THE INFLUENCE OF LUMBER GRADE ON MACHINE PRODUCTIVITY IN THE ROUGH MILL

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ABSTRACT

Lumber grade effect on hardwood-part processing time was investigated with a digitally described lumber database in conjunction with a crosscut-first rough mill yield optimization simulator. In this study, the digital lumber sample was subdivided into five hardwood lumber grades. Three cutting bills with varying degrees of difficulty were Cut." The three cutting bills and the five grade sorts were input into the rough mill simulator. Ten randomized replications were run for each of the lumber grade/cutting bill combinations. These 10 were used in the statistical analysis. The dependent variable for each replication was the number of cuts required at each saw (crosscut. straight-line rip, and salvage). By counting the number of cuts and not measuring actual operator times, as in other studies, operator variation was eliminated from the experiment The lumber database and the rough mill simulator 'isolated the effect of lumber grade on part processing rates. The analysis indicated that significant differences existed among the lumber grades tested and the number of cuts required to fill the three cutting bills. As expected, the general trend showed that as lumber grade improved, the number of required cuts decreased. This trend was true across the three cutting bills and at each of the saws.

Several studies on the relationship between lumber characteristics and crosscut saw and straight-line ripsaw productivity have been performed (1,3,7,8,11). The influence of board grade, width, and length has been related to productivity. For the crosscut saw, productivity has been measured in units of time per volume of lumber input or units of time per volume output of the crosscut board sections often referred to as boardlets. For the straight-line ripsaw, productivity has been measured in units of time per volume of boardlet input (7,8). Some of these studies have arrived at conflicting conclusions regarding the influence of board characteristics on saw throughput.

Studies performed in the rough mill require that numerous extraneous variables be controlled to determine the influence of the variables of interest (e.g., operator variability, board straightness, and end-checking, which impact yield but not lumber grade, material handling system efficiency, etc.). These extraneous variables are difficult to control. Therefore, mill-based studies are subject to considerable experimental error that may mask the true influence of the factors of interest. In addition, some of these studies did not employ statistical analysis to support their conclusions regarding the influence of board characteristics on processing time (1,7,11).

Pepke (7) studied 10 rough mills and developed estimates of lumber volume processed, in board feet (BF) per hour by grade. The data showed that the crosscut saw productivity rate increased as lumber grade increased fr01Il 2 Common (2C) to 1 Common (1 C) to Firsts and Seconds (FAS). Actual crosscut saw productivity values were 660, 603, and 416 BF/hour (1.56, 1.42, and O.98m%r.) for the grades FAS, 1C, and 2C, respectively. Thus, crosscut saw productivity was 45 percent higher when processing 1 C lumber compared to 2C lumber, 59 percent higher when processing FAS lumber compared to 2C lumber, but only 9 percent higher when processing FAS lumber compared to 1 C lumber.

Data from Pepke (7) also showed an increased rate of productivity as lumber

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grade increased at straight-line ripsaws. Straight-line ripsaw productivity based on part volume produced per hour, was 397, 339, and 250 BF/hour (0.94, 0.80, and 0.59 m3/hr.) for FAS, IC, and 2C lumber, respectively. On the straight-line ripSaw, the operator productivity was 13 percent higher when processing 1 C lumber compared to 2C lumber, 35 percent higher when processing FAS lumber compared to 2C lumber, and 17 percent higher when processing FAS lumber compared to IC lumber. Pepke's work: seemed to indicate that 2C lumber compared to higher grade lumber negatively impacts crosscut saw productivity more than straight-line ripsaw productivity. In contrast, 1C lumber seems to be more costly to process (lower productivity) on the straight-line ripsaw than FAS lumber, but processing rates for the two lumber grades are more similar on the crosscut saw. However, because Pepke's measure of crosscut saw productivity was lumber volume processed per hour, not usable parts produced (as for the straight-line ripsaw), this crosscut saw productivity rate would be strongly affected by the defecting strategy. Pepke did not statistically compare the output or input measures of productivity by lumber grade.

Hallett (3) used regression analysis to investigate the influence of lumber length and width characteristics on boardlet out put (area per min.) at the crosscut saws in five crosscut-first rough mills. He noted that a major problem in performing - the study was the difficulty of finding rough mills that processed lumber that had been sorted by grade. Evidently, most rough mills processed mixed lumber grades. For this reason, lumber grade was not isolated as a factor in Hallett's productivity analysis. Based on the regression models he developed, Hallett concluded that only board width influenced the crosscut saw production rate. The relationship of board width to productivity was not linear but was a second order function. Here, productivity increased with increased board width up to the 9- to II-inch (229- to 279-mm) lumber width class. Crosscut saw productivity then decreased as lumber width increased above 11 inches (279 mm).

Hallett (3) also studied the influence of board characteristics on straight-line ripsaw productivity at a single rough mill. Output rates (part area per min.) were evaluated with regression analysis. He found that straight-line ripsaw productivity was chiefly influenced by part length. This relationship was linear with productivity increasing as part length increased.

Anderson (I) developed a simulation of an existing crosscut-first rough mill to evaluate those factors that influenced production cost per part. Regression analysis identified significant variables. Based on a comparison of Selects, I C, and 2C lumber grades, no difference in processing costs (exclusive of raw material costs) among lumber grades was found. These results indicated that processing costs were determined by the amount of time each part spent at each processing step. Anderson's study found processing time to be positively correlated with part length (in contrast to Hallett's findings (3) in which productivity on the ripsaw increased with increasing part length).

Wiedenbeck (1l,12) employed computer simulation to study the effect of lumber length on rough mill productivity in a crosscut-first rough mill. After gathering data on crosscut saw processing speeds, she noted that crosscut time required per part produced varied with lumber length and the number of parts cut from the boards (11). Wiedenbeck indicated that time per part produced was reduced when the number of parts cut per board increased because setup time (the time to load, visually inspect, and endtrim each board) was spread over more parts. She also noted that one factor that increases the. time required per part, from longer lumber, was that longer boards are more difficult for the operator to manipulate. Time data obtained in Wiedenbeck's rough mill study, however, did not exhibit a linear relationship between lumber length and crosscut saw productivity nor did it exhibit a predictable grade-based difference in crosscut saw productivity (12).

Pnevmaticos (8) statistically analyzed crosscut time per thousand BF (m3) volume for 4/4-inch (25.4-mm) hard maple lumber in a crosscut-first rough mill. He found board width to be the predominant factor influencing cutting time. A regression model was developed relating board width to minutes required per BF (m3) volume of processed lumber. Pnevmaticos found that time was a second order function of board width with processing time decreasing until board widths reached about 10 inches (254 mm). For boards greater than 10 inches (254-mm) wide, cutting times increased at an accelerated rate. These results are similar to those of Hallett but Hallett's measure of output was minutes per ft² (m²) area output rather than minutes per BF (m³) volume input (8).

Pnevmaticos (8) found that lumber grade had some influence on crosscut saw productivity. An additional 11.1 min./1,000 BF (4.70 *min./m³)* were required to cut 2C compared to 1C lumber. No significant differences were found, however, among crosscutting times for FAS, 1C, and Select lumber grades.

An important source of variation in the processing times of both crosscut saws and straight-line ripsaws may be differences in operator performance. No research is available to determine the magnitude of the expected differences in operator productivity. This might be due to the difficulty described by Hallett (3) in finding rough mills that separate lumber by grade. When lumber grades are not separated, variation in processing times can be- due to differences in grade mix rather than operator performance.

One- measurement method for determining the relative length of time required to process lumber of different grades is to count the number of saw cuts required to fill a given cutting bill. This is impractical because few rough mills sort the lumber by grade (3). An alternative is to run the different grades through a lumber cut-up simulator. In this case, a database of wood can be separated by grade and each grade can be run in order to fill various cutting bills. The simulated number of cuts performed at each saw for the different grades and bills can be statistically analyzed. In this case, the influence of the individual operator time variable is removed from the experiment Also, the variable of lumber presentation time is eliminated.

The use of lumber cut-up simulator cutting statistics as a predictor of processing rates and costs was employed by Gatchell and Walker (2) in their study of within-grade quality differences for I C and 2A Common (2AC) lumber when processing lumber in a gang-rip-first cutting operation. When gang ripping first to fill an easy cutting bill (mostly short and narrow parts), they found that 1.16 crosscuts were required to produce the parts in the cutting bill when processing high-quality 1C lumber. When processing lowquality lAC lumber, an average of 1.46 crosscuts per part was required. When filling a more difficult cutting bill, 1.08, 1.29, and 1.70 crosscuts were required per part for FAS, high quality IC, and low quality 2AC lumber, respectively.

The Gatchell and Walker (2) analysis was the first to utilize lumber cut-up simulator statistics as a surrogate for processing costs. Their study, however, focused on I) yield, not cutting operations; 2) IC and 2AC lumber; and 3) rip-first, rather than crosscut-first lumber processing. The influence of lumber grade on cutting operations at different sawing stations is a question that can be addressed with simulator output

OBJECTIVES

Possible grade influences on machine productivity when cutting hardwood lumber into wood component parts to fill various cutting bills in a crosscut-first cut-up operation were studied. This is an important question for mills considering grade. mix shifts to reduce raw material costs. Rough mills are often designed to accommodate smooth, balanced flow for a particular lumber grade mix and part size distribution. Shifts in grade mix and cutting bill can impact material flow through individual Sawing stations and the entire rough mill.

ANALYSIS PROCEDURES

Due to the rarity of rough mills that process grade-sorted lumber and the complexities associated with building matched samples in the rough mill, a lumber cut-up simulator was used. In this study, the crosscut-first rough mill simulator "Cut-Sim" was used. Lumber was processed by the crosscut saws, the straight-line ripsaws, and finally the salvage saw. Cut-Sim simulates a crosscutfirst rough mill that employs manually operated crosscut saws and straight-line ripsaws. In this situation, various numbers of saws of each type cut parts and limited part sizes are assigned to be cut by each saw. In this study, depending on the cutting bill, 3 crosscut saws and as many as 10 straight-line ripsaws were employed. Each saw was assigned a limited number of cuttings, e.g., each crosscut saw might get only three possible lengths to cut. This commissioning of certain part sizes to certain saws mimics what occurs in commercial operations. Other rough mill simulators utilize one saw of each type to make all of the possible cuts. Those simulations imply that any given parts might be cut from any given board. In reality, each saw might only be assigned two or three part lengths or widths. Therefore, the Cut-Sim simulations should give a slightly better commercial representation than the other two simulators.

The total number of cuts required to fill each cutting bill in each grade was tabulated. These totals were statistically analyzed. In addition to these totals, the numbers of cuts from each individual saw (crosscut, straight-line rip, and salvage) were analyzed. In cases where significant differences were detected in the analysis of-variance (ANOVA), Fisher's protected least significant differences (LSD) analysis was conducted to separate the means (5). All tests were conducted at the (X. = 0.05 significance level (9).

Lumber from a digitized database was the raw material input to the mill. This database was compiled from 14,500 BF (34.2 m^3) of 4/4-inch- (2S.4-mm-) thick kiln-dried southern red oak lumber from across the state of Mississippi (4,10). A breakdown of the volume within each of five grades is provided (table 1) along with the number of boards and the average board dimensions. The grades were FAS,

TABLE 1. - Volume, number of boards, average width, and average length of red oak lumber in the digitized lumber database.

Grade[a]	Volume	No. of boards	Avg. width	Avg. length
	(BF)		(in.)	(ft.)
FAS	2,717	317	8.36	12.31
FIF	2,176	249	8.56	12.24
IC	2,877	398	7.56	11.39
2AC	3,314	449	7.47	11.77
3AC	1,984	331	6.42	11.00

[a]FAS = Firsts and Seconds; FIF = First One Face; 1C = No. 1 Common; 2AC = No. 2A Common; 3AC= No. 3A Common.

TABLE 2. - Easy cutting bill (a.k.a. "cabinet," USDA Forest Service, Princeton, W. V.).[a]

	Widths (in.)						
Length	1.75	2.00	2.25	3.75	4.50	5.00	5.25
(in.)							
10.00	100 (1,1)	0	0	0	0	0	0
12.25	50 (2,2)	0	0	0	0	0	200 (2,2)
13.00	0	0	200 (3,3)	0	0	0	0
13.50	0	0	0	50 (1,4)	0	0	0
14.50	0	0	75 (2,5)	0	0	25 (2,5)	0
15.00	550 (3,6)	1000 (3,6)	0	0	0	0	100 (3,6)
18.75	400 (1,7)	200 (1,7)	400 (1,7)	0	0	0	0
20.50	100 (2,8)	50 (2,8)	450 (2,8)	0	0	0	0
21.00	0	0	0	0	150 (3,4)	0	0
22.50	0	0	400 (1,3)	0	0	0	0
24.75	1150 (2,9)	650 (2,9)	1150 (2,9)	0	0	0	0
27.75	500 (3,1)	0	0	0	0	0	0
28.25	0	0	700 (1,10)	200 (1,10)	0	0	0
31.50	0	100 (2,2)	0	0	0	0	0

[a] Values given are the number of pieces required for each length-by-width combination; values in parentheses are the individual crosscut and ripsaw machine numbers to which these parts were assigned to be cut. Total number of parts: 8,950; average part width: 2.1 inches; average-part length: 21.5 inches; approximate part volume: 2,806 BF.

TABLE 3. - Moderate cutting bill (a.k.a "squire," USDA Forest Service, Princeton, W. V.).[a]

Length	Widths (in.)						
	1.50	2.25	2.75	3.00	325	4.00	4.25
(in.)							
19.50	0	0	156 (1,1)	0	0	0	0
21.00	0	0	0	0	0	0	183 (2,2)
22.75	0	100 (3,3)	0	0	0	0	0
23.25	0	0	0	0	0	617 (1,4)	0
28.25	0	0	0	43 (2,5)	0	0	0
30.00	605 (3,6)	203 (3,6)	203 (3,6)	203 (3,7)	405 (3,7)	0	0
3325	0	0	0	0	0	0	0
48.25	480 (2,8)	240 (2,8)	240 (2,9)	120 (2,9)	120 (2,9)	0	0
56.00	0	0	0	0	617 (3,4)	0	0
64.50	0	67 (1,3)	0	0	0	0	0
80.50	0	67 (2,1)	0	0	0	0	0
87.75	0	I35 (3,1)	0	0	0	0	0

[a] Values given are the number of pieces required for each length-by-width combination; values in parentheses are the individual crosscut and ripsaw machine-numbers to which these parts were assigned to be cut. Total number of parts: 5,421; average part width: 2.8 inches; average part length: 38.3 inches; approximate part volume: 4,037 BF.

First One Face (FIF), IC, 2AC, and 3A Common (3AC). The Select grade was not included in the study because very few mills in the southeast separate this grade. When this lumber database was established, the distinction between 2A and 2B did not exist in the National Hardwood Lumber Association grade rules (6). However, many recent studies refer to 2AC. Also, the lumber in the database that was graded as 2C is in fact 2AC under the current NHLA grade system, which has been in existence since 1994 when the 2BC grade was introduced. Therefore, in this study, 2AC was used to describe this lumber.

Three different cutting bills were designed to test the different lumber grades within the database. These bills were designated by the USDA Forest Service, Princeton, WV., (2) as "cabinet" (referred to as the "easy" cutting bill throughout this paper), "squire" (our "moderate" cutting bill), and "tough" (the "difficult" cutting bill in this paper). In Tables 2 through 4, a breakdown of the part dimensions and quantities within each bill is given. The crosscut saw and straight line ripsaw machine numbers to which each part size was assigned - for cutting are indicated in parentheses to the right of the parts quantity designations. Some cutting bill statistics that are important for interpreting the results are: the total number of parts in the cutting bill, the average length and width of the parts in the cutting bill, and the (approximate) board footage of parts required by the cutting bill. The easy cutting bill has considerably more parts in it than the other two cutting bills but they are distinctly shorter (average length of 21.5 in. (546 mm»)) and narrower (average width of2.1 in. (53.3 mm)) than the parts in the moderate and difficult cutting bills (average lengths of 38.3 and 39.1 in. (97.3 and 99.3 mm) and average widths of2.8 and 3.0 in. (71.1 and 76.2 nun), respectively).

TABLE 4. - Difficult cutting bill (a.k.a. "tough," USDA Forest Service. Princeton, W. v.). [a]

Length	Widths (in.)			
	2.00	2.75	3.50	4.25
(in.)				
15.00	325 (1,6)	175 (1,6)	250 (1,6)	0
18.00	100 (2,1)	0	0	0
25.00	250 (3,2)	250 (3,2)	0	0
29.00	0	0	0	400 (1,3)
33.00	300 (2,4)	0	0	0
38.00	0	0	250 (3,3)	0
45.00	0	600 (1,4)	0	0
50.00	400 (2,5)	0	600 (2,5)	200 (2,5)
60.00	0	0	100 (3,1)	0
72.00	0	150 (1,3)	0	300 (1,2}

[a] Values given are the number of pieces required for each length-by-width combination; values in parentheses are the individual crosscut and ripsaw machine numbers to which these parts were assigned to be cut. Total number of parts: 4,650; average part width: 3.0 inches; average part length: 39.1 inches; approximate part volume: 3,788 BE.

TABLE 5. - Mean number of total required cuts (for 10 repetitions) from each lumber grade within each cutting bill[a]

Lumber grade	Cutting bill		
	Easy	Moderate	Difficult
FAS	23,031 A	17,567 A	18,175 A
FIF	25,797 B	21,580 B	21,439 B
IC	31,259 C	28,348 C	30,948 C
2AC	40,292 D	48,463 D	62,956 D
3AC	56,453 E	92,393 E	96,602 E
LSD	483.7	1,688.0	2,107.6
p-value, grade	0.0001	0.0001	0.0001
p-value, run	0.7408	0.1757	0.3794

[a]Means with the same capital letter are not significantly different.

The digitized lumber database provided matched raw material samples used across the different cutting bills. To generate replications within each grade and cutting bill, the lumber database was randomized and the individual bill-grade combinations were run several times. This randomization was accomplished by starting each replication on a randomly selected board within the database and proceeding to cut boards in a random order until the cutting bill was filled.

EXPERIMENTAL MODELS

A full model (Model 1) was developed to test the influence of lumber grade, cutting bill, and replication number on the total number of cuts required to fill the particular cutting bill.

Model 1:

$$Ct_{ijk} = \mu + G_i + B_j + G_i \times B_j + S_k + \varepsilon_{ijk}$$

where:

Ct = total number of observed cuts required to fill the bill

μ = population mean number of cuts for all grade-bill combinations

G = effect of the input lumber grade

B = effect of the particular cutting bill

G X B = effect of any grade by bill inter action

S = effect of the replication number .

ε = experimental error term

i = index for the lumber grades, 1...5

j = index for the cutting bills, 1...3

k= index for the replications, LIO

In total, 150 crosscut-first simulation runs were conducted: 5 lumber grades x 3 cutting bills x 10 replications.

Reduced models in which the term Bj and the interaction term Gj x Bj were dropped from the full model and the variability in $Ctilc$ rather than $Ctijt$ was investigated (a within-cutting-bill analysis). Because the interaction term of the full model was found to be significant in the ANOVA analysis, models were reduced.

The reduced model for testing the significance of the variability measured within each cutting bill for the response variable "total cuts required to fill cutting bill" $(CtjkJ$ was tested with Model 1R:

Model 1R:

$$Ct_{ik} = \mu + G_i + S_k + \varepsilon_{ik}$$

where:

Ct = total number of observed cuts required to fill the bill

μ = population mean number of cuts for the grade

G = effect of the input lumber grade on the particular cutting bill

S = effect of the replication number

ε = experimental error term

i = index for the lumber grades, 1...5

k= index for the replication, 1...10

Similarly, reduced models tested the sources of variability within each cutting bill for the response variables: "number of crosscut saw cuts required to fill cutting bill," "number of ripsaw cuts required to fill cutting bill," and "number of salvage saw cuts required to fill cutting bill." These models are designated as Model 2R, Model 3R, and Model 4R, respectively. The form of these three reduced models is:

Model2R:

$$Cc_{ik} = \mu + G_i + S_k + \varepsilon_{ik}$$

where:

Cc = number of crosscut saw cuts required to fill the bill

(Other variables are as previously defined.)

Model 3R:

$$Cr_{ik} = \mu + G_i + S_k + \varepsilon_{ik}$$

where:

Cr= number of straight-line ripsaw cuts required to fill the bill (Other variables are as previously defined.)

Model 4R:

$$Cs_{ik} = \mu + G_i + S_k + \varepsilon_{ik}$$

where:

Cs = number of salvage saw cuts required to fill the bill

(Other variables are as previously defined.)

RESULTS AND DISCUSSION

TOTAL NUMBER OF REQUIRED CUTS

The full model ANOYA analysis detected a statistically significant interaction between lumber grade and cutting bill for the response variable "total cuts required to fill cutting bill." This interaction obscured examination of the main effects in the full model (Model I) be cause only factor combinations could be considered. Therefore, the reduced model (Model 1R) was used to explore the effect of lumber grade on total cuts for each individual cutting bill.

For each of the three cutting bills, lumber grade significantly influenced the total number of cuts required to fill the bill. The results of the separation of means for each cutting bill are presented in Table 5. With the exception of one case of means overlap between grades for the difficult cutting bill (the total number of cuts for grade FIF overlapped with FAS), all means were found to be significantly different for the five grades within each cutting bill.

With FAS as the base, the ratio of the mean number of total cuts required to fill the cutting bill (crosscuts, rips, and salvage cuts combined) for the easy cutting bill was 1.0: 1.12: 1.4: I &. 25 for FAS, FIF, 1C, 2AC, and 3AC, respectively. For the moderate cutting bill, the ratio of total cuts required to fill the cutting bill was 1.0 : 1.23 : 1.6 : 2 8 . 5.3 for FAS, FIF, IC, 1AC, and 3AC, respectively. For the difficult cutting bill, the ratio of total cuts was 1.0 : 1.2: 1.7: 3.5: 5.3 for. FAS, FIF, 1 C, 1AC, and 3AC. The effect . of the replication number was not significant in any of the cutting bills.

On average (for the 10 replications), the BF (m3) volume of lumber required to fill the easy cutting bill was 4,168 (9.84) for FAS, 4,522 (10.66) for FIF, 5,163 (12.18) for 1C, 6,738 (15.90) for 2AC, and 9,415 (22.22) for 3AC. For the moderate cutting bill, the corresponding BF (m3) lumber volumes for the grades were 5,982 (14.12), 7,143 (16.85), 8,885 (20.97), 16,239 (38.32), and 32,600 (76.94), respectively. For the difficult cutting bill. the average input BF (m^3) lumber volume required to obtain the parts was 6,416 (15.14) for FAS, 7,883 (18.59) for FIF, 10,578 (24.96) for 1C, 25,445 (60.05) for 2AC, and 41,537 (98.03) for 3AC. These volumes are important because they lead to an estimate of relative raw-material quantities when processing the different grades for the different cutting bills. The F AS : FI F: 1 C : 2C : 3AC input volume ratio for the easy bill was 1 : 1.09 : 1.24 : 1.62 : 2.26. The corresponding ratios for the moderate and difficult cutting bills were 1 : t .19 : 1 49 : 2.71 : 5.45 and 1 : 1 23 : 1.65 . 3 97 : 6.47, respectively. When a cutting bill has a relatively low ratio (FAS: FIF: 1C:

2AC : 3AC) for both the number of cutting operations required to meet the cutting bill and the total volume of lumber required to meet the cutting bill (as is true in this study for the easy cutting bill) then the opportunity to use lower lumber grades exists.

The volumes required to meet the cutting bills also are important in the analysis of rough mill machine center productivity. The lumber input volumes along with information provided in Table 1 on the average length and width of the lumber in the five grade-based data sets can be used to estimate the number of boards of each grade that were processed in filling the three cutting bills. If the ratio of the number of boards required to fill the cutting bill for any two grades is higher than 1:1, then it follows that the impact of lumber grade on productivity is more dramatic than predicted by the cutting operation comparison alone. This occurs because more boards are required to meet the cutting bill when cutting lower-grade lumber compared to higher-grade lumber. Furthermore, an additional delay occurs at the various machine centers related to material handling and saw loading (setup time per board as referred to by Wiedenbeck (13)).

CROSSCUTT SAW PRODUCTIVITY BY LUMBER GRADE

The reduced model, Model2R, examined the effect of lumber grade on the response variable "number of crosscut saw cuts required" for each of the three cutting bills. Similar results to those found for "total number of cuts" were recorded. for each of the three cutting bills; lumber grade significantly influenced the number of crosscuts required to fill the bill (Table 6). The results of the mean separation for each cutting bill indicated that the crosscut saw productivity levels for each grade were distinctly different when processing the easy and moderate cutting bills. For the difficult cutting bill, some overlap between the grade-based levels occurred but the pattern of influence of lumber grade on crosscutting productivity was consistent: the number of crosscut saw cuts required to fill the cutting bill was lower for higher-grade lumber than for lowergrade lumber (Table 6).

The ratio of the mean number of crosscut saw cuts required to fill the cutting bill for the easy cutting bill was 1.0 : 1.1 : 1.4 : 1.9: 2.9 for the lumber grades with FAS lumber, which required the fewest cuts, set as the index grade. For the moderate cutting bill, the ratio of crosscuts required to fill the cutting bill (with FAS number of cuts set as index value) was 1.0: 1.2: 1.7: 3.0: 6.8 for FAS, FIF, IC, 2AC, and 3AC, respectively. For the difficult cutting bill, the ratio of crosscuts was 1.0: 1.2: 1.87: 4_1 : 7.4 for FAS, FIF, 1C 2AC,and3AC. The effect of the replication number was not significant in any of the cutting bills.

STRAIGHT-LINE RIPSAW PRODUCTIVITY BY LUMBER GRADE

The reduced model, Model 3R, was used to study the impact of lumber grade straight-line ripsaw productivity. For each of the three cutting bills, lumber grade significantly influenced the number of straight-line ripsaw cuts required.

TABLE 6. - *Mean number of crosscut saw cuts required (for 10 repetitions) from each lumber grade within each cutting bill.*[a]

	Cutting bill		
Lumber grade	Easy	Moderate	Difficult
FAS	3,687 A	3,192A	3,149 A
FIF	4,105B	3,875 B	3,865 B
1C	5,318C	5,482 C	5,875 C
2AC	6,906D	9,700 D	13,051 D
3AC	10,683E	21,586 E	23,281 E
LSD	114.6	389.1	218.0
p-value, grade	0.0001	0.0001	0.0001
p-value, run	0.8903	0.2400	0.6306

[a]Means with the same capital letter are not significantly different

TABLE 7. - *Mean number of straight-line ripsaw cuts required (for 10 repetitions) from each lumber grade within each cutting bill.* [a]

	Cutting bill		
Lumber grade	Easy	Moderate	Difficult
FAS	18,317 A	13,125 A	12,248 A
FIF	20,232 B	15,702 B	14,847 B
1C	24,020 C	19,920 C	20,032 C
2AC	29,993 D	32,069 D	38,411 D
3AC	40,434 E	57,819 E	54,213 E
LSD	321.3	979.1	818.4
p-value, grade	0.000 I	0.0001	0.0001
p-value, run	0.7687	0.1595	0.3379

[a] Means with the same capital letter are not significantly different.

TABLE 8. - *Mean number of salvage saw cuts required (for 10 repetitions) from each lumber grade within each cutting bill.* [a]

	Cutting bill		
Lumber grade	Easy	Moderate	Difficult
FAS	1,026 A	1,250 A	1,491 A
FIF	1,460 B	2,003 B	2,778 A
IC	1,921 C	2,946 C	5,040 B
2AC	3,394 D	6,693 D	12,494 C
3AC	5,335 E	12,989 E	19,107 D[b]
LSD	117.1	336.7	1,731.0
p-value, grade	0.0001	0.0001	0.0001
p-value, run	0.3765	0.2688	0.4805

[a]Means with the same capital letter are not significantly different

[b] For the 3AC-tough combination, there was not enough wood to completely fill the cutting bill.

The results of the mean separation for each cutting bill are presented in **Table 7**. All levels of the response variable for each grade were found to be significantly different.

For the easy, moderate, and difficult cutting bills, the ratios of the number of ripsaw cuts were: 1.0: 1.1 : 1.3 : 1.6: 2.2. 1.0: 1.2 : 1.5 : 2.4 : 4.4. and 1.0 : 1.2 : 1.6 : 3.1 : 4.4 for the FAS, FIF, IC, 2AC, and 3AC grades, respectively. These ratios indicate how important it is to consider cutting bill characteristics when making decisions about lumber grade mix for the rough mill. The productivity of both the crosscut saw and the straight-line ripsaw are much less impacted by a lowering of the lumber grade when cutting shorter and narrower parts than they are when cutting larger parts. These ratios also show that crosscut saw productivity, more than ripsaw productivity, is affected by a reduction in lumber grade. Once again, the effect of the replication number was not Significant in any of the cutting bills.

SALVAGE SAW PRODUCTIVITY
BY LUMBER GRADE

In this case, reduced model 4R was tested. The response variable was the number of cuts required at the salvage saw. Within each of the three cutting bills, lumber grade significantly influenced the number of salvage cuts required to fill the bill. The results of the mean separation for each cutting bill are presented in Table 8. The effect of the replication number was not significant in any of the cutting bills.

SUMMARY AND CONCLUSIONS

Possible lumber grade influence on machine productivity when cutting hardwood lumber into wood component parts to fill various cutting bills in a crosscut first lumber cut-up operation was studied

Rough mill operations were simulated with the Cut-Sim program and a digitized lumber database of 4/4-inch (25.4-mm), kiln-dried, southern red oak lumber. The three cutting bills selected for the study have varied part quantity and size characteristics.

For each of the three cutting bills, statistically significant lumber grade-based differences were detected in all response variables: total number of cuts, number of crosscuts, number of straight-line rip cuts, and number of salvage cuts. These results indicate that lumber grade significantly affects the number of cuts required (a surrogate measure for production cost and time) to fill various cutting bills. The general trend that showed up throughout the simulations indicated that as lumber grade improves, the number of required cuts (processing time) decreases. The productivity differences for the primary lumber grades are substantial and significant. Crosscut saw productivity, more than ripsaw productivity, is affected by a reduction in lumber grade. Productivity ratios indicate the importance of considering cutting bill characteristics when making decisions about lumber grade mix for the rough mill. The productivity of both the crosscut saw and the straight line ripsaw are much less impacted by a reduction in the lumber grade when cutting shorter and narrower parts than when cutting larger parts. The changes in sawing productivity at specific saws should be carefully considered if a rough mill's current material flow has certain machine centers operating at capacity. This analysis should prove useful for mills that might be considering raising their grade mix due to capacity limitations just as it will for mills considering shifting their grade mix to reduce raw material costs.

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