Validating LORCAT, the Log Recovery Analysis Tool

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Abstract

The Log Recovery Analysis Tool (LORCAT) is a simulation tool that allows users to examine the impact of changes in the hardwood log-sawing process on sawn volume, grade recovery, and profit. LORCAT was designed to be simple to use and requires a minimum of user data entry. While the results of LORCAT have been informally compared to sawmill results by users, no formal validation of results has yet been performed. This study compared LORCAT's simulated recovery results to that of an actual sawmill. For the 42 hardwood log samples we examined, we found no significant statistical difference in the total sawn volume produced. However, significant differences were found with the number of boards produced, which resulted from differences in the accuracy of targeting the opening-face board size.

Simulation, "the imitation of the operation of a real-world process or system over time" (Banks 1998, p. 3) allows users to emulate a process with changing input variables to obtain results that are the same or close to the actual results from the real process. Users thus can assume realistic or not-so-realistic scenarios that can be analyzed and compared for problem-solving and decision-making purposes without the need to execute the actual process (Thomas and Buehlmann 2002). However, for the simulation to be of value, it must be validated so that its accuracy and precision are known and can be taken into account when comparing results (Schlesinger et al. 1979, Sargent 1992).

Simulating the sawing of hardwood lumber is a complex proposition. The interaction of several variables determines lumber recovery in hardwood sawmills (Steele 1984). Steele (1984) identified the most important factors that affect log recovery, which include the diameter, length, taper, and quality of the log, kerf thickness, sawing variation, green lumber size, and dry/dressed lumber size. Lin et al. (2011) examined hardwood sawmills in West Virginia and found lumber recovery at all the mills they sampled differed significantly ($\alpha = 0.05$). These authors found that log grade, species, log diameter, log length, and sawmill parameters had statistically significant effects on lumber volume recovery. Further, due to variability in processing and the log resource, these factors are rarely consistent from mill to mill (Steele 1984). Thus, the simulation must be sufficiently configurable to accurately model the variety of factors in a given mill.

Over the years, several sawmill simulation tools have been developed to assist sawmill managers in exploring the effects of these factors on mill operations. One of the earliest computer tools developed was SOLVE by Adams (1972) to determine the maximum value of hardwood lumber that can be produced from a log sample given a mill's operational setup. SOLVE was followed by the Best Opening Face (BOF) program by Lewis and Hallock (1974), which determined the optimum placement of saw lines in a log that resulted in the maximum recovery based on log size and quality characteristics. Adams followed with an updated version of Solve in 1977 (Adams and Dunmire 1977). Solve II allowed users to answer many questions related to everyday mill operations, such as identifying the break-even log, analyzing conversion costs by log grade and size, analyzing downtime, and more. The break-even log is a log such that when it is sawn, the total value of all products from the log equals the total of

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all costs involved in obtaining and sawing the log. In 1995, Adams published and made available SOLVE III, an easier-to-use and updated version of SOLVE II to help sawmill managers improve efficiency and analyze common hardwood mill issues such as low lumber grade yields, low lumber recovery factors, overrun log costs, and break-even log costs (Adams 1995). SOLVE III required users to conduct a comprehensive mill study and collect data related to various aspects of the mill's operation, such as operating costs, lumber grades, lumber thicknesses, lumber prices, and, most importantly, log grades, log sizes, and the volumes of lumber recovered by National Hardwood Lumber Association (NHLA) grade. SOLVE III (Adams 1995) proved popular with the industry, and hence Palmer et al. (2009) upgraded the program, adding functionality and ease of use.

In 2005, Govett et al. created a spreadsheet-based sawmill analysis tool, PROYIELD (Govett et al. 2005), capable of projecting sawmills' yields. PROYIELD was designed to develop initial estimates of sawmill yields for planning and feasibility studies and to explore and test what-if questions related to processing. However, PROYIELD was not designed to optimize recovery and saw-line placement or to make opening-face decisions for maximum value recovery, since the program only returns summaries of lumber and residual expectations for specific scenarios.

In 2021, the Log Recovery Analysis Tool (LORCAT) was made available to the public (Thomas et al. 2021). LORCAT is a spreadsheet-based log recovery estimation tool that was developed to permit sawmill operators and researchers the ability to determine the potential outcomes in sawmill recovery due to changes in operation. LORCAT was designed to be simple to use with a minimum set of data to enter and results being displayed in a clear and easy-to-understand manner (Fig. 1). For its calculations, LORCAT uses the geometric shape of a truncated cone to represent logs. The user controls the shape of the log by specifying the length and the small- and the large-end diameters. LORCAT simulates the sawing of logs using one of five common sawing strategies. The first strategy simulates grade sawing, where the log is rotated, and boards are sawn from the highest-grade face until a user-specified cant thickness is achieved. The cant is then ripped into lumber by a simulated gang-resaw. (Fig. 2a). The second strategy simulates grade sawing with the production of a cant of a specified size that is not sawn into boards (Fig. 2b). The third strategy simulates using a gang-resaw to saw the cant produced from sawing the first two faces into lumber (Fig. 2c). The fourth method simulates sawing logs to a cant with a specified size (Fig. 2d). The fifth method simulates the European method of live or flitch sawing where the log is sawn through-and-through (Fig. 2e). LORCAT users can select the method and all pertinent sawing parameters such as kerf size, green allowance, opening-face size, sawing variation, and others to suit their operation and their analysis needs. For all five sawing methods (Fig. 2), users can choose either split-taper or full-taper sawing (Malcolm 1961). In split-taper sawing, the taper of the log is split between opposite faces, and the log is sawn parallel to its central axis (Hallock et al. 1978). This sawing method has the potential to

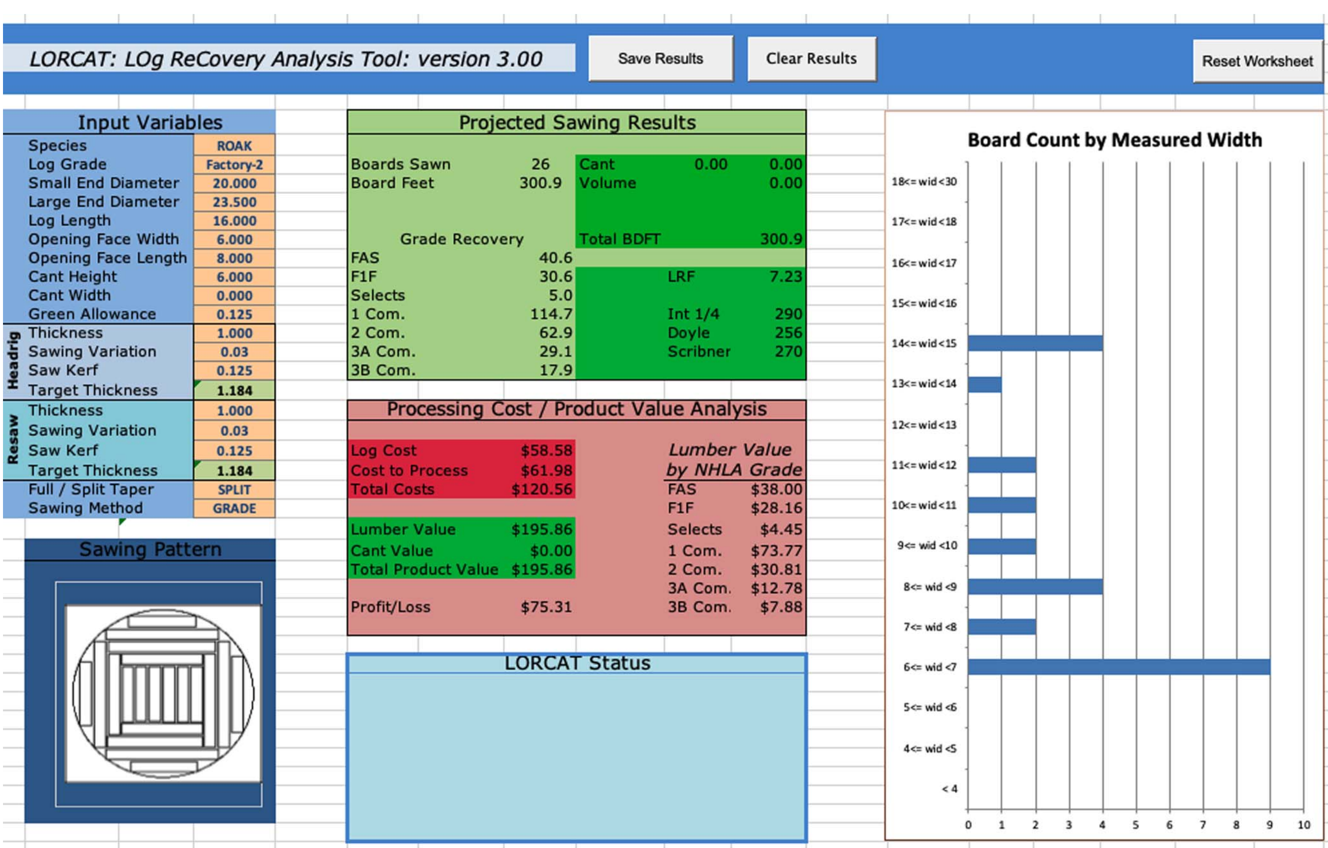

Figure 1.—Screenshot of the Log Recovery Analysis Tool (LORCAT) interactive sawing screen showing data entry and results.

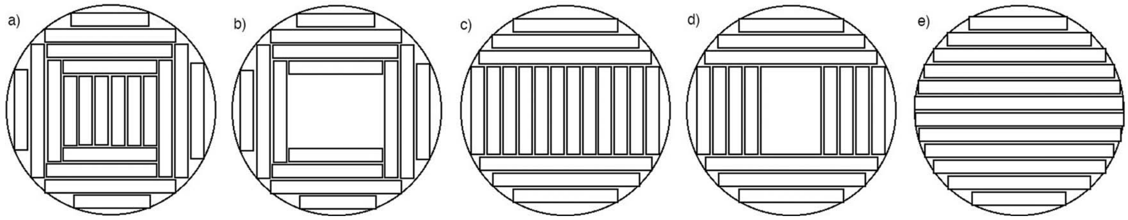

Figure 2.—(a) Simulated grade sawing to a specified cant thickness and then completion sawing with a gang-resaw; (b) simulated grade sawing to a specified cant thickness; (c) sawing to specified cant thickness and then completion sawing with a gang-resaw; (d) sawing to a specified cant size; (e) live sawing.

produce shorter boards if the amount of taper is large enough yet increase the recovery of lumber. Full-taper sawing saws the log parallel to the outside faces of the log (Hallock et al. 1978). Thus, the grain will be parallel to the board surface in the resulting boards, making the lumber sawn stronger in general than split-taper sawn lumber. Thus, LORCAT is able to simulate a wide variety of sawing processes and sawing parameters. However, the accuracy of LORCAT's results has not been validated so far. This paper presents data from a study that validated LORCAT results using 42 logs from the Appalachian region.

Objectives

The goal of this research was to validate LORCAT 3.0, the current version of LORCAT available online (Thomas and Buehlmann 2023), against the actual sawing of logs. For that purpose:

1. We statistically compared LORCAT's estimated total sawn volume recovery to a sawmill's observed sawn recovery for a random sample of hardwood logs.
2. We statistically compared LORCAT's estimated board counts to a sawmill's board counts for a random sample of hardwood logs.

We defined the validation as successful if we did not find statistically significant differences ($\alpha = 0.05$) between the results achieved in a sawmill as opposed to the results from LORCAT. However, when significant differences were detected, we analyzed, discussed, and resolved these differences in results between LORCAT and the sawmill.

Methods

Log sample

Three groups of logs that were sawn as part of past research projects (Xu et al. 2018, Bennett and Thomas 2019) were analyzed for this validation project. This group of logs was selected because it represented four US Department of Agriculture (USDA) Forest Service log grades (Rast et al. 1973). The first group of logs was selected from a random sample of 15 yellow-poplar (*Liriodendron tulipifera*) trees that were harvested from a MeadWestvaco leased and managed forest near Rupert, West Virginia, in the Central Appalachian region in late January of 2015. Each tree was bucked to commercial lengths with three to five logs being cut from each tree, resulting in a total of 52 logs. From this, a sample set of 21 logs was selected to be sawn into lumber for a defect detection and quality assessment study (Xu et al. 2018), and these results were re-used for this validation study. However, we removed two logs from the sample. One log had extensive felling damage that resulted in approximately 20 percent of the log volume splitting off the log. Another log was dismissed because of a sawing error in the original study (Xu et al. 2018). A lift knee remained raised during the entire sawing process, which resulted in a wedge-shaped cant. Hence, as LORCAT is not able to duplicate this type of sawing error, that log was removed. Thus, this study used 19 yellow-poplar (*Liriodendron tulipifera*) logs from the study by Xu et al. (2018).

A second group contained a sample of 13 white oak (*Quercus alba*) logs that were randomly selected from a log concentration yard in Bluefield, West Virginia, in 2019. The logs were sawn into lumber used as part of a cold-weather dehumidification kiln test in 2019 (Bennett and Thomas 2019). Another random sample of six red oak (*Quercus rubra*) logs and four white oak logs (*Quercus alba*) was selected in 2022 (Group 3) from the same log concentration yard in Bluefield, West Virginia. The Group 3 sample set was acquired specifically to provide additional logs for the LORCAT validation study.

All logs were transported to the USDA Forest Service Forestry Sciences Laboratory in Princeton, West Virginia. The logs were graded to US Forest Service log grades (Rast et al. 1973), and small-end diameter (SED) and large-end diameter (LED), length, and crook and sweep were measured and recorded (Table 1).

Sawmill sawing specifications

The sawing was performed by an experienced sawyer who worked to maximize the yield and value of the lumber with respect to the NHLA rules (NHLA 2015). The general sawing strategy was to open the log on the best face and rotate the log when the face grade of the cant dropped. This is typical of grade sawing, where the log is sawn to maximize the resulting NHLA grade of the lumber. In addition, the logs were sawn such that the amount of taper was split between opposite faces, commonly referred to as split-taper sawing (Malcolm 1961).

All sawing was performed on a single portable sawmill with a kerf size of 0.095 inches and a measured total sawing variation of 0.035 inches. The final lumber thickness for lumber sawn from logs in Groups 1 and 3 was 1.0 inch; when accounting for green allowance and sawing variation, the target thickness for sawing was 1.132 inches. The final lumber thickness for Group 2 logs was 1.5 inches with a target thickness of 1.695 inches including green allowance and sawing variation.

Logs in Group 1 were sawn to produce a cant that was 6.0 by 6.0 inches. In situations where there was a No. 1 Common or better board face on at least one of the cant

Table 1.—Specifications of logs used in validation study.

Log no.	Sample set	Species[a]	SED[b]	LED[b]	Scale length	Sweep/crook	Log grade	Int ¼-inch scale volume
1	Group 1	YPOP	17.40	18.42	11	1.62	Construction	137
2	Group 1	YPOP	21.39	24.18	12	1.05	Factory 1	235
3	Group 1	YPOP	20.61	23.99	15	0.87	Factory 1	270
4	Group 1	YPOP	13.29	14.85	16	1.13	Factory 2	115
5	Group 1	YPOP	19.16	19.39	14	0.96	Factory 1	225
6	Group 1	YPOP	15.67	17.00	16	0.83	Factory 2	155
7	Group 1	YPOP	11.09	11.92	13	0.52	Factory 3	62
8	Group 1	YPOP	17.05	19.27	13	0.79	Factory 1	165
9	Group 1	YPOP	16.37	16.98	10	1.69	Factory 2	110
10	Group 1	YPOP	14.97	15.12	10	1.57/2.13	Factory 2	85
11	Group 1	YPOP	13.30	13.70	13	1.70	Factory 3	92
12	Group 1	YPOP	13.01	14.13	12	1.65	Factory 2	85
13	Group 1	YPOP	21.44	21.80	11	1.53	Factory 1	215
14	Group 1	YPOP	21.47	22.35	9	1.13	Factory 3	172
15	Group 1	YPOP	15.53	17.12	16	1.81	Factory 3	155
16	Group 1	YPOP	24.15	24.35	16	0.91	Factory 1	425
17	Group 1	YPOP	17.34	18.46	11	1.44	Factory 2	137
18	Group 1	YPOP	14.85	17.31	16	1.59	Factory 2	135
19	Group 1	YPOP	14.39	15.02	14	1.25	Factory 2	120
20	Group 2	WOAK	14.54	16.16	8	0.88	Factory 3	65
21	Group 2	WOAK	13.28	14.61	12	2.96	Factory 3	85
22	Group 2	WOAK	12.18	12.92	12	1.23	Factory 3	70
23	Group 2	WOAK	17.27	17.49	10	0.98	Factory 3	125
24	Group 2	WOAK	11.31	12.18	10	0.89	Factory 3	45
25	Group 2	WOAK	11.71	12.35	10	1.48	Factory 3	45
26	Group 2	WOAK	11.31	11.66	12	0.83	Factory 2	55
27	Group 2	WOAK	12.33	12.64	12	0.32	Factory 3	70
28	Group 2	WOAK	12.67	13.75	10	0.69	Factory 3	60
29	Group 2	WOAK	14.27	17.14	10	2.07	Factory 2	85
30	Group 2	WOAK	11.39	15.15	12	1.33	Factory 2	55
31	Group 2	WOAK	12.61	15.62	10	2.13	Construction	60
32	Group 2	WOAK	14.16	14.16	8	0.97	Factory 3	65
33	Group 3	WOAK	12.37	12.71	8	0.05	Factory 3	45
34	Group 3	ROAK	11.18	11.46	12	0.73	Factory 2	55
35	Group 3	WOAK	11.88	12.36	8	0.14	Factory 3	35
36	Group 3	ROAK	11.65	12.43	8	0.70	Construction	35
37	Group 3	WOAK	13.36	13.93	10	0.79	Factory 2	70
38	Group 3	ROAK	10.87	11.58	10	0.71	Construction	40
39	Group 3	ROAK	11.53	12.95	10	0.15	Factory 3	45
40	Group 3	ROAK	11.61	12.28	10	0.21	Factory 2	45
41	Group 3	WOAK	12.80	15.24	12	0.94	Factory 3	70
42	Group 3	ROAK	15.23	17.19	10	1.76	Construction	95

[a] YPOP = yellow-poplar (*Liriodendron tulipifera*); WOAK = white oak (*Quercus alba*); ROAK = red oak (*Quercus rubra*).
[b] SED = small-end diameter; LED = large-end diameter.

faces, then an additional board was sawn from the cant. The measurements of the final resulting green cant dimensions are listed in Table 2 for each log. Logs in Groups 2 and 3 were sawn to cant heights of 6 inches, where the cant was then sawn into boards of the specified thickness, i.e., 1.5 inches for Group 2 and 1.0 inch for Group 3.

The opening-face width, e.g., the width of the board produced by the first cut on the face of a log, was, on average, 5.5 inches for Groups 1 and 2. Because logs in Group 3 were smaller and of lower grade (Table 1), a narrower opening-face width of 5 inches was used at the sawmill to reduce waste of log volume in the form of excess slabbing. The minimum opening-face length, e.g., the minimum acceptable length of a board produced by the opening cut, for all log groups was 8 feet (Tables 2 and 3).

LORCAT setup

LORCAT was configured to match the sawing methods used by the sawmill as closely as possible. LORCAT was set to emulate grade sawing (Fig. 1a) or grade sawing with a cant (Fig. 1b) when a cant was produced. For all logs sawn, split-taper sawing was specified, which splits the log taper between the faces, as was done at the mill. A summary of all sawing parameters for the sawmill and LORCAT, by log sample group, is presented in Tables 2 and 3.

Statistical methods

Using the R statistical software package (R Core Team 2022), Shapiro-Wilk tests (Royston 1982) for normality were conducted on lumber volume, board counts, and differences in lumber volume and board counts for the mill's

Table 2.—Lumber target thicknesses and cant sizes.

Log no.	Sample set	SED[a] (in.)	Lumber thickness (in.)	Cant width (in.)	Cant height (in.)	Opening face	
						Width (in.)	Length (ft)
1	Group 1	17.40	1.00	6.40	6.00	5.50	8
2	Group 1	21.39	1.00	5.30	5.50	5.50	8
3	Group 1	20.61	1.00	5.25	5.75	5.50	8
4	Group 1	13.29	1.00	4.86	5.60	5.50	8
5	Group 1	19.16	1.00	5.37	5.87	5.50	8
6	Group 1	15.67	1.00	6.25	5.40	5.50	8
7	Group 1	11.09	1.00	5.40	4.60	5.50	8
8	Group 1	17.05	1.00	5.24	4.03	5.50	8
9	Group 1	16.37	1.00	5.24	5.20	5.50	8
10	Group 1	14.97	1.00	6.23	6.01	5.50	8
11	Group 1	13.30	1.00	6.13	6.11	5.50	8
12	Group 1	13.01	1.00	5.39	5.11	5.50	8
13	Group 1	21.44	1.00	5.87	6.50	5.50	8
14	Group 1	21.47	1.00	6.28	6.28	5.50	8
15	Group 1	15.53	1.00	6.51	5.49	5.50	8
16	Group 1	24.15	1.00	6.87	6.41	5.50	8
17	Group 1	17.34	1.00	5.24	6.61	5.50	8
18	Group 1	14.85	1.00	5.67	5.52	5.50	8
19	Group 1	14.39	1.00	5.17	4.27	5.50	8
20	Group 2	14.54	1.50	0.00	6.00	5.50	8
21	Group 2	13.28	1.50	0.00	6.00	5.50	8
22	Group 2	12.18	1.50	0.00	6.00	5.50	8
23	Group 2	17.27	1.50	0.00	6.00	5.50	8
24	Group 2	11.31	1.50	0.00	6.00	5.50	8
25	Group 2	11.71	1.50	0.00	6.00	5.50	8
26	Group 2	11.31	1.50	0.00	6.00	5.50	8
27	Group 2	12.33	1.50	0.00	6.00	5.50	8
28	Group 2	12.67	1.50	0.00	6.00	5.50	8
29	Group 2	14.27	1.50	0.00	6.00	5.50	8
30	Group 2	11.39	1.50	0.00	6.00	5.50	8
31	Group 2	12.61	1.50	0.00	6.00	5.50	8
32	Group 2	14.16	1.50	0.00	6.00	5.50	8
33	Group 3	12.37	1.00	0.00	6.00	5.00	8
34	Group 3	11.18	1.00	0.00	6.00	5.00	8
35	Group 3	11.88	1.00	0.00	6.00	5.00	8
36	Group 3	11.65	1.00	0.00	6.00	5.00	8
37	Group 3	13.36	1.00	0.00	6.00	5.00	8
38	Group 3	10.87	1.00	0.00	6.00	5.00	8
39	Group 3	11.53	1.00	0.00	6.00	5.00	8
40	Group 3	11.61	1.00	0.00	6.00	5.00	8
41	Group 3	12.80	1.00	0.00	6.00	5.00	8
42	Group 3	15.23	1.00	0.00	6.00	5.00	8

[a] SED = small-end diameter.

Table 3.—Summary of sawing parameters used.

Sawing parameter	Log group	Value
Opening-face length	All	8 feet
Opening-face width	1 & 2	5.5 inches
Opening-face width	3	5.0 inches
Total sawing variation	All	0.035 inches
Cant height	1	As specified (Table 2)
Cant height	2 & 3	6 inches
Cant width	1	As specified (Table 2)
Lumber thickness	1 & 2	1 inch
Lumber thickness	3	1.5 inches
Green allowance	All	0.125 inches

and LORCAT's simulated results. A significance level of 0.05 was used for all statistical tests. We found that in all cases the lumber volumes and board counts were not normally distributed. Levene's test for homogeneity of variance across groups (Fox and Weisberg 2011) was then used to compare the variances of the mill and LORCAT simulated lumber volume and board counts. We found no significant differences in the variances between the mill and the LORCAT results. Next, a Wilcoxon signed-rank test (Hothorn et al. 2008, Corder and Foreman 2009) was used to compare the distributions and medians of the mill and the LORCAT data. The Wilcoxon test is a nonparametric test that requires that the data being compared be independent and have equal variances.

Limitations

LORCAT uses the USDA Forest Service hardwood lumber yield tables (Hanks 1973, Hanks et al. 1980) to estimate the lumber recovery by NHLA grade (Thomas et al. 2021). Hence, LORCAT, currently does not simulate crook and sweep or the presence of any large, visible defect in a log (Thomas et al. 2021). Therefore, logs with sweep and/or crook and logs with major visible defects on one or more sides of the log, to account for which sawmill operators make every effort to maximize the value of the lumber sawn by rotating the log into the best position prior to sawing, may result in differences between reality and simulation. To simulate such logs, the scaling deduction (percent) for that log using the USDA Forest Service Log Grading rules (Rast et al. 1973) would have to be applied to the recovery results.

Results

Lumber volume

Table 4 lists the mill and the LORCAT sawing results for each of the sample logs. For each log, the volume in sawn boards, cant, and total volume, as well as the number of boards sawn, are tallied and presented for the mill and LORCAT. The five rightmost columns in Table 4 list the differences between the mill and LORCAT for volume and

Table 4.—Mill and Log Recovery Analysis Tool (LORCAT) recovery comparison.

	Sawmill observed recovery				LORCAT simulated recovery				LORCAT versus sawmill observed				
Log no.	Board count	Board volume (bdft)	Cant volume (bdft)	Total recovery (bdft)	Board count	Board volume (bdft)	Cant volume (bdft)	Total recovery (bdft)	Board count difference	Board volume difference (bdft)	Cant volume difference (bdft)	Total recovery difference (bdft)	Absolute total recovery difference (bdft)
1	15	124.2	35.0	159.2	16	117.9	35.2	153.1	1	−6.3	0.2	−6.1	6.1
2	22	231.3	31.3	262.6	24	232.7	29.2	261.8	2	1.4	−2.2	−0.7	0.7
3	22	273.8	37.7	311.5	24	275.9	37.7	313.6	2	2.1	0.0	2.2	2.2
4	9	85.7	36.5	122.2	11	86.7	36.3	123.0	2	1.1	−0.2	0.8	0.8
5	18	198.9	36.8	235.7	19	190.3	36.8	227.0	1	−8.6	0.0	−8.7	8.7
6	12	135.0	45.1	180.1	14	129.2	45.0	174.2	2	−5.8	0.0	−5.9	5.9
7	6	40.4	27.0	67.3	7	36.0	26.9	62.9	1	−4.4	−0.1	−4.4	4.4
8	17	162.5	22.9	185.4	19	153.5	22.9	176.4	2	−9.0	0.0	−9.0	9.0
9	13	89.6	25.0	114.6	15	95.7	22.7	118.4	2	6.1	−2.3	3.8	3.8
10	7	43.5	34.3	77.9	11	66.9	31.2	98.1	4	23.4	−3.1	20.3	20.3
11	7	48.5	40.6	89.0	8	54.1	40.6	94.7	1	5.6	0.0	5.6	5.6
12	11	73.3	27.5	100.8	10	62.5	27.5	90.0	−1	−10.8	0.0	−10.8	10.8
13	20	196.1	35.0	231.1	22	200.4	35.0	235.4	2	4.3	0.0	4.3	4.3
14	20	153.9	29.6	183.5	22	167.0	29.6	196.6	2	13.1	0.0	13.1	13.1
15	11	113.7	47.6	161.3	13	119.4	47.6	167.0	2	5.7	0.0	5.7	5.7
16	23	354.3	62.4	416.7	25	364.7	58.7	423.5	2	10.4	−3.7	6.8	6.8
17	14	103.8	31.8	135.6	15	111.5	31.8	143.3	1	7.7	0.0	7.7	7.7
18	11	110.0	41.7	151.7	14	121.3	41.7	163.0	3	11.3	0.0	11.3	11.3
19	11	94.2	25.7	119.9	13	98.1	25.7	123.8	2	3.9	0.0	3.9	3.9
20	9	82.5	0.0	82.5	11	71.8	0.0	71.8	2	−10.7	0.0	−10.7	10.7
21	6	75.0	0.0	75.0	9	77.4	0.0	77.4	3	2.4	0.0	2.4	2.4
22	7	70.5	0.0	70.5	8	66.7	0.0	66.7	1	−3.8	0.0	−3.8	3.8
23	12	136.5	0.0	136.5	13	127.5	0.0	127.5	1	−9.0	0.0	−9.0	9.0
24	5	45.0	0.0	45.0	7	45.9	0.0	45.9	2	0.9	0.0	0.9	0.9
25	6	49.5	0.0	49.5	7	47.4	0.0	47.4	1	−2.1	0.0	−2.1	2.1
26	7	61.5	0.0	61.5	7	50.4	0.0	50.4	0	−11.1	0.0	−11.1	11.1
27	8	67.5	0.0	67.5	7	66.7	0.0	66.7	−1	−0.8	0.0	−0.8	0.8
28	8	69.0	0.0	69.0	9	62.5	0.0	62.5	1	−6.5	0.0	−6.5	6.5
29	10	84.0	0.0	84.0	11	87.1	0.0	87.1	1	3.1	0.0	3.1	3.1
30	6	67.5	0.0	67.5	8	68.1	0.0	68.1	2	0.6	0.0	0.6	0.6
31	7	52.5	0.0	52.5	9	64.7	0.0	64.7	2	12.2	0.0	12.2	12.2
32	7	60.0	0.0	60.0	10	68.8	0.0	68.8	3	8.8	0.0	8.8	8.8
33	11	55.0	0.0	55.0	12	49.6	0.0	49.6	1	−5.4	0.0	−5.4	5.4
34	8	51.0	0.0	51.0	10	52.0	0.0	52.0	2	1.0	0.0	1.0	1.0
35	11	52.0	0.0	52.0	11	46.4	0.0	46.4	0	−5.6	0.0	−5.6	5.6
36	9	48.0	0.0	48.0	11	45.3	0.0	45.3	2	−2.7	0.0	−2.7	2.7
37	9	80.0	0.0	80.0	14	74.5	0.0	74.5	5	−5.5	0.0	−5.5	5.5
38	10	47.0	0.0	47.0	9	43.5	0.0	43.5	−1	−3.5	0.0	−3.5	3.5
39	9	50.0	0.0	50.0	11	54.3	0.0	54.3	2	4.3	0.0	4.3	4.3
40	10	56.0	0.0	56.0	11	53.8	0.0	53.8	1	−2.2	0.0	−2.2	2.2
41	13	80.0	0.0	80.0	14	83.5	0.0	83.5	1	3.5	0.0	3.5	3.5
42	16	90.0	0.0	90.0	17	100.9	0.0	100.9	1	10.9	0.0	10.9	10.9
Total	473	4162.6	673.3	4835.9	538.0	4192.6	662.0	4854.6	65	30.0	−11.3	18.7	247.7
Mean	11.3	99.1	16.0	115.1	12.8	99.8	15.8	115.6	1.5	0.7	−0.3	0.4	5.9

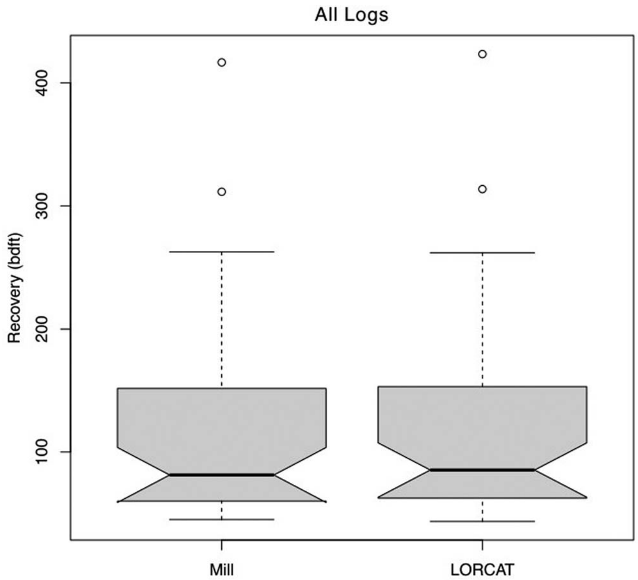

Figure 3.—Box-and-whisker plot comparing mill and Log Recovery Analysis Tool (LORCAT) total recovery results.

board counts. Across the entire sample of 42 logs, the observed mill total volume was 4835.9 board feet (bdft) compared to LORCAT's estimate of 4854.6 bdft, giving a difference of 18.7 bdft, with an average of 0.4 bdft per log. However, a more accurate examination of accuracy is the total absolute volume difference (Table 4). The total difference calculated with this method is 247.7 bdft, with an average difference of 5.9 bdft per log. An examination of the Total Recovery Difference column shows that the mill achieved better volume recovery on 22 logs, with LORCAT doing better on the remaining 20 logs.

A statistical comparison of the mill and LORCAT total volume sawn using a paired two-sample Wilcoxon signed-

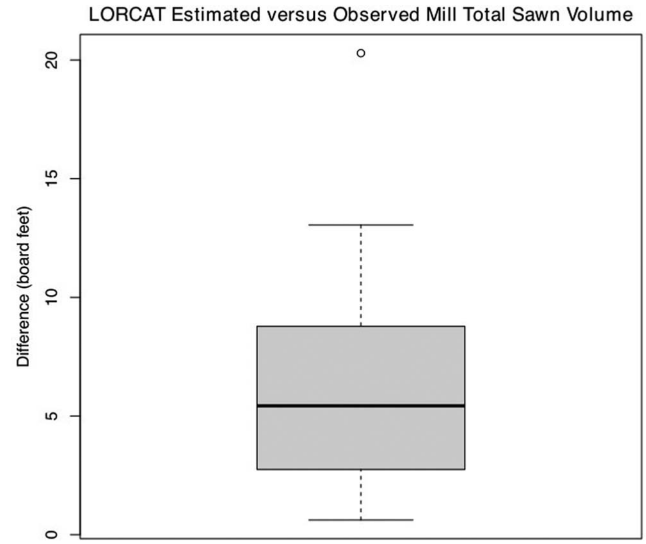

Figure 5.—Box-and-whisker plot of volume (bdft) differences between the mill and Log Recovery Analysis Tool (LORCAT) total sawn volume results.

rank test turned out to be nonsignificant (p value $= 0.743$). Given a significance level of 0.05, no significant difference was found between the distributions of sawn lumber volume and the median volumes sawn for the mill versus LORCAT. The median mill volume was 84.0 bdft, while the median LORCAT volume was slightly higher at 87.12 bdft. The 95 percent confidence interval for the volume difference between the mill and LORCAT was found to be between -2.605 and $+2.220$ bdft.

Figure 3 graphically compares the mill's and LORCAT's total sawn volumes in a box-and-whisker plot. The plots for the observed mill and LORCAT estimated recovery are similar, with nearly identical outliers at around 300 and 400 bdft (depicted as circles in Fig. 3). These are observations

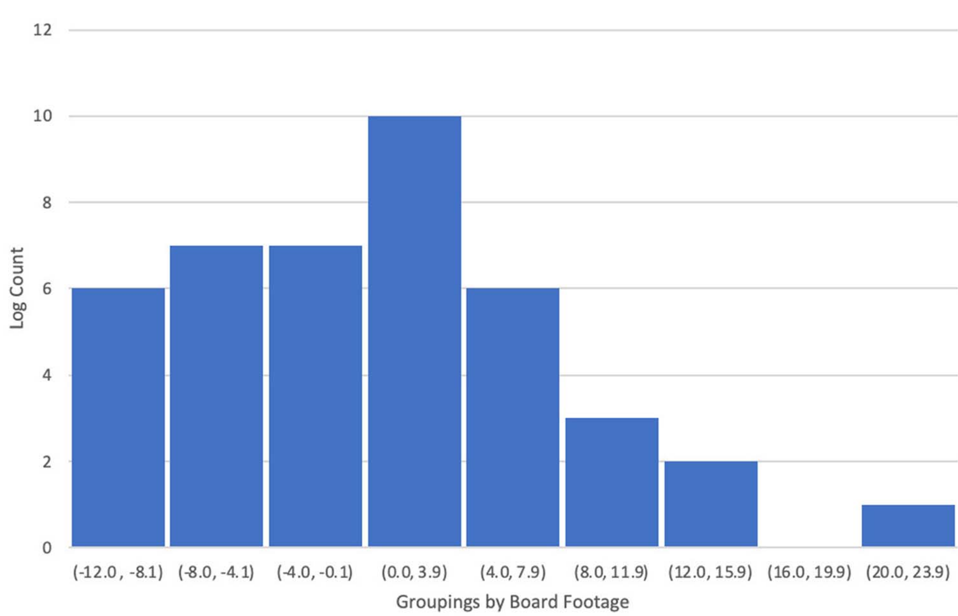

Figure 4.—Histogram of absolute volume of recovery differences between mill and Log Recovery Analysis Tool (LORCAT) total recovery results.

Figure 6.—Top and side photos of Log 10 showing crook and sweep.

that represent the total recovery of the two largest logs of the sample (Logs 3 and 16; Tables 1 and 4), which lie outside the fourth quartile of all results. Thus, while the box-and-whisker plot analysis regards these observations as potential outliers, in reality they are not.

Figure 4 summarizes the absolute total volume difference (bdft) between the mill and LORCAT results. Of the 42 logs in the sample, 17 had an absolute total volume difference of less than ±4.00 bdft (10 in the 0.0 to 3.9 bracket; 7 in the −0.1 to −4.0 bracket). An additional seven logs had a volume difference between −8.0 and −4.1 bdft, and six logs had a difference between 4.0 and 7.9 bdft. Thus, 30 logs had a volume difference less than ±8.0 bdft. Overall, the mill achieved higher sawn volumes on 20 logs, while LORCAT achieved higher volumes on the remaining 22 logs. Three logs had a volume difference greater than 12.00 bdft. Of these, only the 20.2 bdft difference of Log 10 was identified as a potential outlier (Fig. 5). The international $\frac{1}{4}$-inch log scale estimates the sawn volume of Log 10 as 85 bdft, compared to the mill volume of 77.9 bdft and the LORCAT volume of 98.1 bdft. Log 10 had both crook and sweep: At 31 inches from the small end, the log crooked to one side by 2.13 inches, and the remainder of the log had a sweep or bow to the side of 1.6 inches (Fig. 6). Neither the sweep nor the crook was severe by itself. But combined, these features gave the log a slight "S" shape and had a negative effect on sawn volume. As the current version of LORCAT is not programmed to consider sweep and crook, differences in volume between observed mill and LORCAT results will occur.

Board counts

The median number of boards sawn from each log for both the mill and LORCAT was 11. The average number of boards sawn from each log was 11.76 at the mill and 13.18 for LORCAT. The median board count difference between the mill and LORCAT was two boards. The histogram in Figure 7 shows the distribution of the board count differences (mill vs. LORCAT) presented in Table 4. For 19 logs, the board count difference was one board or less. A difference of two boards was observed for 18 logs. For the remaining five logs, the board count difference ranged from three to five boards. The 95 percent confidence interval for the board count difference between the mill and LORCAT was between 2.00 and 1.49 boards. A statistical comparison of the mill and LORCAT board counts was conducted using a paired two-sample Wilcoxon signed-rank test (Hothorn et al. 2008, Corder and Foreman 2009) with a significance level of 0.05. The test value (0.000002) was significant and indicates that the board count distributions are significantly different.

Discussion

We validated the LORCAT results (Thomas et al. 2021) by comparing a sample of yellow-poplar (18 logs), white oak (18 logs), and red oak (six logs) logs representing all four USDA Forest Service log grades (Rast et al. 1973): Factory 1 (six logs), Factory 2 (14 logs), Factory 3

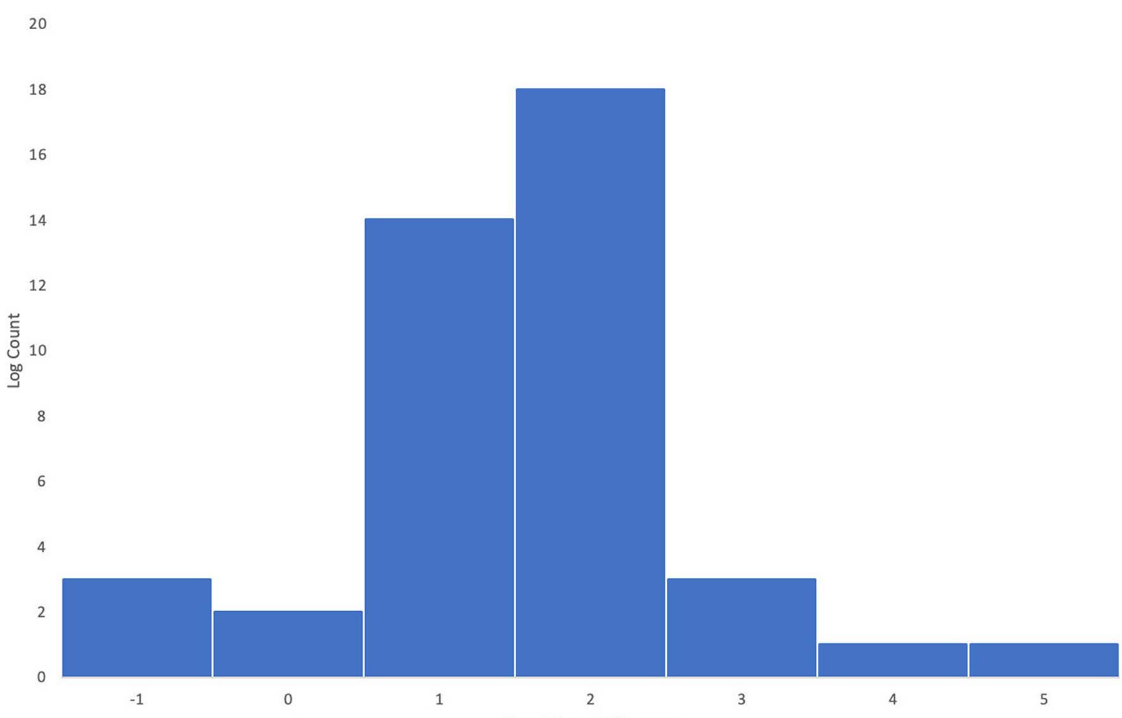

Figure 7.—Histogram of board count differences between mill and Log Recovery Analysis Tool (LORCAT) recovery results.

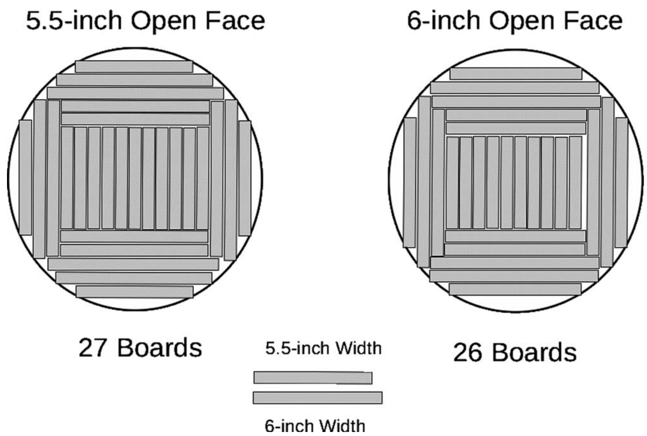

Figure 8.—Comparison of board counts from different opening-face widths.

(17 logs), and Construction (five logs) logs were sawn on a single portable sawmill operated by an experienced operator. No significant difference was found between the mill's and LORCAT's total sawn volume recovery. The total observed mill volume recovery was 4162.6 bdft, while LORCAT's total estimated volume recovery was slightly higher at 4192.6 bdft. Overall, the average mill recovery per log was 115.1 bdft, while LORCAT's average recovery was 115.6 bdft. No significant statistical difference between the mill and LORCAT's volume recovery was found, and hence LORCAT was successfully validated.

However, significant differences were found when comparing the mill's and LORCAT's board counts. Overall, we observed a total of 473 boards sawn at the mill, while LORCAT produced a total of 538 boards. This equates to an average difference of 1.5 boards per log sawn. An examination of the board count differences shows that LORCAT obtained three or more additional boards on five logs. Furthermore, LORCAT obtained two additional boards when sawing 16 logs (Table 4). For these 21 logs, LORCAT obtained 52 additional boards out of the total 65-board difference. One explanation for the difference in board count is due to a key difference in opening-face methodology. At the sawmill, the sawyer manually adjusted the blade position to achieve the opening-face size while viewing the log from the small end. While the operator often achieved the target opening-face size, the positioning was not optimal in several instances. LORCAT represents a computer-controlled decision, which will always compute and execute the optimal opening-face decision. A small error in opening-face decision can result in additional slab or waste volume and lost opportunities for board sawing (Fig. 8). As a result, LORCAT cut a greater number of slightly smaller boards than the mill, while overall volume was much the same.

Summary

This study validated the LORCAT sawmill simulation tool (which allows users to examine the impact of changes in the hardwood log-sawing process) against a portable sawmill used by an experienced sawyer. Forty-two hardwood sawlogs (19 yellow poplar, 17 white oak, six red oak) from earlier studies and specifically obtained for this study were used to compare the volume of lumber achieved by the mill and by LORCAT. While LORCAT is unable to model the natural crook and sweep present in real-world logs, no significant differences were found between the mill and LORCAT, with the observed total volume from the 42 logs being 4835.9 bdft for the mill compared to 4854.6 bdft for LORCAT.

However, significant differences were found between the mill's average board count (11.76) and LORCAT's average board count (13.18). One explanation for this difference centers on the ability of the sawyer to find the best opening-face depth, while LORCAT's algorithm will always find the best opening-face depth. LORCAT processes a standardized conical representation of a log, whereas the mill operator has to make a more complicated decision that considers all the variation present in a log. However, as lumber is sold by volume and not by the board, sawmills still can rely on LORCAT to simulate potential changes to their operation to evaluate any effects on profits.

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