

REDUCING LUMBER THICKNESS VARIATION USING REAL-TIME STATISTICAL PROCESS CONTROL

Timothy M. Young

Research Assistant Professor
The University of Tennessee

Brian H. Bond

Assistant Professor
The University of Tennessee

Jan Wiedenbeck

Research Forest Products Technologist
U.S. Forest Service – Northeastern Research Station

ABSTRACT

A technology feasibility study for reducing lumber thickness variation was conducted from April 2001 until March 2002 at two sawmills located in the southern U.S. A real-time statistical process control (SPC) system was developed that featured Wonderware® human machine interface technology (HMI) with distributed real-time control charts for all sawing centers and management offices. The thickness data were distributed to all PCs at the instant of measurement by way of wireless transmitters attached to calipers.

There was statistical evidence in the study that suggested that the average thickness of 4/4 ash (*Fraxinus caroliniana*) declined by 0.060" and the average thickness of 4/4 cottonwood (*Populus deltoides*) declined by approximately 0.035" at Mill #2. Lumber produced at the resaw machine center generally had the largest standard deviation for all species at both sawmills. The large variation at the resaw was the most limiting factor for further target size reductions. The average overrun for Mill #1 for all species increased by approximately 2.6 percent after the installation of the real-time SPC thickness improvement system. Unfortunately, a change in log grading procedures confounded the overrun results at Mill #2 so that the impact of the SPC implementation on lumber recovery could not be determined.

The average "Common and Better" lumber grade recovery increased 3 percent at Mill #1 after installation of the real-time SPC system due to a reduction in wedge-shaped, undersized lumber. The average daily recovery of "Common and Better" lumber at Mill #2 increased by 4.4 percent after installation of the real-time SPC system. The estimated annual financial cost savings realized by the two mills combined was approximately \$752,100.

INTRODUCTION

Hardwood lumber is intentionally over-sized in thickness to allow for sawing variation, surfacing, and shrinkage. The amount of material that must be removed from rough-cut hardwood lumber depends on the variation due to surface roughness (within-board variation), size variation between sawn boards (between-board variation), and size variability caused by irregular drying (Young and Winistorfer 1998; Young et al. 2000a). Brown's (1982) model of this relationship was:

$$T = F + P + (Z \times St)$$

[1]

where,

T = target thickness for lumber (inches),

F = final dried lumber thickness (inches),

P = planer allowance (inches),

Sh = percent thickness shrinkage due to drying (decimal),

St = thickness standard deviation of lumber (inches),

Z = Z-score, the lower $\alpha/2$ percentage point of the unit normal distribution.

Even though Brown (1982) admits limitations to this model [1], the general principle of the equation holds, i.e., greater thickness variation during sawing (St) requires larger target sizes.

The hardwood lumber industry has noted the importance of thickness variation and target sizes as indicated by their response to a National Hardwood Lumber Association (NHLA) survey in 1996. Two of the industries top three research priorities were: (#2) develop techniques or technologies to improve sawing accuracy and reduce thickness variation; and (#3) develop decision support tools which maximize quality recovery from logs (NHLA 1996).

The over-sizing of hardwood lumber during the sawing process leads to financial losses that impair an organization's competitiveness. Some have suggested that the over-sizing of rough sawn lumber can lead to opportunity costs of \$50,000 to \$250,000 per year depending on the capacity of the sawmill (Brown 1997; Cassens et al. 1994; Wengert 1993).

Traditional quality control programs in the hardwood lumber industry vary greatly and are tailored to the individual needs of a sawmill. One quality control function that almost all sawmills have in common is the grading of lumber, which is based on criteria established by the NHLA. Even though the grading of hardwood lumber is a quality control technique, it does not ensure continuous improvement of the process and it is not focused on reducing lumber target sizes and thickness variation. Excessive lumber thickness variation can also reduce the grade of lumber, e.g., wedge-shaped lumber below minimum specification thickness.

The contemporary philosophy of continuous improvement is based on using statistical methods, primarily the Shewhart control chart, to quantify sources of variation. Defining and quantifying variation is considered to be the starting point of any continuous improvement process (Shewhart 1931; Deming 1986, 1993). After variation is quantified, short-term variation reduction occurs from the prevention of assignable causes that lead to special-cause variation (e.g., elimination of cants that are not square, elimination of variation at shift change, elimination of product setup variation). Long-term variation reduction comes from improvements to the manufacturing system, which reduces the amount of common-cause variation (e.g., change from circular saw to band saw, more consistent carriage speed, long-term mechanical improvements to carriage).

Real-time SPC is a powerful continuous improvement tool where machine operators and managers see real-time process data on control charts. Real-time SPC enhances Shewhart's concept of preventing the manufacture of defective product by reducing the time interval between the viewing of process data and taking action on special-cause variation (Young and Winistorfer 1998,1999). We believe that viewing control charts from historic production runs is less effective for continuous improvement than is the use of real-time SPC.

This study was part of a larger research initiative titled the "Tennessee Quality Lumber Initiative." The Tennessee Quality Lumber Initiative (TQLI) is an applied research initiative at The University of Tennessee, Forest Products Center. The purpose of the TQLI is to assess the impact that real-time SPC has on lumber thickness variation and target sizes.

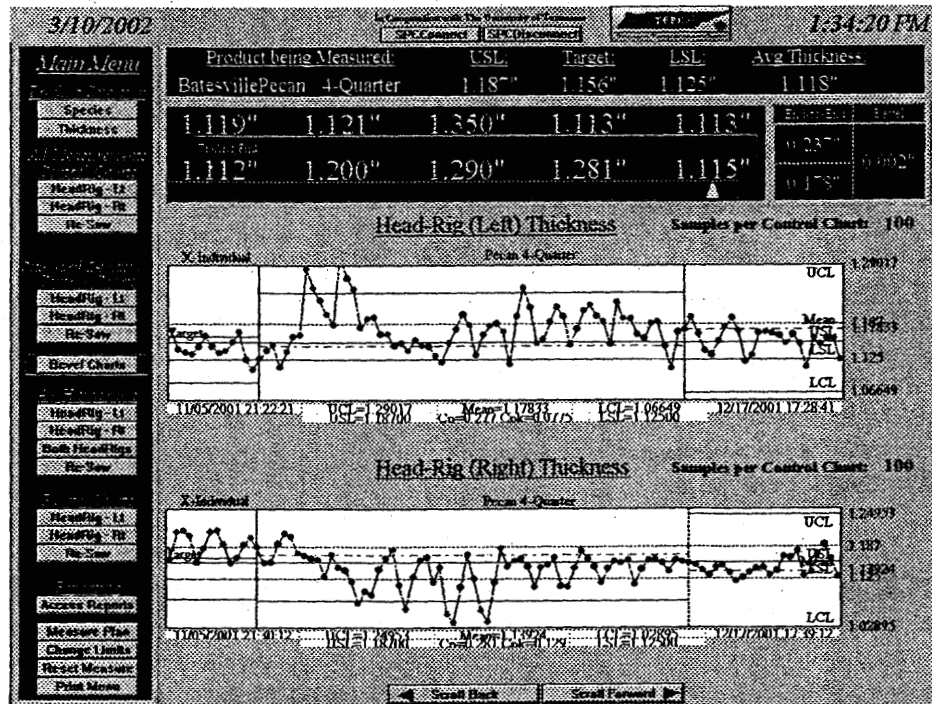
This report summarizes the findings of a research study that was conducted at two hardwood sawmills in the southern U.S. There were four study objectives for each mill: (1) develop a low cost, real-time SPC system to monitor lumber thickness variation; (2) distribute the real-time SPC system to all sawing centers and supervisor offices at Mills K and D; (3) train key personnel at the two sawmills in the principles of statistical process control; and (4) determine if the real-time SPC system had an effect on lumber thickness variation, target sizes, log recovery, and manufacturing costs.

METHODS

Real-Time Statistical Process Control System

Wonderware®'s InTouch 7.1 SPCPro software package was used to develop the display screens and encode the scripting required for communication with the wireless caliper system. InTouch SPCPro was also encoded to communicate with Microsoft Access 2000®. All data were stored in Microsoft Access 2000® within which a reporting system was developed. The main display screen for each mill included control charts of lumber thickness (Figure 1).

Figure 1. Main Wonderware® InTouch SPCPro display window for Mill #2.



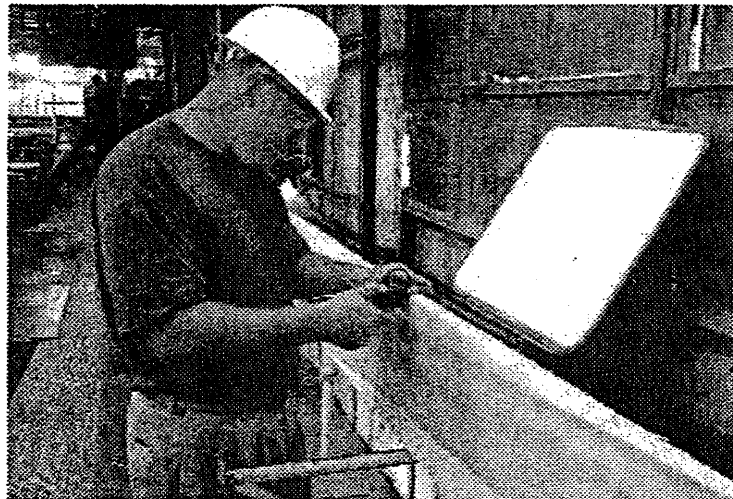
Features of the system included visual alarms for "out of control" points and real-time data collection of assignable causes that lead to special-cause variation. Real-time recording of "corrective actions" for "out of control" samples was also part of the system. Real-time viewing of histograms and Pareto charts were part of the real-time SPC system. Histograms were created from the raw measurement data used for the control charts and were used to display the distribution and frequency of the collected data. Pareto charts were used to graphically present the number of occurrences of special-cause variation.

The system architecture was based on a Windows NT 4.0® operating system. PC monitors were displayed in both mills at all sawing centers, management offices, and lumber sampling stations using a "splitter-box with booster" and 450 feet of monitor cable. The system was available to users on the sawmills' local area networks (LANs) using Carbon Copy® software. The research objective of developing a low cost, real-time SPC system was satisfied using this system architecture.

Wireless Caliper and Software Interface

Lumber thickness measurements were taken immediately behind each sawing station using a digital caliper with wireless data communication to the PC server (Figure 2). A wireless Mitutoyo® caliper with transmitter and receiver-box were used in conjunction with Wonderware® InTouch SPCPro HMI software to measure lumber thickness in a real-time setting. The wireless caliper transmitted data up to 150 feet from the antenna of the receiver. Omniserver® software was used with a copyright encode to interface Wonderware® InTouch SPCPro with the Mitutoyo caliper measurement signal (Young 2000).

Figure 2. Board measurement using Mitutoyo® caliper with transmitter.



Ten measurements were taken for each piece of lumber. The measurements were dispersed uniformly along the board with two sets of five measurements each taken along each edge (Brown 1982). All measurements were taken in the same sequence along the board to detect patterns in the thickness.

Board sampling was based on a stratified random sampling scheme. The scheme was derived from the historic lumber production by species and thickness. The stratified random sampling scheme was based on estimating the average thickness for a piece of lumber with a certainty level of 95 percent and an error level of 10 percent (Levy and Lemeshow 1991).

RESULTS

The real-time SPC system was developed for approximately \$13,500 per sawmill (equipment costs only). The system was distributed to all sawing centers and management offices. The impact of the real-time SPC system on the sawyers' quality awareness and performance is important. The questions posed by sawyers about thickness variation gave a strong indication that sawyers were more aware of thickness variation and actual target sizes after PC monitors were installed in sawing control centers.

Three upper management personnel were trained in the principles of statistical process control at The University of Tennessee, Tennessee Forest Products Center. In addition, on-site training in the principles of SPC was delivered to 15 sawmill personnel in October 2001. A final assessment of quality control personnel, management personnel, and saw operators indicated that our training of key sawmill employees in the principles of statistical process control was successful.

Lumber Thickness Averages and Variation

Mill #1. The resaw sawing center at Mill #1 had the highest lumber thickness standard deviation and coefficient of variation. The left headrig at Mill #1 had a declining coefficient of variation during the study period. There was statistical evidence ($\alpha = 0.05$) that the thickness variation for 4/4 lumber at Mill #1 declined during the last 3 months of the study. There was statistical evidence ($\alpha = 0.05$) that the standard deviations for 4/4-thickness hackberry (*Celtis occidentalis*), red oak (*Quercus rubra*), and white oak (*Quercus alba*) lumber for all machine centers at Mill #1 declined in the last 2 months of the study.

Both the left and right headrigs for Mill #1 had less variation for 4/4 red oak lumber than did the resaw sawing center. The higher standard deviation for the resaw center for this species was a constraint to lower target sizes. The 4/4-thickness lumber sawn on Mill #1 headrigs had higher target sizes than were necessary. However, unless the company develops target sizes that are sawing center specific, the resaw will be the limiting factor for further target size reductions. Resources should be dedicated to determining the sources of variation in 4/4 lumber at the resaw.

Mill #2. The right headrig at Mill #2 had the smallest standard deviation for lumber thickness and the resaw had the highest. The resaw at Mill #2 had a consistently higher coefficient of variation than the left or right headrig. The left headrig had the smallest coefficient of variation.

Mill #2 experienced a statistically significant reduction ($\alpha = 0.05$) in average thickness for 4/4 ash (*Fraxinus caroliniana*) lumber 1 month after the real-time SPC system was installed (Figure 3, Table 1). Average thickness for this species declined by 0.056" in the second month and another 0.031" in the third month. The average thickness stabilized for the remaining months of the study at approximately 1.110". The long-term decline of 0.060" represents a significant cost savings.

Figure 3. Box-Whisker plots of thickness for 4/4 ash lumber for all sawing centers at Mill #2.

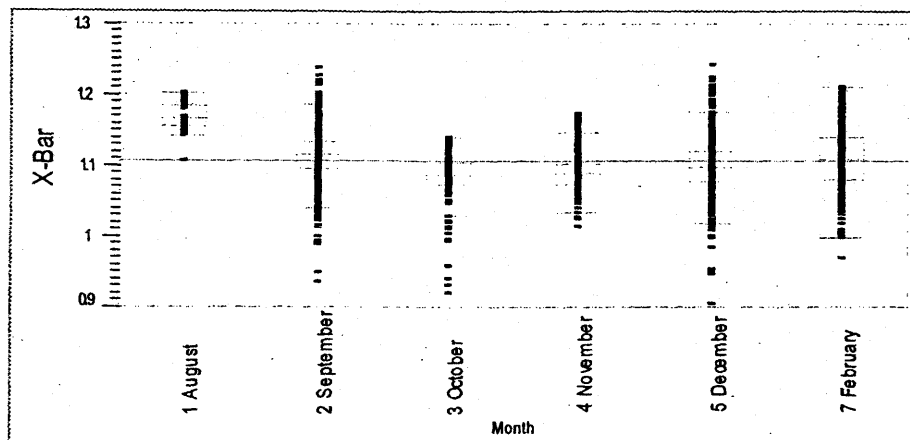


Table 1. Average, median, and standard deviations for 4/4 ash lumber at Mill #2.

Month - Year	Number Number of samples*	Average Average thickness	Means Means test**	Sample standard deviation	Sample variance test***	Median	Median test ****
March - 2001	—	—	—	—	—	—	—
April - 2001	—	—	—	—	—	—	—
May - 2001	—	—	—	—	—	—	—
June - 2001	—	—	—	—	—	—	—
July - 2001	—	—	—	—	—	—	—
Aug. - 2001	33	1.170"	a	.019496"	a	1.169"	a
Sept. - 2001	1015	1.114"	b	.035765"	b	1.116"	b
Oct. - 2001	232	1.083"	c	.037046"	b c	1.088"	c
Nov. - 2001	240	1.094"	d	.031639"	b c d	1.090"	c d
Dec. - 2001	409	1.101"	d e	.046329"	e	1.098"	e
Jan. - 2002	—	—	—	—	—	—	—
Feb. - 2002	627	1.112"	b	.043201"	e	1.110"	—

* Blank cell indicates that no data were available.

** Each subscript letter corresponds to a specific row. For example, "a" corresponds to the first row with data and the significance test compares to the first row with subsequent rows. The letter "b" corresponds to row two, etc. Rows with different letters have significantly different averages at an $\alpha=0.05$ using the Tukey Kramer HSD test for mean comparisons with unequal variance.

*** Rows with different letters have significantly different variances at an $\alpha=0.05$ using the modified Levene test.

Mill #2 also experienced a statistically significant reduction ($\alpha = 0.05$) in average thickness for 4/4 cottonwood (*Populus deltoides*) lumber 1 month after the real-time SPC system was installed. The average thickness for this species declined in successive months by approximately 0.035" (Figure 4, Table 2). The long-term decline of 0.035" represented a significant cost savings.

Figure 4. Box-Whisker plots of thickness for 4/4 cottonwood lumber for all sawing centers at Mill #2.

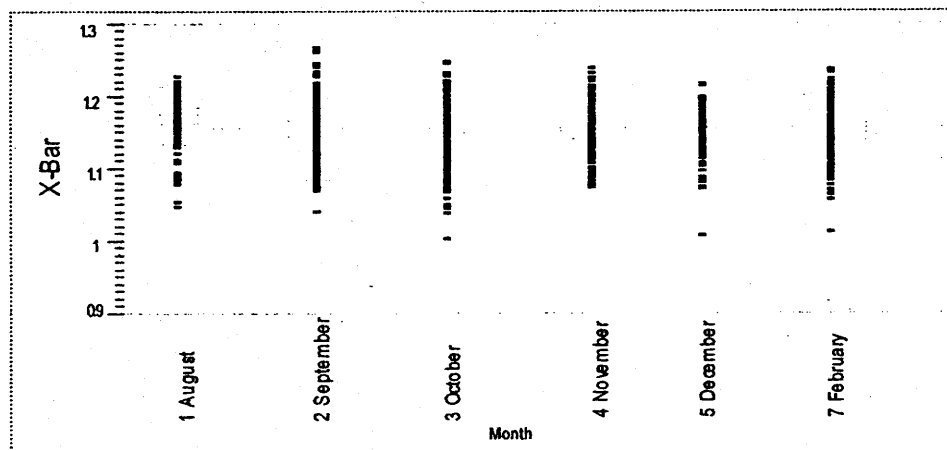


Table 2. Average, median, and standard deviations for 4/4 cottonwood lumber at Mill #2.

Month - Year	Number Number of samples*	Average Average thickness	Means Means test**	Sample standard deviation	Sample variance test***	Median	Median test ****
March - 2001	—	—	—	—	—	—	—
April - 2001	—	—	—	—	—	—	—
May - 2001	—	—	—	—	—	—	—
June - 2001	—	—	—	—	—	—	—
July - 2001	—	—	—	—	—	—	—
Aug. - 2001	422	1.173"	a	.022411"	a	1.176"	a
Sept. - 2001	602	1.165"	b	.031267"	b	1.167"	b
Oct. - 2001	393	1.147"	c	.034648"	b c	1.151"	c
Nov. - 2001	707	1.152"	d	.022387"	a d	1.152"	d
Dec. - 2001	118	1.147"	c d e	.030644"	b c e	1.151"	c d e
Jan. - 2002	—	—	—	—	—	—	—
Feb. - 2002	840	1.150"	c d e	.025374"	d	1.151"	c d e

* Blank cell indicates that no data were available.

** Each subscript letter corresponds to a specific row. For example, "a" corresponds to the first row with data and the significance test compares to the first row with subsequent rows. The letter "b" corresponds to row two, etc. Rows with different letters have significantly different averages at an $\alpha=0.05$ using the Tukey Kramer HSD test for mean comparisons with unequal variance.

*** Rows with different letters have significantly different variances at an $\alpha=0.05$ using the modified Levene test.

Components of Variance

Sanders et al.'s (1994) statistical technique for estimating "within-board" and "between-board" variance as two components of total variance was used in this study. Since the resaw machine center had the largest total variance relative to other machine centers, the components of variance analysis may be helpful to the sawmills in focusing resources on improving the most limiting machine center for further lumber target size reductions.

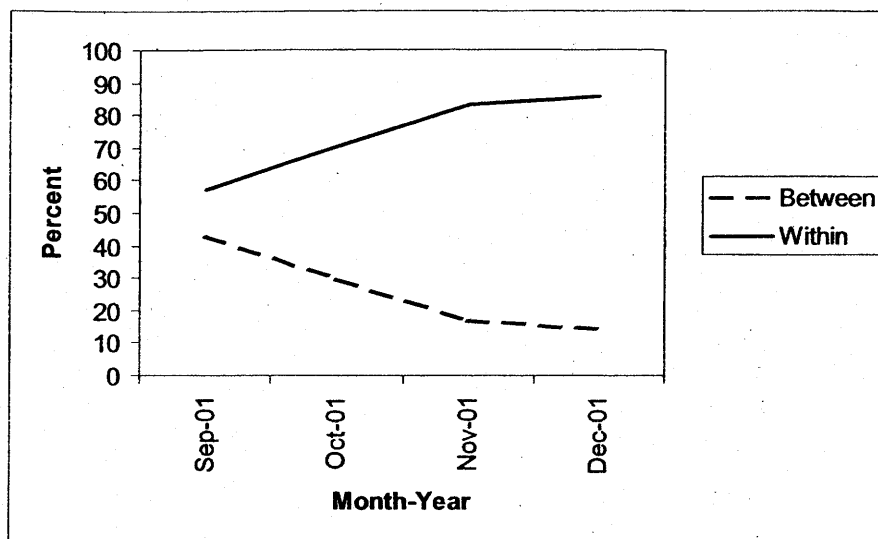
Mill #1. "Within-board" variation was generally the largest component of variance for every species for all of Mill #1's machine centers. A discussion with company quality control personnel revealed that "timber-bind" might be an important source of "within-board" variation at both headrigs. "Timber-bind" is the delay in the movement of the middle-knee of the log carriage, which has a direct impact on the amount of movement of the middle portion of the log during sawing. The log is allowed to move less relative to the position of the middle knee if the "timber-bind" is set to a greater thickness (e.g., from 1/5" to 1/2").

An analysis of "within-board" and "between-board" variance for 4/4-thickness red oak (*Quercus rubra*) for Mill #1 suggested that the "within-board" variance was the largest component of variation for all machine centers (Figure 5).

The “within-board” variance as a proportion of total variance was especially pronounced for both headrigs.

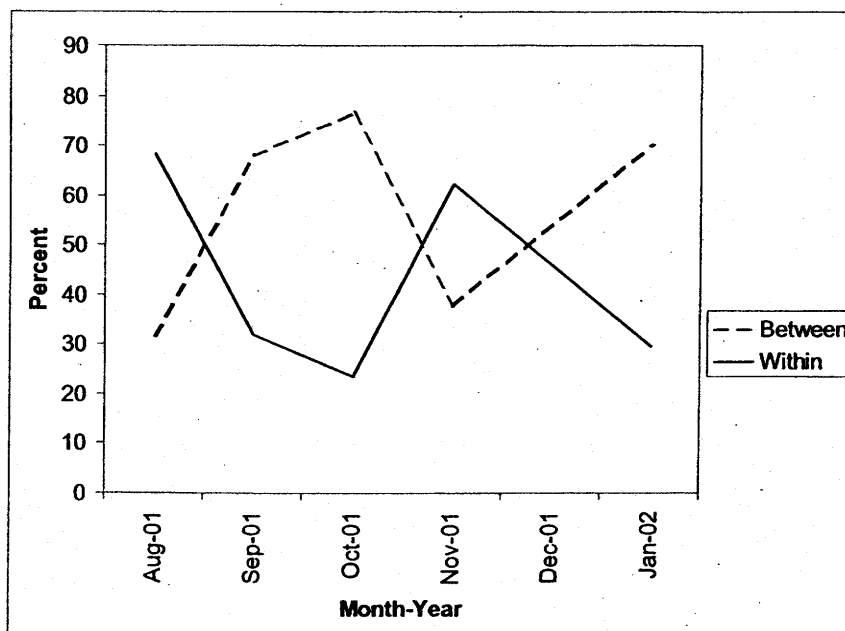
Mill #2. “Within-board” variation was the largest component of variation for every species of 4/4-thickness lumber produced on both the left and right headrigs at Mill #2. The resaw machine-center for Mill #2 had a larger component of “between-board” variance than “within-board” variance.

Figure 5. Mill #1 “within” and “between” variation for 4/4 red oak lumber sawn on the left headrig.



For 4/4 cottonwood (*Populus deltoides*) sawn at Mill #2, the “within-board” variance was the more significant source of variation overall but the “between-board” variance was pronounced at the resaw (Figure 6).

Figure 6. Mill #2 “within” and “between” variation for 4/4 cottonwood lumber sawn on the resaw.



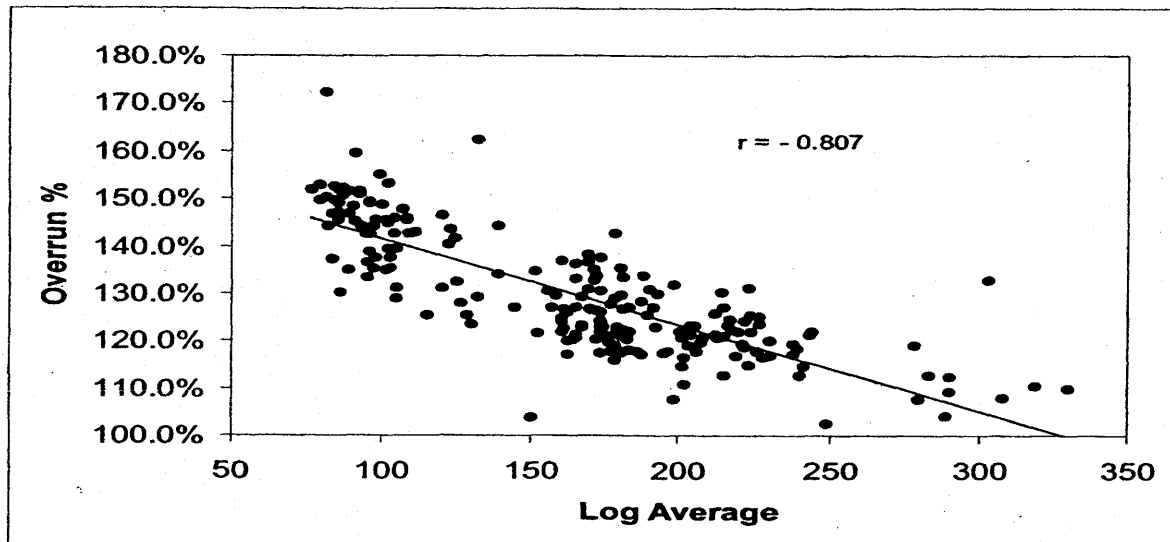
Impact on Lumber Recovery and Grade

A statistical analysis that consisted of analyzing the daily overrun using univariate and multivariate control charts was performed (Hotelling 1947, Young et al. 1999). Overrun is defined as the ratio of lumber recovered from a set of logs to the board-foot scale of the logs. Many authors have noted the limitations of the use of the overrun lumber recovery statistic, i.e., overrun is dependent on log diameter (Brown 1982, 1997; Wengert 1993). Both of our study sawmills used the Doyle log rule to estimate the board footage of lumber in a log. The Doyle log rule estimates the volume based on log length, diameter, slabs, edgings, shrinkage, and production of sawdust. In the Doyle log rule the allowance for slabs and edgings is too large for small logs and is too small for large logs. Therefore, the rule under-scales small logs and over-scales large logs. Inaccuracies of

the rule also include a 4.5 percent reduction of log volume for sawdust and shrinkage (most rules allow between 10-30 percent) and no allowance for taper.

Analytical limitations of the overrun lumber recovery statistic may be reduced with the use of multivariate control charts (Young et al. 1999). Multivariate control charts were used in the overrun analysis since a significant correlation between daily overrun and average log volume was observed (Figure 7).

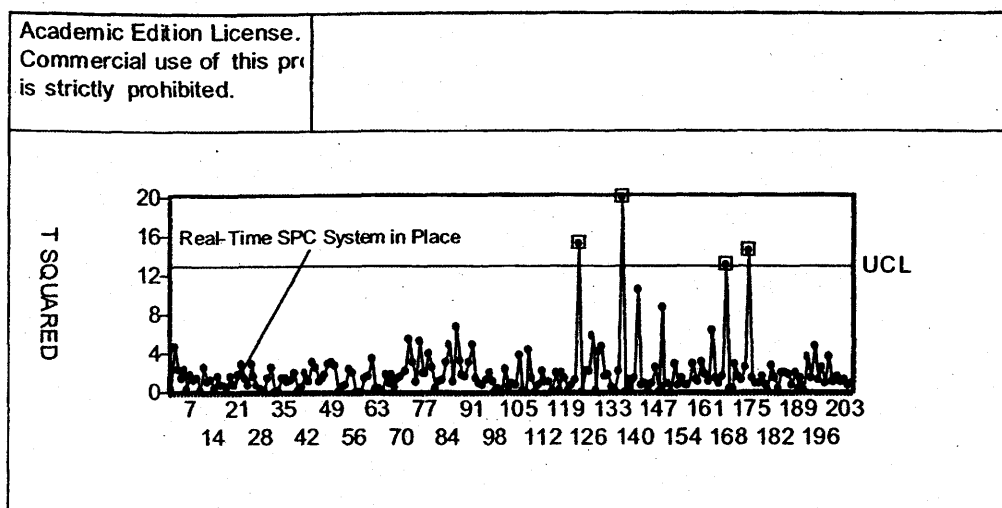
Figure 7. Mill #1 correlation of overrun and average log volume - Doyle scale.



A second recovery analysis addressed the daily change in "Common and Better" (i.e., 1 Common and Better grade lumber) grade recovery percentage. Improvements in lumber quality may result from a reduction in "thin-edges" caused by excessive within-board thickness variation. "Thin-edge" lumber is defined as wedge-shaped lumber with thickness on the long-edge of the lumber that is below the minimum thickness specification. The occurrence of "thin-edges" on FAS grade lumber lowers the grade to 3C. The economic loss associated with FAS to 3C grade reductions was significant at both sawmills prior to the implementation of real-time SPC.

Mill #1. After installation of the SPC thickness monitoring system: the average overrun for Mill #1 for all species increased by approximately 2.6 percent ; the variation in overrun was greater; the average log volume was statistically unchanged; and the variation in average log volume was greater (which may correspond to the increase in overrun variation). As expected, the correlation between overrun and average log volume for Mill #1 was significant ($r = -0.807$, Figure 7). A multivariate control chart (Hotelling's T2) of the overrun and average log volume indicated that an increase in variation had occurred after installation of the real-time SPC thickness improvement system (Figure 8). The out-of-control points of the multivariate control chart were due to atypically higher overrun. It was not clear as to the cause of the increased variation in both overrun and average log volume. The installation of SPC to monitor sawing variation should not have had any effect on the log supply or the method of estimating the board footage in the logs. It was likely that some variation in log supply (log diameters) also occurred at this time, which was indicated by the variance in the average log volume.

Figure 8. Hotelling's T2 control chart of overrun and average log volume for Mill #1



A review of overrun by species for Mill #1 indicated that Doyle overrun for hackberry increased by 4 percent after installation of the real-time SPC thickness improvement system. Overrun increased despite an increase of 1 percent in the average log volume. There was an improvement in red oak overrun of 5 percent despite an increase of 1.1 percent in average log volume for red oak after installation of the real-time SPC thickness improvement system. Since the Doyle log rule typically over estimates the amount of lumber volume in a large diameter log and underestimates lumber volume on small diameter logs, it would be expected that as the average log volume increases, that overrun would decrease. The increases in both overrun and average log volume for hackberry and red oak seem to indicate that increases in lumber recovery occurred after installation of the real-time SPC thickness improvement system.

Typically the financial success of sawmills is dependent on the amount of No.1 "Common and Better" lumber that can be produced from the log supply. Increases in profitability and log utilization occur if more "Common and Better" lumber can be produced out of the same log supply.

The "Common and Better" average grade percentage increased by a statistically significant amount (3 percent) after installation of the real-time SPC thickness improvement system. The increases in the "Common and Better" lumber grade yields for the different species were partially the result of quality improvements from use of the real-time SPC thickness improvement system realized from reductions in "thin-edges" on lumber. The reduction in "thin edges" was an example of using SPC as a continuous improvement methodology to prevent the manufacture of defective products.

Mill #2. The average overrun for Mill #2 for all species declined by approximately 1 percent after installation of the real-time SPC thickness improvement system. The variation in overrun also declined after installation of the real-time SPC thickness improvement system. There was a statistically significant increase of 1.1 percent in average log volume for all species after installation of the real-time SPC thickness improvement system. The variation in average log volume declined after installation of the real-time SPC thickness improvement system. It is unlikely that the installation of the real-time SPC thickness improvement system had an effect on log supply or log scaling that would have led to the changes observed. As expected, the correlation in overrun percent and average log volume for Mill #2 was significant ($r = -0.681$). Given the moderate negative correlation between overrun percent and average log volume, Hotelling's T2 multivariate statistic was estimated and charted. The multivariate control chart indicated more long-term stability in overrun after installation of the real-time SPC thickness improvement system.

A review of overrun percentages by species for Mill #2 indicated that every species had an increase in average log volume by approximately 1 percent during the October to November 2001 time frame. This resulted in a corresponding decline of approximately 1 percent in overrun for every species. The 1 percent increase in average log volume was believed to be the result of a change in the log scaling procedure introduced at this

sawmill. The log grading procedural change at Mill #2 eliminated the opportunity to detect the level of improvement in overrun attributable to the installation of the SPC system. The average daily "Common and Better" grade recovery for Mill #2 increased by statistically significant 4 percentage points after installation of the real-time SPC thickness improvement system. Also, the regression relationship between the "Common and Better" grade yield percentage and the number of days since the beginning of the study was statistically significant.

Financial Return

The economic significance of reductions in lumber target sizes has been well documented (Brown 1982, 1997; Wengert 1993; Young et al. 2000b, 2002). Wengert (1993) suggested that reductions in target sizes of 0.030" could result in annual cost savings of \$250,000 for larger capacity sawmills (like the ones studied here).

The estimated annual potential financial cost savings resulting from the installation of the real-time SPC thickness improvement system based on the two sawmills in this study was estimated to average \$376,050 per sawmill (Table 3). Cost-savings estimates were based on confidential financial data supplied by the two sawmills that participated in the study. The majority of the savings, a combined \$709,120 for the two mills, was associated with the estimated 1.5 percent average improvement in overrun. An additional combined savings of \$42,980 was attributed to the improvements in the percentage of "Common and Better" grade lumber.

Table 3. Average cost savings associated with a 1 percent increase in overrun at the study sawmills.

<u>Species</u>	<u>Bd Ft</u>	<u>Log Ft</u>	<u>Overrun</u>	<u>1 % Increase*</u>	<u>Savings</u>
Ash	7,059,735	4,872,239	1.45	70,597	\$ 51,183
Cottonwood	20,405,509	17,424,778	1.17	204,055	\$111,822
Hackberry	8,131,668	5,506,458	1.48	81,317	\$ 29,274
Red Oak	19,501,147	15,717,298	1.24	195,011	\$121,102
White Oak	3,921,508	2,989,362	1.31	39,215	\$ 11,960
Pecan	6,941,772	5,527,055	1.26	69,418	\$ 34,084
Poplar	3,572,359	2,856,757	1.25	35,724	\$ 28,328
Sycamore	3,916,313	2,894,923	1.35	39,163	\$ 25,573
Willow	4,458,580	3,547,697	1.26	44,586	\$ 29,872
All Species	77,908,591	61,336,567			\$443,198

* Note the 1 percent increase was estimated by the participating sawmills using average prices for 4/4 lumber for each species, i.e., it assumes that the additional 4/4 lumber footage realized for each species could be sold at existing prices.

CONCLUSIONS

Competitive pressures in the hardwood lumber industry are not likely to subside in the future. Improved sawmill efficiency and manufacturing cost control will be critical for the successful hardwood sawmill of the 21st century. Continuous improvement including SPC provides manufacturers with the ability to reduce lumber thickness variation, improve yield and lower manufacturing costs.

Two case studies were conducted to determine if the application of real-time SPC to hardwood lumber manufacture improves lumber recovery and financial performance. There was statistical evidence that suggested that the average thickness of some species declined by 0.060" over the course of the study period. There also was statistical evidence that lumber thickness variation declined after the implementation of real-time SPC for certain species at some sawing centers. The resaw sawing center had the most thickness variation and thus constrained the degree to which target sizes could be reduced at other machine centers.

The estimated annual financial cost savings due to improvements in overrun and grade after installation of the real-time SPC thickness improvement system was \$752,100 per year for both sawmills combined or \$376,050 per mill. Cost-savings were derived from a net 1.5 percent average overrun gain at the two mills and a slight improvement in the percentage of "Common and Better" grade lumber.

The potential benefits from adopting a "low-risk" technology such as real-time SPC should not be ignored by the hardwood lumber industry. Even though this study was an applied statistical study at two hardwood sawmills, there is ample evidence that other hardwood sawmills can benefit from the use of real-time SPC by reducing lumber thickness variation and target sizes.

REFERENCES

- Brown, T.D. 1982. Quality control in lumber manufacturing. Miller Freeman Publications. San Francisco, CA. 288p.
- Brown, T.D. 1997. Lumber size control systems. IN: Proceedings of Process and Business Technologies for the Forest Products Industry. Forest Products Society Proc. No. 7281. p 94-98.
- Cassens, D.L., J.R. Bankston and J.S. Friday. 1994. Statistical process control of hardwood lumber target sizes: Is it time? Forest Products Journal. 44(1): 48-50.
- Deming, W.E. 1986. Out of the crisis. Massachusetts Institute of Technology, Center for Advanced Engineering Study. Cambridge, MA. 507p.
- Deming, W.E. 1993. The new economics. Massachusetts Institute of Technology, Center for Advanced Engineering Study. Cambridge, MA. 240p.
- Hotelling, H. 1947. Multivariate quality control. In C. Eisenhart, M.W. Hastay, and W.A. Wallis, eds. Techniques of Statistical Analysis. McGraw-Hill. New York, NY. P.113-185.
- Levy, P.S. and S. Lemeshow. 1991. Sampling of populations: methods and applications. John Wiley and Sons, Inc. New York, NY. 420p.
- National Hardwood Lumber Association. 1996. Research priorities for North American hardwoods. National Hardwood Lumber Association. Memphis, TN. 31p.
- Sanders, R.D., M.G. Leitnaker and D. Sanders. 1994. The analytic examination of time-dependent variance components. Quality Engineering. 7(2): 315-336.
- Shewhart, W.A. 1931. Economic control of quality of manufactured product. D. Van Nostrand Company. New York, NY. 501p.
- Wengert, G. 1993. Troubleshooting and quality at the mill. Instruction notes from National Hardwood Lumber Association seminar. Memphis, TN.
- Williston, E.M. 1988. Lumber manufacturing - the design and operation of sawmills and planer mills. Miller Freeman Publications, Inc. San Francisco, CA. 486p.
- Young, T.M. 2000. Final report of project titled, "Electronic micrometer interfaces for human machine interface platforms in hardwood lumber manufacture." The University of Tennessee, Institute of Agriculture Faculty Idea Grant R11221835/B11997401. Unpublished manuscript.
- Young, T.M. and P.M. Winistorfer. 1998. Recovering more from your hardwood lumber: reducing thickness variation. Proc. of the 26th Annual Hardwood Symposium (Technology and Market Information for the Next Millennium). National Hardwood Lumber Association. Cashiers, NC. p 109-120.
- Young, T.M. and P.M. Winistorfer. 1999. Statistical process control and the forest products industry. Forest Products Journal. 49(3): 10-17.
- Young, T.M., P.M. Winistorfer, and S. Wang. 1999. Multivariate control charts of vertical density profile attributes. Forest Products Journal. 49(5): 79-86.
- Young, T.M., B.H. Bond and P.M. Winistorfer. 2000a. Statistical process control for sawmills. Proc. of the 28th Annual Hardwood Symposium. (West Virginia Now - The Future for the Hardwood Industry?). National Hardwood Lumber Association. Canaan, WV. p. 31-42.
- Young, T.M., P.M. Winistorfer and J.D. Cox. 2000b. Tennessee Quality Lumber Initiative (TQLI) - Phase I: Reducing lumber target sizes using real-time statistical process control. Final Report for USDA special Wood Utilization Grant R112218-54. The University of Tennessee. Knoxville. 124p.
- Young, T.M., J.H. van Houts, R. Shaw, J. Peterson, R. Springer, M. Looslie. 2002. Tennessee Quality Lumber Initiative (TQLI) - Reducing lumber thickness variation using real-time statistical process control at Boise Cascade Corporation's La Grande, Oregon sawmill. Final Report for University of Tennessee contract R11-2218-080 with Boise Cascade Corporation. Knoxville, TN. 179p.