Implementation of a real-time statistical process control system in hardwood sawmills

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Abstract

Variation in sawmill processes reduces the financial benefit of converting fiber from a log into lumber. Lumber is intentionally oversized during manufacture to allow for sawing variation, shrinkage from drying, and final surfacing. This oversizing of lumber due to sawing variation requires higher operating targets and leads to suboptimal fiber recovery. For more than two decades, global businesses strategies have involved the use of statistical methods to reduce variation, improve quality, and lower costs as a means to ensure competitiveness. However, the use of statistical methods by the sawmill industry as a strategy to reduce process variation and improve competitiveness appears to be an exception rather than the norm. Only a few highly competitive sawmills are currently using statistical methods to maximize recovery, minimize costs, and improve product quality. Given the current and future economic pressures faced by this industry, sawmills of the future may need to consider the use of statistical methods to maximize fiber recovery. In our study, a real-time statistical process control system was developed and implemented for green lumber thickness measurement. The system used wireless measurement of lumber thickness displayed on control charts and histograms distributed real-time to all sawyers and management. Use of the system by four hardwood sawmills located in the United States resulted in significant cost savings. Target size reductions occurred at each sawmill and ranged from 0.030 inch to 0.120 inch for 4/4 green hardwood lumber. Lumber recovery increased at all sawmills, ranging from 0.2 percent to 1.6 percent per annum. Financial performance from use of the system improved for all sawmills with an average return on investment of 17:1.

Lumber is intentionally oversized to allow for sawing variation, surfacing of rough lumber and shrinkage during the drying process. The amount of material that must be removed from rough-cut lumber depends on the variation due to surface roughness and size variability caused by differential shrinkage during drying (Young and Winistorfer 1998). Brown's (1982) model of this relationship was:

$$T = \frac{F + P}{(1 - s_h / 100)} + (z \cdot s_t) \qquad [1]$$

where:

T = target thickness of lumber,

F = final dried lumber thickness,

P = planer thickness allowance,

s_h = percent shrinkage from drying,

s_t = thickness standard deviation of lumber,

z = z-score for the lower $\alpha/2$ percentage point of the standard normal distribution.

Even though Brown (1982) noted limitations of his non-probabilistic equation [1], the general principle of the equation holds, i.e., greater thickness variation during sawing (s_t) requires higher target sizes.[1]

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 survey (NHLA 1995). Out of 19 research needs cited in the NHLA study summary (see Table 1 in NHLA 1996), development of statistical process control technology was ranked as the 6th most important.

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[1] Brown (1982) has indicated in personal conversations with the authors (2001) that s_h and s_t are probability density functions which makes equation [1] estimate of T an approximation of the median T.

Table 1. — Descriptive statistics for 4/4 lumber for the resaw by mill, by species.

| | First six-month period | | | | | Second six-month period | | | |
| | n | Average $\bar{x}$ | Median (M) | Avg. SD ($\bar{s}$) | COV | n | Average $\bar{x}$ | Median (M) | Avg. SD ($\bar{s}$) | COV |
4/4 Lumber		--------------- (in) ---------------			(%)		--------------- (in) ---------------			(%)
Mill A										
Liriodendron tulipifera	966	1.112	1.114	0.046	4.1	977	1.116	1.116	0.033	3.0
Quercus rubra	1291	1.123	1.121	0.040	3.6	1217	1.123	1.108	0.032	2.8
Quercus alba	885	1.112	1.113	0.040	3.6	1035	1.119	1.121	0.033	2.9
Mill B										
Fraxinus caroliniana	2868	1.133	1.133	0.035	3.1	3035	1.125	1.126	0.032	2.8
Populus deltoides	3531	1.127	1.134	0.044	3.9	769	1.136	1.132	0.029	2.6
Carya illinoensis	1967	1.140	1.140	0.040	3.5	1352	1.151	1.251	0.032	2.7
Quercus falcata	577	1.131	1.135	0.044	3.9	5658	1.117	1.119	0.036	3.2
Quercus alba	2010	1.134	1.134	0.037	3.3	637	1.130	1.126	0.031	2.7
Mill C										
Fraxinus caroliniana	1048	1.142	1.143	0.028	2.5	1508	1.098	1.099	0.040	3.6
Populus deltoides	1024	1.169	1.172	0.027	2.3	2058	1.149	1.151	0.028	2.4
Carya illinoensis	309	1.164	1.171	0.031	2.6	1053	1.165	1.165	0.036	3.1
Mill D										
Fraxinus caroliniana	390	1.127	1.126	0.023	2.0	320	1.124	1.127	0.028	2.5
Prunus serotina	809	1.116	1.115	0.029	2.6	150	1.115	1.113	0.027	2.4
Acer saccharum	1154	1.129	1.126	0.033	2.9	530	1.125	1.122	0.033	2.9
Populus deltoides	5939	1.120	1.123	0.027	2.7	3848	1.121	1.124	0.024	2.4
Quercus rubra	7089	1.119	1.121	0.024	2.1	2258	1.122	1.125	0.023	2.0
Acer rubrurm	979	1.126	1.123	0.033	2.9	953	1.116	1.115	0.027	2.4
Quercus alba	2188	1.131	1.128	0.035	3.1	2262	1.126	1.125	0.029	2.6

The oversizing of lumber during the sawing process leads to financial losses and impairs an organization's competitiveness. Wengert (1993) and Brown (1997) have suggested that the oversizing of rough sawn lumber can lead to losses of $50,000 to $250,000 per year depending on the capacity of the sawmill.

Traditional quality control programs in the lumber industry vary greatly and are tailored to the business strategies of sawmills. One quality control function that all sawmills have in common is the grading of lumber, which is based on standardized criteria to ensure an accurate and consistent grade of lumber (Brown 1982; Williston 1988). The grading of lumber does not ensure improvement of the lumber manufacturing process and is not intended to address reducing thickness variation and target sizes. However, excessive lumber thickness variation may reduce the grade of lumber, e.g., thin edges below lower specification (NHLA 2006). In other industries, traditional quality control programs were replaced by those that offer continuous improvement and the prevention of manufacturing product that does not meet specification.

Continuous improvement of manufacturing processes is based on using statistical methods to quantify natural variation. Natural variation is typically attributable to variability associated with factors such as raw material, equipment, work methods, measurement and people (Ishikawa 1976). Quantifying natural variation is considered by all notable scholars to be the genesis of continuous improvement (Shewhart 1931; Deming 1986, 1993). After natural variation is quantified, the first-step towards variation reduction is the prevention of assignable causes that lead to special-cause variation, e.g., excessive over-feed on dull saws, elimination of cants that are

not square, elimination of variation at shift change and saw change, elimination of product setup variation, etc. Long-term variation reduction comes from improvements to the manufacturing system, which results in a reduction in natural variation (common-cause variation), e.g., change to better band saw technology, more consistent speed of head-rig carriage, long-term mechanical improvements, etc.

This study was a culmination of prior research by Young (1997), Young and Winistorfer (1998, 1999), and Young et al. (2000a, 2000b, 2002a, 2002b, 2005). The study built upon the statistical principles developed by Walter Shewhart (Shewhart 1931). As Shewhart noted simply but eloquently, ". . . the purpose of statistical process control (SPC) is to quantify variation and prevent the manufacture of defective product." Most credit the popularization of Shewhart's work to W. Edward Deming (Deming 1986, 1993). Traditional quality control suffers in that it is reactive with an overemphasis on inspection and sorting. Young (1997) believes that ". . . process improvement cannot be initiated without first quantifying variation." This 5-year research study used real-time statistical process control to quantify lumber thickness variation; this ultimately led to variation reduction, quality improvement and financial gains. Lumber thickness data were presented at the time of measurement to sawyers, saw filers, and managers in the form of control charts and histograms so that lumber thickness and variation could be managed during actual production.

Others have studied applications of SPC to sawmill operations (Brown 1982, Brown and Page 1994, Cassens et al. 1994, Copithorne et al. 1994, Leicester 1994, Brown 1997). Previous studies advanced the application of SPC to improve

sawmill processes, but the studies focused more on postprocessing measurements and did not address the use of real-time SPC in sawmill operations to reduce variation as product is being produced

This study was part of a long-term research program known as the Tennessee Quality Lumber Initiative (TQLI). The TQLI[2] was established at the University of Tennessee, Forest Products Center with the long-term goal of improving the quality of lumber produced by the sawmill industry and promoting wiser use of forest resources. The hypotheses a priori of the study were: "*the use of real-time statistical process control quantifies lumber thickness variation, results in variation reduction, improves lumber recovery and improves financial performance*." The research objectives required for these hypotheses were: (1) develop a wireless, real-time statistical process control (SPC) system for measuring lumber thickness; (2) distribute the real-time SPC system results to all sawing centers, filing rooms and management offices; (3) train operations personnel and management in the concepts of SPC; and (4) for a 12-month period determine if the real-time SPC system had an affect on lumber thickness variation, target sizes, lumber recovery, lumber grade, and financial performance.

Methods

Case study sites

The TQLI was conducted from January 1999 to May 2004 and involved case studies at four hardwood sawmills located in Mississippi, Tennessee, and West Virginia. Sawmill A was a hardwood sawmill located in Tennessee and had one headrig, one resaw, and one gangsaw. Sawmill A produced primarily 4/4-thickness red oak (*Quercus rubra*).

Sawmill B and Sawmill C were hardwood sawmills located in Mississippi. Both had two headrigs, one resaw, and one gangsaw. Sawmill B produced primarily 4/4 cottonwood (*Populus deltoides*) but had a large mix of other hardwood product types. Sawmill C produced primarily 4/4 ash (*Fraxinus caroliniana*) and 4/4 cottonwood (*Populus deltoides*) but also had a large mix of other hardwood product types.

Sawmill D was a hardwood sawmill located in West Virginia and contained the most modern processing equipment relative to the other sawmill case study sites. Sawmill D had one headrig, one resaw, and one gangsaw. Sawmill D produced primarily 4/4 red oak (*Quercus rubra*), poplar (*Populus deltoides*), and hard maple (*Acer saccaharum*) lumber.

Lumber from the resaw center was the predominant sawing center sampled across all participating sawmills and is the focal point of comparison. The predominant lumber sampled was 4/4, which reflected the production and order file of the participating sawmills. **Table 1** in the Results section has a more detailed list of lumber sampled by mill and by species for the resaw sawing center.

Comparisons of the descriptive statistics were made for the first six months and the last six months of the study. Justification for this categorization by six-month time interval was that during the first six-month time period, visits by research staff to the sawmills were made once a month or once every two months to conduct training and facilitate the use of real-time statistical process control system. No active training or

facilitation was conducted at the sawmills after the first six-month period.

Real-time statistical process control system

The real-time statistical process control (SPC) system developed and tested at the four hardwood sawmills utilized the fundamentals of control charting, wireless calipers for measurement, and human machine interface technology. The system was unique in that the real-time lumber thickness measurements were taken by sawing center and distributed throughout the sawmill in the context of real-time SPC.

Statistical process control

The primary tool of SPC is the Shewhart control chart. The Shewhart control chart quantifies variation as either special-cause or common-cause (natural) variation (**Fig. 1**). The control limits on control charts quantify variation as that inherent to the process (natural variation data inside the control limits), or variation caused by an event or assignable-cause (special-cause variation data located outside the control limits). Data outside the control limits are also referred to as "out of control" points.

The study documented the change in sawyer operating targets when sawyers are presented with real-time thickness data in the form of control charts. Young et al. (2000a, 2000b, 2002a, 2002b, 2005) documented that most sawyers have an anecdotal knowledge of historical lumber thickness averages and variation, i.e., thickness measurements are made infrequently for setup at saw change, shift change, production reporting from last shift, or as a reaction to extreme variation. As saws wear from continuously sawing lumber, the sawyer may experience greater saw deflection at a constant carriage speed (i.e., increased within board variation). Sawyers are reluctant to slow carriage speed and tend to over-size lumber thickness given their imperfect knowledge of real-time lumber thickness at the time of sawing. Oversizing lumber is a costly "hedge" and is not competitive as a long-term business strategy.

Real-time human machine interface platform

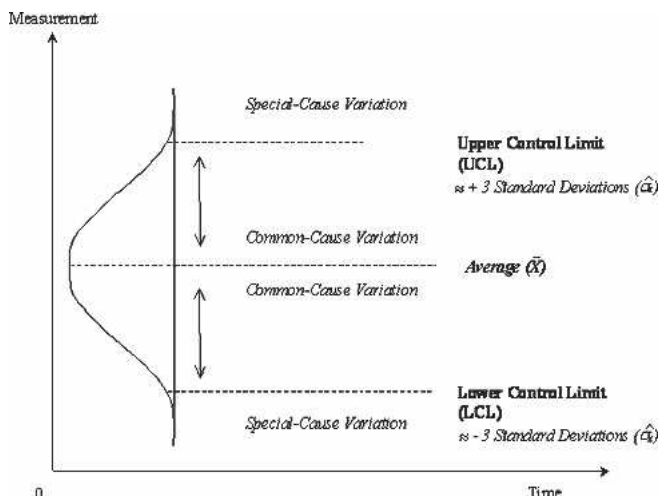The real-time SPC system was displayed at the sampling stations, resaw, headrig, gangsaw, supervisor's office, saw-

Figure 1. — Basic form of a control chart.

Figure 2. — Board sampling station at sawmill B and display at resaw at sawmill C.

Figure 3. — Real-time SPC display of thickness for six boards at the resaw at sawmill D.

filing room, and management offices (**Fig. 2**). An example of one real-time SPC display window used in this study is presented in **Figure 3**.[3] System features included color-coded alarms for "out of control points," "assignable cause" tracking, and "corrective action" storage. Pareto charts displayed sources of special-cause variation by species, product, and sawing center. The system included real-time histograms of lumber thickness in the context of specification limits for real-time capability analysis.

Wireless caliper and HMI interface

Lumber thickness measurements were taken manually with a digital caliper and a wireless transmitter. The data were received by 4-channel receivers with RS-232 connectivity to a PC server. The wireless caliper transmitted data up to 125 feet from the receiver.

System architecture

The system architecture consisted of a Dell™ PC Server with a Windows® 2000 Server OS and Wonderware® In-Touch 8.0 SPCPro. The headrig, resaw, gangsaw, and sampling stations had "view-only" PC monitors that were connected to the PC server. The saw-filing room had a PC Client
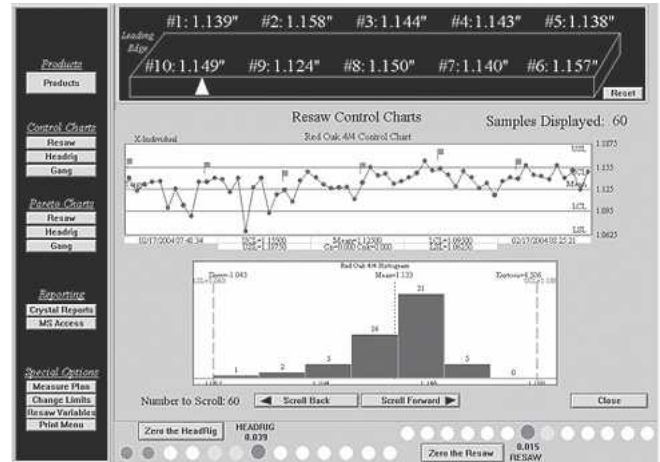
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[3] Wonderware®'s InTouch 8.0 with SPCPro software were used to develop the display screens and encode the the wireless caliper system. All data were stored in Microsoft SQL 2000® from which a reporting system was developed. Omniserver® software was used to interface the wireless micrometer with Wonderware®.

with LAN connectivity to a server. This enabled full access to all of the features of the real-time SPC system.

Board measurements and stratified random sampling scheme

Sampling stations were developed near the sawing centers to take lumber thickness measurements. Sampling stations were designed to maximize safety and be ergonomically friendly, i.e., boards were removed from conveyors without lifting. Ten measurements were taken on each piece of lumber (representing a sample). Five measurements were equidistantly dispersed along each board edge and were approximately 12 inches apart. All measurements were taken in the same order to enhance the ability to detect patterns in lumber thickness variation.

Recommended board sampling plans were initially developed using a stratified random sampling scheme. Prestudies were conducted at each sawmill to derive initial estimates of average thickness and variance required for the stratified random sampling plans. The strata of the sampling plans were species, thickness, and sawing center. Schemes were developed for each case study sawmill using an acceptable level of confidence and error on the average lumber thickness estimate. However, participating sawmills selected stratified random sampling plans that were deemed most affordable and practical given their production schedules and customer order file (**Table 1**); see Deming's famous works as related to industrial sampling (Deming 1986, 1993). The largest (worst) confidence interval and standard error recorded for board thickness at any one site, were approximately 90 percent and 5 percent, respectively. The smallest (best) confidence interval and standard error recorded at any site were approximately 95 percent and 3 percent, respectively. Deviations from the recommended sampling plans occurred throughout the 12-month studies of the sawmills given changes in market conditions, mill conditions, and the customer order file.

It is important to note that the Shewhart control chart is not a confidence interval or any type of test of statistical significance that are common to enumerative research studies (Shewhart 1931). This research was an analytical research study conducted in a real-time sawmill setting and as stated earlier, the hypothesis was "*the use of real-time statistical process control quantifies lumber thickness variation, results*

Table 2 — Daily summary report for resaw, red oak, 4/4 lumber.

Sawing center	Product	Day	Average	SD	Minimum	Maximum	Count
Resaw	Redoak44	05/29/2003	1.135	0.019	1.059	1.197	610
		05/30/2003	1.117	0.018	1.051	1.150	150
		06/02/2003	1.122	0.025	0.967	1.628	1765
		06/03/2003	1.118	0.017	1.068	1.159	80
		06/10/2003	1.115	0.022	1.005	1.174	1229
		06/11/2003	1.119	0.025	0.957	1.388	2627
		06/12/2003	1.118	0.024	0.960	1.270	2729
		06/19/2003	1.122	0.023	1.017	1.213	1460
		06/20/2003	1.124	0.017	1.056	1.165	500
		06/23/2003	1.119	0.014	1.084	1.156	260

Shift 1 (Day)

Saw Center	Products	Average	Target	SD	Minimum	Maximum	Count
Resaw	Ash 44	1.124	1.125	0.024	0.982	1.183	700
Resaw	Hardmaple44	1.139	1.125	0.025	0.933	1.214	740
Resaw	Softmaple44	1.136	1.125	0.022	1.020	1.222	839

Shift 2 (Night)

Saw Center	Products	Average	Target	SD	Minimum	Maximum	Count
Gang 1	Ash44	1.089	1.125	0.072	0.855	1.141	30
Headrig	Ash44	1.389	1.125	0.017	1.368	1.402	5
Gang 1	Basswood54	1.386	1.375	0.062	1.258	1.558	60
Headrig	Basswood54	1.394	1.375	0.025	1.337	1.454	46
Resaw	Basswood54	1.380	1.375	0.024	1.281	1.444	90
Gang 1	Softmaple44	1.113	1.125	0.021	1.079	1.154	10
Resaw	Softmaple44	1.121	1.125	0.019	1.059	1.164	70
Gang 1	Softmaple44	3.510	3.500	0.237	2.596	3.622	17

in variation reduction, improves lumber recovery and improves financial performance." Descriptive statistics such as the average, median, standard deviation and coefficient of variation of 4/4-lumber thickness were used as important statistical outcomes of the study to test the overall research hypothesis.

Reporting system in Access/SQL 2000™

A reporting system was developed in MS Access 2000™ using the MS SQL 2000 database architecture of InTouch 8.0 SPCPro. The reporting system featured daily, weekly and monthly reports by shift, species, thickness, and sawing center. A graphical user interface was developed in the reporting system that allowed the user to easily query the system for a desired report type (**Table 2**).

Results

The effect of real-time SPC on
4/4 lumber thickness variation at the resaw

The predominate product manufactured and sampled by the four participating sawmills throughout the study was 4/4 lumber. Sampling of 4/4 lumber was predominately done at the resaw for the four sawmills, i.e., most hardwood sawmills saw the highest grade lumber and largest production volumes at the resaw which makes it a logical focal point for quality improvement. For the sake of meaningful comparisons and conciseness the results that follow are presented in the context of 4/4 lumber sampled from the resaw.

Sawmill A. — The coefficient of variation (COV) declined for the three predominate species manufactured (**Table 1**). The COV for poplar (*Liriodendron tulipifera*) declined from 4.1 percent to 3.0 percent between the first and last six-month time periods. The COV for red oak (*Quercus rubra*) declined from 3.6 percent to 2.8 percent between the first and last six-month time periods. The COV for white oak (*Quercus alba*) declined from 3.6 percent to 2.9 percent between the first and last six-month time periods.

For the predominately manufactured product (4/4 red oak), there was statistical evidence ($\alpha < 0.05$) that both the means and medians were smaller at the end of the 12-month study period (**Table 3**). There was strong statistical evidence that the variation of 4/4 red oak as measured by the sample standard deviation (derived from the sample variance) was smaller in the last six months of the study period (**Table 3**).

This sawmill had no prior experience using SPC in sawmill operations. Discussions with experienced sawyers revealed that most had historically oversized lumber because of inadequate knowledge of real-time thickness and variation (Young et al. 2000a, 2000b).

Sawmill B. — The coefficient of variation (COV) declined for all species sampled that were also predominately manufactured (**Table 1**). The COV for poplar (*Populus deltoides*) declined substantially from 3.9 percent to 2.6 percent between the first and last six-month time periods. The COV for white ash (*Fraxinus caroliniana*) declined from 3.1 percent to 2.8 percent between the first and last six-month time periods. The COV for white oak (*Quercus alba*) declined from 3.3 percent to 2.7 percent between the first and last six-month time periods.

For a key product (4/4 poplar), there was no statistical evidence ($\alpha < 0.05$) that both the means and medians were

Table 3. — Descriptive statistics for 4/4 red oak (Quercus rubra) at the resaw at sawmill A.

Month, Year	n	Average $\bar{x}$ (in)	Changes in $\bar{x}$[a]	Median (M) (in)	Changes in M[b]	SD $\hat{\sigma}_X$ (in)	Changes in $\hat{\sigma}_X$[c]
August, 1999	171	1.134	a	1.135	a	0.044	a
September, 1999	230	1.124	a	1.117	ab	0.044	ab
October, 1999	61	1.126	a	1.123	ab	0.027	c
November, 1999	188	1.108	ab	1.109	c	0.040	abcd
December, 1999	641	1.121	a	1.121	ab	0.045	abcd
January, 2000[d]	--	--	--	--	--	--	--
February, 2000[d]	--	--	--	--	--	--	--
March, 2000[d]	--	--	--	--	--	--	--
April, 2000	328	1.103	ab	1.115	abc	0.035	cd
May, 2000	414	1.114	a	1.112	abc	0.033	cd
June, 2000	431	1.180	a	1.106	c	0.035	cd
July , 2000	44	1.096	b	1.097		0.024	c

[a]Rows with different letters have significantly different averages at $\alpha = 0.05$ using the Smith-Satterthwaite procedure for means comparisons with unequal variances.
[b]Rows with different letters have significantly different medians at $\alpha = 0.05$ using one-sided
Wilcoxon Rank Sum test.
[c]Rows with different letters have significantly different variances at $\alpha = 0.05$ using the two-tailed F-test.
[d]Insufficient data were collected for this species during this month.

Table 4. — Descriptive statistics for 4/4 poplar (Populaus deltoides) at the resaw at sawmill B.

Month, Year	n	Average $\bar{x}$ (in)	Changes in $\bar{x}$[a]	Median (M) (in)	Changes in M[b]	SD $\hat{\sigma}_X$ (in)	Changes in $\hat{\sigma}_X$[c]
March, 2001[d]	--	--	--	--	--	--	--
April, 2001[d]	--	--	--	--	--	--	--
May, 2001	1199	1.113	a	1.125	a	0.043	a
June, 2001	512	1.140	b	1.146	b	0.041	ab
July, 2001	1820	1.127	c	1.131	c	0.049	c
August, 2001[d]	--	--	--	--	--	--	--
September, 2001[d]	--	--	--	--	--	--	--
October, 2001[d]	--	--	--	--	--	--	--
November, 2001[d]	--	--	--	--	--	--	--
December, 2001	715	1.141	b	1.133	c	0.030	d
January, 2002[d]	--	--	--	--	--	--	--
February, 2002	54	1.131	bc	1.130	c	0.027	d

[a]Rows with different letters have significantly different averages at $\alpha = 0.05$ using the Smith-Satterthwaite procedure for means comparisons with unequal variances.
[b]Rows with different letters have significantly different medians at $\alpha = 0.05$ using one-sided Wilcoxon Rank Sum test.
[c]Rows with different letters have significantly different variances at $\alpha = 0.05$ using the two-tailed F-test.
[d]Insufficient data were collected for this species during this month.

smaller at the end of the 12-month study period (**Table 4**). There was strong statistical evidence that the variation of 4/4 polar as measured by the sample standard deviation was smaller in the last six months of the study period (**Table 4**).

Sawmill C. — The coefficient of variation (COV) increased for all species sampled (**Table 1**). The COV for poplar (*Populus deltoides*) increased slightly from 2.3 percent to 2.4 percent between the first and last six-month time periods. The COV for white ash (*Fraxinus caroliniana*) increased from 2.5 percent to 3.6 percent between the first and last six-month time periods. The COV for pecan (*Carya illinoenis*) increased from 2.6 percent to 3.1 percent between the first and last six-month time periods. The increase in COV at this sawmill was unexpected but upon review of the statistics, the average had significant reductions for all species. The standard deviation

had a significant increase for one species and slight increases for the other two species studied. This explains the increase in COV between the two time periods.

For the predominately manufactured product (4/4 poplar), there was statistical evidence ($\alpha < 0.05$) that both the means and medians were smaller at the end of the 12-month study period (**Table 5**). There was inconclusive statistical evidence that the variation of 4/4 poplar was smaller during the last six months of the study period (**Table 5**). The increase in COV previously mentioned may be the result of a smaller average with a somewhat constant standard deviation which may still be considered a positive outcome of the study for two species, i.e., analysis of any one statistic by itself may be misleading.

Sawmill D. — The coefficient of variation (COV) declined for two of the predominately manufactured species (**Table 1**).

*Table 5. — Descriptive statistics for 4/4 poplar (*Populaus deltoides*) at the resaw at sawmill C.*

Month-Year	n	Average $\bar{x}$	Changes in $\bar{x}$[a]	Median (M)	Changes in M[b]	SD $\hat{\sigma}_X$	Changes in $\hat{\sigma}_x$[c]
		(in)		(in)		(in)	
March, 2001[d]	--	--	--	--	--	--	--
April, 2001[d]	--	--	--	--	--	--	--
May, 2001[d]	--	--	--	--	--	--	--
June, 2001[d]	--	--	--	--	--	--	--
July, 2001	422	1.173	a	1.176	a	0.022	a
August, 2001	602	1.165	b	1.167	b	0.031	b
September, 2001	393	1.147	c	1.151	c	0.035	bc
October, 2001	707	1.152	c	1.152	c	0.022	ad
November, 2001	118	1.147	c	1.151	c	0.031	bc
December, 2001[d]	--	--	--	--	--	--	--
January, 2002	840	1.150	c	1.151	c	0.025	ad
February, 2002[d]	--	--	--	--	--	--	--

[a]Rows with different letters have significantly different averages at $\alpha = 0.05$ using the Smith-Satterthwaite procedure for means comparisons with unequal variances.
[b]Rows with different letters have significantly different medians at $\alpha = 0.05$ using one-sided Wilcoxon Rank Sum test.
[c]Rows with different letters have significantly different variances at $\alpha = 0.05$ using the two-tailed F-test.
[d]Insufficient data were collected for this species during this month..

The COV for poplar (*Populus deltoides*) declined from 2.7 percent to 2.4 percent between the first-six and last six-month time periods. The COV for white oak (*Quercus alba*) declined from 3.1 percent to 2.6 percent between the first six-month and last six-month time periods. The COV for red oak (*Quercus rubra*) was approximately unchanged from 2.1 percent to 2.0 percent between the first six-month and last six-month time periods.

There was some statistical evidence ($\alpha < 0.05$) for the second highest manufactured product (4/4 poplar) that both the means and medians were smaller at the end of the 12-month study period (**Table 6**). There was some statistical evidence that the variation 4/4 poplar declined during the last six months of the study period (**Table 6**).

Variation by sawing center

Sawing variation for hardwood lumber producing machines has been related to the feedworks and setworks used with the lowest total sawing variation being for gangsaws and the highest for headrigs (Steele et al. 1992). In this study, total sawing variation was analyzed for two components: within-board and between-board variation.

Sawmill A. — Lumber produced at the resaw had the largest variance for all species at the beginning of the study. "Within-board" variation was the largest component of variance for all species at all sawing centers. Total board variance at the resaw declined by 225 from 0.00135 inch to 0.0006 inch by the end of the 12-month study period (Young et al. 2000a).

Sawmill B. — Lumber produced at the resaw had the largest variance for all species at sawmill B. Within-board variation was overwhelmingly the largest component of variance for all species at sawmill B. "Within-board" variation was the largest component of variance manufactured at the headrig sawing center at sawmill B. At the resaw, between-board variance was the largest component of total variance at this mill (Young et al. 2002b).

Sawmills C. — As was the case for sawmill B, for all species, lumber produced at the resaw had the largest variance at sawmill C. Within-board variation was the largest component of variance for all species at all sawing centers at sawmill C. Within-board variation was particularly pronounced at Sawmill C's two headrigs.

Sawmill D. — A limiting factor for target size reduction at sawmill D was higher variation of 4/4 lumber produced at the headrig relative to the variation in 4/4 lumber produced at the resaw or gangsaw. Even though the variability over time was not stable by sawing center, the headrig had a consistently higher average variance over the 12-month study period relative to other sawing centers (**Fig. 4**). While it may not be operationally feasible, establishment of target sizes by sawing center may lead to improved green lumber recovery and appears possible as each machine center has different potential sawing variations as indicated by this work and by Steele et al. (1992).

An example of improvements made by Sawmill D was an attempt to reduce an identified source of variation, e.g., movement in the knees on the headrig that stabilize the log on the carriage during sawing. Movement in the knees was caused by bolt movement on the knees due to carriage vibration. This source of variation was reoccurring because of equipment wear and design flaws of the headrig. Even though the source of variation was not eliminated, the real-time control charts acted as an early-warning device to alert operators of this reoccurring problem.

Important practical outcomes—financial leverage

As defined in equation [1], reducing variation in the sawing processes leads to lower target sizes and improvement in the amount of fiber converted from the log to lumber. The average return on investment for the four sawmills was approximately 17:1 (**Table 7**).[4]

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[4] All financial return estimates were made and validated by company accountants at the sawmills. Most accountants used a financial leverage ratio statistic, e.g., net income after taxes gained from use of the SPC system divided by investment

Table 6. — Descriptive statistics for 4/4 poplar (Populaus deltoides) at the resaw at sawmill D.

Month-Year	n	Average $\bar{x}$	Changes in $\bar{x}$[a]	Median (M)	Changes in M[b]	SD $\hat{\sigma}_x$	Changes in $\hat{\sigma}_x$[c]
		(in)		(in)		(in)	
June, 2003	1297	1.118	a	1.120	a	0.022	a
July, 2003	745	1.121	ab	1.123	ab	0.027	ab
August, 2003	806	1.119	abc	1.121	abc	0.027	abc
September, 2003	1335	1.122	abc	1.125	bcd	0.029	bcd
October, 2003	978	1.120	abc	1.123	abcd	0.027	abcd
November, 2003	779	1.121	abc	1.124	abcd	0.028	abcd
December, 2003	701	1.118	abc	1.122	abcde	0.026	abcd
January, 2004	1007	1.123	bcd	1.125	bcde	0.023	bcd
February, 2004	823	1.121	abc	1.125	bcde	0.024	bcd
March, 2004	321	1.123	bc	1.126	bcdg	0.020	bcdefg
April, 2004	442	1.116	abcdi	1.121	abcdehi	0.026	abcd
May, 2004	555	1.123	bc	1.126	bcde	0.022	bcd

[a]Rows with different letters have significantly different averages at $\alpha = 0.05$ using the Smith-Satterthwaite procedure for means comparisons with unequal variances.
[b]Rows with different letters have significantly different medians at $\alpha = 0.05$ using one-sided Wilcoxon Rank Sum test.
[c]Rows with different letters have significantly different variances at $\alpha = 0.05$ using the two-tailed F-test.

Sawmill A. — Estimates of financial gain from target size reductions over the 12-month study period were approximately $180,000, a 12:1 financial leverage on invested assets in the SPC system. Most of the gain during the study was due to a consistent, yet unexplained increase (by management and accountants) in overrun for 4/4 red oak lumber, which was analyzed to be independent of red oak log size (Young et al. 2000a and 2000b).

Sawmill B. — The average overrun for sawmill B for all species declined by approximately 1.1 percent after installation of the real-time SPC system. The decline in overrun at sawmill B was due to a consistent 1 percent increase in average log volume for all species, which was due a log grading procedural change at the sawmill. The log grading procedural change denied us the opportunity to detect any improvement in overrun from the installation of the SPC system. The average Common and Better grade had a statistically significant shift of 3 percent at sawmill B after installation of the real-time SPC thickness improvement system due to a reduction in "thin-edges" on lumber (e.g., wedge-shaped lumber with an edge less than 1inch in thickness), see NHLA (2003).

Sawmill C. — The average overrun for sawmill C for all species increased by approximately 2.6 percent after the installation of the real-time SPC system which was independent of log size changes (i.e., a 2.6% increase was analyzed to be independent of log size change). The Common and Better average grade for sawmill C had a statistical shift of 4 percent after installation of the real-time SPC thickness improvement system.

The annual financial improvement from use of the real-time SPC system for sawmills B and C combined was approximately $752,000, a 28:1 leverage on SPC system assets at both sawmills. This financial improvement was estimated by company accountants and management which preferred combining both sawmills in the financial analysis. The $709,120 return was estimated to be due to overrun improvement and

in the SPC system asset. This financial leverage statistic was adopted for consistency and comparison. The financial data presented in Table 6 were rounded to the nearest thousand dollars.

$42,980 return was from the improvements in the percentage of Common and Better grade lumber (Young et al. 2005).

Sawmill D. — There was no statistical evidence that the return on investment at this sawmill was due to improved lumber recovery as measured by the overrun data. Even though the bias between overrun and log volume was stable during the 12-month study period, unexplained increases in overrun did not occur. However, management and accounting personnel attributed the SPC system with the improvement in grade of lumber at the end of the study period. Reductions in lumber with thin edges did occur. Reductions in thin edges resulted in an improvement of 190,308 board feet (BF) in No.1 Common and Better lumber. The financial gain from this improvement in lumber grade was estimated by company accountants to be approximately $158,000, a 7:1 leverage on invested SPC system assets.

Summary and conclusions

There was substantial statistical evidence from the results of this study to support the alternative or working hypotheses (i.e., reject the null hypotheses in the statistical tests), i.e., use of real-time statistical process control quantifies lumber thickness variation, leads to variation reduction, improved lumber recovery and improved financial performance. The research study was conducted at four hardwood sawmills in the United States over a five-year time period starting in 1999. The study showed that use of real-time SPC leads to target size reduction, variation reduction, improved lumber recovery, and improved financial performance.

There was strong statistical evidence at each hardwood sawmill test site that median lumber thickness and thickness variation declined for rough-sawn lumber of various species. Reductions in median lumber thickness and thickness variation also varied by sawing center, i.e., gangsaw, resaw, or headrig. Increases in overrun (independent of log size change) and improvements in lumber grade were validated by participating company accountants and estimated financial gains ranged from $128,000 to $752,000 per year. The financial leverage on invested assets in the SPC system for the four

Table 7. — Return on investment for participating sawmills.

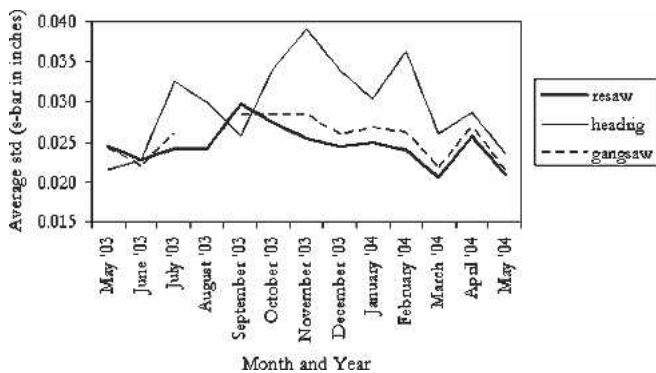| Company	Study	Investment in SPC system	Net income	Leveraged return
		--------------($)--------------		(%)
A	8/99 to 07/00	15,000	180,000	12:1
(Sawmills B and C)	3/01 to 12/02	27,000	752,000	28:1
D	6/03 to 5/04	22,000	158,000	7:1
	Average:	21,000	363,000	17:1

Figure 4. — Average of the standard deviations ($\bar{S}$) for all 4/4 lumber produced at the sawmill D by sawing center.

hardwood sawmills ranged from 7:1 to 28:1. Development costs for the real-time SPC systems ranged from $15,000 to $27,000 per sawmill and were highly dependent on sawmill capacities and sawing configurations.

Competitive pressures in the hardwood lumber industry from international imports and substitution of non-renewable products are not likely to subside in the future. Improved sawmill efficiency and reduced manufacturing costs will be critical issues for sawmills. The philosophy of continuous improvement and real-time statistical process control (SPC) provide sawmill owners with the ability to reduce lumber thickness variation, lower target sizes, and improve the recovery of fiber from log to lumber. Real-time SPC is a contemporary philosophy of using the Shewhart control chart in a real-time setting with distribution of the information throughout the manufacturing environment. Real-time SPC enhances the ability to prevent the manufacture of defective product by reducing the time interval between the viewing of process data and taking action on product variability. Variation cannot be reduced unless it is quantified.

The potential benefits from adopting a low-risk strategy of continuous improvement and real-time SPC should not be ignored by the hardwood sawmill industry. Even though this case study of four hardwood sawmills represented a small fraction of the sawmill industry, there is reason to believe that the results of this study are transferable to the entire industry. A parallel study is ongoing by the primary author with the softwood lumber industry.

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