and Best Value respectively).

Table 5: Regression coefficients and statistics relating value to SED and DC for the US and NZ samples

		Multiple Linear: $y = m_1x_1 + m_2x_2 + c$ where x_1 = SED, x_2 = DC, y = value			Standard Error (SE)		
	R^2	m_1	m_2	c	$SE(x_1)$	$SE(x_2)$	SE(c)
			US Sample: Simplified DC				
Best Volume	.93	.019	-.008	-.21	.001	.001	.02
Best Core	.93	.019	-.008	-.21	.001	.001	.02
Best Value	.93	.020	-.009	-.20	.001	.001	.02
			NZ Sample: Intensive DC				
Best Volume	.87	.024	-.011	-.36	.001	.002	.05
Best Core	.87	.026	-.014	-.35	.001	.002	.05
Best Value	.88	.026	-.013	-.36	.001	.002	.05

DISCUSSION AND CONCLUSION

In this paper we tested the hypothesis that increased value can be extracted from a pruned log when the cutting strategy is based on a measure of DC. We considered both simplified and intensive methods for determining DC and applied cutting strategies that set the cant size and position according to SED ("Best Volume"), DC ("Best Core"), or optimal value ("Best Value"). The sizes and positions were not always unique to these strategies.

With the intensively measured DC of the NZ sample significant increases in yield were noted, not only for the optimal value solution but also for the Best Core strategy. The yield increases averaged 11 % and 5 % respectively. If a price of US\$840/MBF (US\$356/m^3) is assumed for knot-free lumber, then optimal value ("Best Value") would generate an average increase of about \$24/MBF (\$10/m^3) and the "Best Core" strategy would generate an average increase of about \$11/MBF (\$5/m^3).

The simplified DC measurement technique for the US sample did not demonstrate a significant increase in value. However, the mean values using the "Best Value" strategy were statistically significant when compared to "Best Volume" and "Best Core".

Based on our research findings of value yield we conclude that:

1) Small changes in sawpattern have a significant effect on lumber value
2) Selection of the cant size and position is critical to optimizing value yield
3) Volume optimization is not a good strategy when it comes to sawing pruned logs
4) Increased value can be extracted from a pruned log when the DC is derived from intensive measures of the internal knotty core structure

Thus a system that includes a NDE tool that scans the log for the internal knotty core, determines the DC, selects the appropriate cant size, and then applies an optimization procedure to position the cant would yield significant benefits in terms of increased value

However we cannot conclude that a single measure of the DC taken nearest to the large end is insufficient. We surmise that we have found a lower bound or tolerance on our data depiction methodology; namely in the structure of the internal knotty core. To determine whether or not a simplified measure of DC is sufficient will require further experimentation.

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