Rough-mill yield and cutting efficiency for No. 3A Common lumber compared to other lumber grade mix options

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Abstract

The percentage of low-grade material comprising the annual hardwood lumber production in the United States is increasing. As a result, finding markets for low-grade/low-value lumber has been identified as a top priority by researchers and industry associations. This research used the ROMI-RIP and ROMI-CROSS simulation programs to examine part yield, cutting efficiency, and value recovery that can be expected when No. 3A Common lumber is processed in the rough mill. Cutting bills having narrow part widths and short part lengths are the most feasible to use while processing No. 3A Common lumber. The No. 3A Common results were compared to results obtained for No. 2A Common lumber and a lumber grade mix comprised of 50 percent No. 2A Common and 50 percent No. 3A Common. Simulation results demonstrated that as the percentage of No. 3A Common lumber in a grade mix increases, part yields and cutting efficiencies decrease. For a grade mix consisting entirely of No. 2A Common lumber, part yields were between 12 and 20 percent higher than for a grade mix consisting entirely of No. 3A Common lumber. Also, the number of sawlines (a processing expense) required to produce 1,000 board feet (MBF) of parts from No. 3A Common lumber was 10 to 20 percent higher. Based on these yield and cutting efficiency results, it is estimated that a minimum lumber price difference between these two grades of approximately $217/MBF needs to exist for No. 3A Common to be a viable raw material option.

In the 1996 Hardwood Symposium Proceedings, the National Hardwood Lumber Association (NHLA) stated that out of 322 identified research needs of the industry, the highest priority was identifying and developing new and better markets for low-value, low-grade lumber and products, including smaller pieces (NHLA 1996). Likewise, the Research Steering Committee for the Center for Forest Products Marketing and Management at Virginia Tech identified as a top priority finding profitable markets for low-grade lumber (Center for Forest Products Marketing and Management 2001). Nearly 50 percent of the sawmill managers surveyed by the Center indicated they had seen an increase in low-grade lumber production since 1996 (Cumbo et al. 2001). These same managers expressed an acute need for stronger, more reliable, and more diverse markets for their low-grade and low-value lumber.

The Forest Service's Forest Inventory and Analysis (FIA) assessments only very recently began measuring tree grade so historical quality data is inadequate for conducting a trend analysis. While reliable and consistent indicators are lacking that the quality of the harvested hardwood sawtimber resource has declined, other factors that impact

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the quality of the logs processed by hardwood sawmills can be cited. In particular, there has been an unmistakable increase in competition for high-quality hardwood logs. For instance, hardwood log exports to Europe, which are almost exclusively veneer logs and high-end Grade 1 sawlogs (Luppold 1994) have increased substantially over the last several years. Comparing the periods 1994 to 1996 and 1999 to 2001, the volume of U.S. hardwood log exports to 10 European markets (i.e., countries) increased by 40 percent. This is one competitive force that impacts the quality of logs entering domestic sawmills (Foreign Agric. Serv. 1998a, 2002).

The second major competitive force impacting the availability of high-quality hardwood logs is demand for these logs by domestic veneer manufacturers. U.S. Census Bureau (1999) statistics on the quantity (square footage) of hardwood veneer production are incomplete, but the growth in value of veneer manufactured in the United States between 1992 and 1997 was substantial (55%). During this same period, there was a 49-percent increase in the quantity of veneer exported from the United States (Foreign Agric. Serv. 1998b). This growth trend has continued. Between 1997 and 2002, veneer exports increased by an additional 21 percent (Foreign Agric. Serv. 2003). The percentage of total hardwood sawlog and veneer log harvests in the northern United States sold directly to veneer plants increased from 4.7 to 5.7 percent between 1991 and 1996 (Powell et al. 1993, Smith et al. 2001). All of these numbers point to an increase in demand for high-quality logs by the veneer industry. Consequently, these top-grade logs are being siphoned from the input stream of hardwood sawmills today more so than in the past.

Today it is standard practice for loggers and/or sawmill log graders to sort through and separate veneer-quality logs from Grade 1 logs of lesser quality; the veneer logs are then sold to veneer manufacturers for two to six times (or more) their Grade 1 sawlog price (Hoover and Gann 2002). Removing these highest quality logs from the sawmill's log input stream has a large impact on the mill's lumber grade yield recovery. For hard maple, the yield of No. 1 Common and Better lumber from Grade 1 logs drops 3.1 percent when the highest value logs are removed (Woodfin 1964). For red oak, the reduction is 5.3 percent and for white oak the recovery of No. 1 Common and Better lumber drops 4.8 percent (Woodfin 1964). Withdrawing veneer-quality logs from the Grade 1 log set has a considerably greater impact on the recovery of the top two lumber grades (FAS and Selects). For hard maple, red oak, and white oak, the reduction in the FAS and Selects lumber recovery was 6.8, 9.5, and 15.0 percentage points, respectively (Woodfin 1964).

As the availability of higher grade hardwood lumber decreases, manufacturers need to sell their low-grade material at a reasonable price to stay in business (Meyer 1996). New manufacturing techniques will be required in order for the processing of higher percentages of low-grade logs to be economically feasible. There are several methods that have been and are currently being studied as possible alternatives for efficiently manufacturing products from today's low-grade hardwood lumber supply. Some of these include green dimensioning, composite materials, modified sawmilling operations, finger-jointing, and the use of lower quality logs for structural hardwood lumber (Lin et al. 1994, Wiedenbeck and Araman 1995, Youngquist and Hamilton 1999).

Simulation modeling offers a good alternative to running an actual experiment in a rough mill as it does not cause costly disruptions in production (Wiedenbeck 1992). Numerous computer programs have been used to simulate various aspects of rough mills, including production scenarios, production costs sensitivities (Gazo and Steele 1995), lumber length-based processing effects (Hamner et al. 2002), and the effects of equipment (Gazo and Steele 1995) and cutting bill changes (Buehlmann et al. 1998) on yields, productivity, costs, and efficiency (Wiedenbeck and Araman 1995).

The ROMI-RIP 2.0 (Thomas 1999b) and ROMI-CROSS 1.0 (Thomas 1997) rough-mill simulation software has been widely used and recently upgraded, making it the rough-mill simulation software of choice. Thomas and Buehlmann (2002) determined the validity of ROMI-RIP results when simulating operations using 4/4 kiln-dried red oak. They collected lumber from a sawmill in Appalachia, digitized the boards, ran ROMI-RIP with the database created from digitizing the boards, and ran the actual boards through a rough mill. They compared the overall ripsaw and chopsaw yield results derived from the simulations and from the actual cut-up study and found that ROMI-RIP 2.0 reasonably simulates actual rough-mill production; thus, the simulation results can be used with confidence for analytical purposes.

Objectives

The goal of this research was to evaluate potential utilization opportunities for No. 3A Common (3AC) lumber to facilitate efficient and profitable use of this lumber grade in the manufacture of high-value appearance products. The objective was to compare part yields and cutting efficiencies when No. 2A Common (2AC), 3AC, and a 50-50 mix of grades 2AC and 3AC (50/50 mix) red oak lumber were used to produce the parts required in each of two feasible low-grade lumber cutting bills.

Methods

Before conducting the simulations to address this objective, approximately 1,500 board feet (BF) (125 boards) of 3AC, 4/4 thickness, kiln-dried red oak lumber was collected from three sawmills and one flooring plant. Digital board defect and dimension maps were created for this lumber (Anderson et al. 1993), which were then used in combination with the 3AC lumber in the 1998 data bank for kiln-dried red oak lumber (Gatchell et al. 1998). The additional 3AC lumber data was required because Gatchell et al's. 3AC lumber sample contained only 239 boards and the width distribution of these boards was narrower than the distribution measured in another 3AC sample (Wiedenbeck et al. 2003).

The ROMI-RIP and ROMI-CROSS simulation programs were used to compare the part yield and cutting efficiency obtained when processing 3AC lumber with that obtained using 2AC lumber or a 50/50 mix (Thomas 1997, 1999b). Part yield was calculated as the ratio of the board feet of parts produced to the board feet of dry lumber input into the production process. Cutting efficiency was determined by calculating the number of sawcuts required per board foot of parts produced. For the rip-first efficiency analysis, only the number of chopsaw cuts was included in the analysis since the number of gang-ripsaw sawcuts is not grade dependent but rather board-and cutting-width dependent. For the crosscut-first efficiency analysis, the number of crosscut sawlines and the number of rip sawlines were summed to derive the sawcuts per board foot of parts figure.

Primary parts are those that are produced in the first two cutting stages (rip or crosscut) that meet cutting bill requirements. Salvage parts are produced in additional cutting operations beyond the initial two stages. Salvage operations are cumbersome and lead to substantially higher processing costs. In this study, part yield was based only on primary parts; no parts produced from salvage operations were included. Similarly, cutting efficiency was based only on the number of saw kerf lines used to produce the primary parts; salvage operations were not included.

Part quality definitions describe the defects (or character marks) permitted on the face and/or back of each of the parts in a cutting bill. For the simulations in this research, the clear two-face (C2F) part quality definition was applied to all parts in all cutting bills. This definition allows no defects on the face or backside of the parts. Therefore, our simulated part yields represent the most conservative yield estimates that should be expected when processing 3AC lumber.

Part prioritization strategy refers to the priority weighting that is placed on the different sizes of parts as the simulation progresses (Thomas 1997). For this research, the complex dynamic exponent (CDE) strategy with continuous feedback on parts produced was used (Thomas 1996). A detailed description of the CDE part prioritization strategy, including equations for weighting factors, is given in Thomas (1996).

Saw blades in a circular-blade gang ripsaw like that simulated in ROMI-RIP (in this cased a fixed-blade best feed ripsaw) are mounted on an arbor. The gang ripsaw optimizer (GRO) arbor design program (Mitchell and Zuo 2001) was used to design efficient arbors for the two cutting bills used in this research. The specific arbor designs are found in Shepley et al. (2004).

The specific ROMI-RIP processing and control options used throughout this study were:

1. all cutting/processing sizes are in inches to the nearest 1/16 inch,
2. primary strip yield optimized for best priority fit,
3. full strip scanned and optimized at once,
4. primary operations avoid producing orphan parts,
5. random-width strip parts acceptable in panel production,
6. part priorities are continuously updated,
7. arbor type: fixed-blade-best-feed,
8. ripsaw kerf size is 2/16 inch,
9. left and right edging sizes are 4/16 inch,
10. board cutup solution optimized at every 1/16-inch position on the arbor, and
11. end-trim allowance for each board end is 16/16 inch.

For the ROMI-CROSS simulations, the processing and control options were:

1. cutting and processing sizes are in inches (to nearest 1/25 in.),
2. part lengths are specified,
3. primary operations avoid orphan parts,
4. crosscuts optimized for best length fitting to board features,
5. scanner optimizes over entire board length,
6. chopsaw kerf is 2/16 inch, ripsaw kerf is 2/16 inch, and
7. end-trim allowance for each board end is 4/4 inch.

Selecting cutting bills for grade-mix comparison

In a related study (Shepley et al. 2004), four "low-grade" cutting bills were collected from industry operations for analysis with ROMI-RIP and ROMI-CROSS. The contributing operations included a flooring plant, a rough mill for cabinet parts, a rough mill for dimension parts, and a rough mill for moulding and millwork. In addition, the "easy" cutting bill used by Gatchell et al. (1999) also was used. The width, length, and part quantity descriptions of these five cutting bills are given in **Table 1**.

From these five cutting bills, the two "best" cutting bills for use with 3AC lumber were identified (Shepley et al. 2004). Part yields and cutting efficiencies were the simulation output variables used to determine the "best" cutting bills. "Best" cutting bills were identified independently for the rip-first and crosscut-first simulations.

In Shepley et al's. rip-first simulations (2004), cutting bill C had the highest part yield at 38.4 percent (**Table 1**). A and E were tied for the second best part yield at 36.7 percent and 37.2 percent (difference not statistically significant at question $\alpha = 0.05$), respectively (Shepley et al. 2004). Cutting bills B and D had much lower yields – 18.2 percent and 14.1 percent, respectively.

The most efficient to process rip-first cutting bill when using 3AC lumber was E, followed by A, D, C, and B (Shepley et al. 2004). Although cutting bills A and E exhibited no statistical difference in part yields, E was a more efficient cutting bill to process. As a result, cutting bill C, having the highest part yield, and cutting bill E, having the second best part yield and best cutting efficiency, were selected as the two "best" rip-first cutting bills for yield and cutting efficiency. Cutting bill C originated from a rough mill producing cabinet parts and cutting bill E originated from a rough mill producing parts for moulding and millwork.

In the crosscut-first simulations conducted by Shepley et al. (2004), the highest part yields were obtained from cutting bills C and E, followed by A, B, and D. Their part yields were 37.1 and 36.4, 31.4, 18.8, and 14.3 percent, respectively (**Table 1**). The most efficient to cut crosscut-first cutting bill was D, followed by E, B, A, and C. Though cutting bills C and E had approximately equal yields, cutting bill A was much more efficiently processed than cutting bill C. As a result, cutting bills A and E were selected as the two "best" crosscut-first cutting bills. Cutting bill A originated from a rough mill producing dimension parts and cutting bill E originated from a rough mill producing parts for moulding and millwork. Differences in cutting bill part size and quantity characteristics are reported in **Table 1**.

Lumber data file set-up

Once the "best" cutting bills were identified, several more preliminary steps had to be completed. Thomas' Makefile program (Gatchell et al. 1998; Thomas 1997, 1999a) was used to create the board data files. The new board files, derived by digitizing 1,500 BF of 3AC red oak lumber, were used along with Gatchell et al.'s 3AC board data (1998). The 4-foot lumber in the Gatchell et al. databank (1998) was not used in this research. As a result, the complete 3AC board source for this research consisted

Table 1. — Descriptions of cutting bills considered for use in this study along with their respective rip and crosscut-first primary part yields derived through simulation by Shepley et al. (2004).

Cutting bill	Origin	Part width range[a]	Average width[a]	Part length range[b]	Average length[b]	% of part area < 24 in. long	% of parts < 24 in. long	No. of part sizes < 24 in. long	% of part area > 40 in. long	Rip-first yield[c]	Cross-cut first yield[c]
		(in.)									
A	Dimension producer	2.5	2.5	13.0 to 40.1	23.4	38	58	6 of 9	30	36.7	31.4
B	Gatchell's "easy"	1.5 to 4.2	2.0	11.9 to 78.9	28.5	45	73	7 of 15	51	18.2	18.8
C	Cabinet producer	2.3	2.3	3.9 to 40.2	19.9	57	70	10 of 13	11	38.4	37.1
D	Strip flooring producer	2.2 to 2.5	2.4	36.0 to 84.0	60.0	0	0	0 of 10	88	14.1	14.3
E	Moulding producer	2.1 to 3.0	2.5	10.0 to 46.0	28.0	23	38	15 of 39	30	37.2	36.4

[a] The part width range and average part width calculations do not include random widths assembled into panels.

[b] The part length range, average part length, and part length distribution by volume includes panel parts in their calculations.

[c] Rip and crosscut-first rough mill yields are from Shepley et al. (2004).

of 314 digitally mapped boards (1,627 BF).

Makefile was used to create the board files containing the three different grade mixes. To assure the results of the ROMI simulations would be attributable to the grade mix, several other variables had to be held constant in creating the board files. These variables were lumber crook (sidebend), length, and width. The 2AC and 3AC boards in the 1998 databank for kiln-dried red oak lumber contained no more than 0.25 inches of crook (Gatchell et al. 1998). The new 3AC lumber acquired for this research contained several boards with crook greater than 0.25 inches. These crooked boards were excluded from this study to maintain consistency with the boards in the 1998 databank for kiln-dried red oak lumber.

Since the 3AC board population was more limited than the 2AC population, the length and width distributions (**Table 2**) of the 3AC board population were determined and the population of 2AC boards available for sampling was adjusted (using Makefile) to have the same size distributions. Adjusting the length distribution reduced the population of 2AC boards by 4.3 percent (192 BF). Since the primary goal was to evaluate performance differences between lumber grade mixes, using the same lumber width distribution in creating the grade mix files eliminated the possibility that width effects would confound the results and make them harder to interpret. To ensure that the length and width distributions had carried through to the final board files, analyses of variance (ANOVA) ($\alpha = 0.05$) were conducted using the Statistical Package for the Social Sciences (SPSS© 1999). No length or width differences were detected between the 2AC and 3AC board files.

Past research has shown that a minimum of 150 boards are desirable for ROMI simulations to eliminate yield influences due to board sequence and selection (i.e., adding more boards to the input data file does not have a significant influence on the results of the simulation; $\alpha = 0.05$) (Buehlmann et al. 1998). Therefore, simulations in this research were designed to process at least 150 boards per simulation to ensure unbiased yield results. Before any simulations were conducted, the required part quantities for the cutting bills had to be adjusted so the size of the cutting bill matched the size of the lumber input files. This adjustment was accomplished by trial and error. Relative part quantity proportions for the parts in each cutting bill were maintained during this iterative process (e.g., if the initial requirements specified 100 parts for A, 50 for B, and 30 for C, the adjusted quantities would still maintain this 10:5:3 ratio).

Experimental design for simulations

For each of the three grade mixes, three files (replicates) were created. These nine files were each processed through the two "best" cutting bills using both ROMI-RIP and ROMI-CROSS. Thus, the total number of simulations conducted was 36 (3 grades × 3 replications × 2 cutting bills × 2 simulation programs).

Table 2. — No. 3A Common width distributions adapted from Wiedenbeck et al. (2003).

Width	Percentage
(in.)	
3.00 to 4.75	17
5.00 to 6.75	43
7.00 to 8.75	27
9.00 to 10.75	10
11.00 to 12.75	2
13.00 to 14.75	1
15.00 to 16.75	0
17.00+	0

Statistical methodology

Multivariate repeated measures analysis of variance (MANOVA) tests were conducted on the part yield and cutting efficiency results using SAS ($\alpha = 0.05$). The first three null hypotheses tested addressed yield differences between the three lumber grade classes. The second set of null hypotheses concerned cutting efficiency differences between the grade classes. Three replications (simulations conducted on discrete board files) were performed in each cell for each trial. SAS© was used for the statistical analyses.

Two-way fixed effects repeated measures ANOVA tests were conducted for each of the dependent variables: yield and efficiency. The class variables in these models were lumber grade mix and cutting bill. Because the same lumber data input files were used for both of the cutting bills in the simulations, the samples in the "between cutting bill" comparisons were not independent. Therefore, yields and efficiencies between cutting bills are correlated and this correlation must be addressed in the MANOVA tests. Thus, a repeated measures design with board file serving as the repeated measure (also known as the within-subject effect) was used. Using the repeated measures MANOVA, three null hypotheses were tested ($\alpha = 0.05$) for each dependent variable for both the rip and crosscut-first simulation experiments. For yield, the tested models were:

$Yield_{cross/rip} = f$ (cutting bill, grade mix, cutting bill × grade mix)

And the three null hypotheses investigated were:

$H0_A$: There is no effect of grade mix on mean part yield

$H0_B$: There is no effect of cutting bill on mean part yield

$H0_C$: There is no interaction of grade mix and cutting bill on the mean part yield.

For cutting efficiency, the tested models were:

$Cutting\ efficiency_{cross/rip} = f$ (cutting bill, grade mix, cutting bill × grade mix)

And the three null hypotheses were:

$H0_D$: There is no effect of grade mix on mean cutting efficiency

$H0_E$: There is no effect of cutting bill on mean cutting efficiency

$H0_F$: There is no interaction of grade mix and cutting bill on mean cutting efficiency.

While lumber grade mix was the principal main effect of interest, by conducting the MANOVA the significance of the interaction effect between cutting bill and lumber grade mix class could be determined.

Because the sample size for this study was small (three board files per grade mix), multiple comparison tests could not be run on the full model that includes the interaction term, grade × cutting bill; there were insufficient degrees of freedom available. To be able to conduct multiple-comparison testing on the factor of greatest interest, lumber grade mix, an alternate ANOVA model was examined. For this, each of the full models was reduced to two (one per cutting bill), one-way, fixed effect (effect = lumber grade mix), ANOVAs to enable us to conduct multiple comparison testing. Tukey's honestly significant difference (HSD) multiple comparison tests were conducted in cases where significant differences were indicated by the ANOVA tests ($\alpha = 0.05$). Tukey's HSD test was chosen over other methods because it is less likely to detect borderline significance between factors that may, in fact, not be significant.

Results

Yield results for rip-first processing

Table 3 summarizes the results of all 18 simulation runs performed in the rip-first study. In the tests on yield, both main effects (grade mix and cutting bill) and the second level effect (lumber grade mix × cutting bill) were highly significant ($p < 0.01$), thus all three null hypotheses were rejected.

The results of the two, one-way ANOVA tests that were conducted independently for each cutting bill (C and E) confirmed the result of the repeated measures MANOVA – the differences in mean part yields achieved from the three lumber grade mixes were statistically significant ($p < 0.0001$, power of performed test = 0.999). Tukey's HSD ($\alpha = 0.05$) indicated that the mean part yield for each grade mix was different (**Table 3**). As one would expect, for both cutting bills the highest part yield (primary yield only) was achieved while running 2AC lumber, followed by the 50/50 mix, and lastly the 3AC lumber. The part yields were approximately 54 percent, 49 percent, and 42 percent for cutting bill C and 60 percent, 51 percent, and 40 percent for cutting bill E. The impact of grade mix on lumber yield appears to be smaller for cutting bill C than for cutting bill E (5% versus 9% difference in yield per grade step). This difference in the yield effects between cutting bills is indicated by the significance of the interaction term in the yield model.

For both cutting bills, the yield loss suffered when the grade mix is reduced from pure 2AC to a 50/50 mix is less than the yield loss suffered when the 50/50 mix is further reduced to pure 3AC lumber as can be seen in column 4 of **Table 3**. This indicates that a mix of grades including 3AC lumber can be successfully utilized for these cutting bills, but if any longer or wider parts are needed some 2AC or higher grade lum-

Table 3.—Average part yields and cutting efficiencies achieved for two cutting bills from three low-grade lumber mixes processed in rip-first simulations using ROMI-RIP.

Cutting bill	Grade mix	Average yield (%) and Tukey's HSD grouping	Yield difference	Average cutting efficiency[a] (kerf lines per BF of parts) and Tukey's HSD grouping	Cutting efficiency difference (kerf lines/BF parts)
			(%)		
C	2A Common	54.3 A	5.7	5.0 A	–0.3
	50/50 mix	48.6 B		5.3 B	
	3A Common	42.2 C	6.4	5.7 C	–0.4
		2A yield – 3A yield = 12.1		2A efficiency – 3A efficiency = –0.7	
E					
	2A Common	59.9 A	8.9	3.6 A	–0.1
	50/50 mix	51.0 B		3.7 B	
	3A Common	40.2 C	10.8	3.9 C	–0.2
		2A yield – 3A yield = 19.7		2A efficiency – 3A efficiency = –0.3	

[a] Cutting efficiency for the rip-first studies was calculated by dividing the total number of chopsaw cuts required by the board footage of parts produced. Within each cutting bill, means with the same capital letter are not significantly different (5% level).

ber must be used or yield losses will be inflated.

Since all boards with more then 0.25 inches of crook were removed from the sample population, the rip-first yields obtained while processing 3AC in this study were somewhat higher (3% to 4%) than those obtained in the Shepley et al. study (2004) comparing low-grade cutting bills. The influence of crook on yields in crosscut-first processing is known to be less than for rip-first processing (Gatchell 1990, Gatchell et al. 1999). This is supported by the results of this study. Excluding boards with crook from this analysis changed the 3AC crosscut-first yields for cutting bills A and E less than 0.5 percent from those measured in Shepley et al's. study (2004) when 3AC boards with crook were included in the input data files.

Cutting efficiency results for rip-first processing

Statistical analysis of the cutting efficiency (number of chopsaw kerf lines per board foot of parts produced) for the rip-first simulations indicated that the two main effects and the interaction effect were highly significant ($p < 0.01$).

The results of the one-way ANOVA tests on cutting efficiency that were conducted independently for each cutting bill (C and E) confirmed the result of the repeated measures MANOVA; the differences in mean cutting efficiencies achieved from the three lumber grade mixes were statistically significant ($p < 0.0001$, power of performed test = 0.999). Tukey's HSD ($\alpha = 0.05$) indicated that the mean cutting efficiency for each grade mix was different (**Table 3**). Similar to the yield results for both cutting bills C and E, the best cutting efficiency was achieved while running 2AC lumber, followed by the 50/50 mix. Processing 3AC required the highest number of cutting operations (chopsaw kerf lines) to produce 1 board foot of clear two-face parts. For cutting bill C, an average of approximately 5.0, 5.3, and 5.7 chopsaw lines were required, respectively, per board foot of parts produced (**Table 3**). For cutting bill E, an average of approximately 3.6, 3.7, and 3.9 chopsaw lines were required, respectively, per board foot of parts produced (**Table 3**).

Yield results for crosscut-first processing

Repeated measures ANOVA conducted on the crosscut-first simulation results for yield indicated that both main effects (grade mix and cutting bill) and the second level effect (lumber grade mix × cutting bill) were highly significant ($p < 0.01$), thus all three null hypotheses were rejected. **Table 4** summarizes the results of all 18 simulation runs performed in the crosscut-first study.

Tukey's HSD ($\alpha = 0.05$) multiple comparison tests were conducted after the one-way ANOVA tests confirmed that lumber grade mix had a significant influence on part yields. The multiple comparison tests indicated that for each grade mix part yields were different for both cutting bills A and E. Similar to the rip-first results, the highest part yield was achieved while running the 2AC grade mix, followed by the 50/50 mix, and lastly the 3AC grade mix. For cutting bill A, the part yields were approximately 46, 39, and 31 percent (**Table 4**). For cutting bill E, the part yields were approximately 55, 47, and 37 percent for 2AC, the 50/50 mix, and 3AC, respectively (**Table 4**). Again, yields for cutting bill E were more strongly influenced by grade mix than were the yields for cutting bill A.

Cutting efficiency results for crosscut-first processing

In tests on efficiency for the crosscut-first simulations, both main effects (grade mix and cutting bill) and the second level effect (lumber grade mix × cutting bill) were highly significant ($p < 0.01$), thus all three null hypotheses were again rejected.

Again, the reduced ANOVA tests that were run for each cutting bill (A and E) to examine the effect of lumber grade mix on cutting efficiency were significant ($p < 0.0001$, power of performed test = 0.999). Tukey's HSD ($\alpha = 0.05$) multiple comparison tests indicated that average cutting efficiency was different for each grade mix (**Table 4**). For both cutting bills, the best cutting efficiency was obtained while running the 2AC lumber, followed by the 50/50 mix, and lastly the 3AC lumber. For cutting bill A, approximately 6.8, 7.0, and 7.7 saw lines were required, on average, per board foot of parts produced (**Table 4**). For cutting bill E, approximately 5.6, 6.0, and 6.5 saw lines were required, on average, per board foot of parts produced (**Table 4**).

Table 4.—Average part yields and cutting efficiencies achieved for two cutting bills from three low-grade lumber mixes processed in crosscut-first simulations using ROMI-CROSS.

Cutting bill	Grade mix	Average yield (%) and Tukey's HSD grouping	Yield difference	Average cutting efficiency[a] (kerf lines per BF of parts) and Tukey's HSD grouping	Cutting efficiency difference (kerf lines/BF parts)
			(%)		
A	2A Common	40.6 A	6.9	6.8 A	−0.2
	50/50 mix	39.1 B		7.0 B	
	3A Common	31.4 C	7.7	7.7 C	−0.7
		2A yield − 3A yield = 14.6		2A efficiency − 3A efficiency = −1.2	
E					
	2A Common	54.7 A	7.9	5.6 A	−0.4
	50/50 mix	46.8 B		6.0 B	
	3A Common	36.8 C	10.0	6.5 C	−0.5
		2A yield − 3A yield = 17.9		2A efficiency − 3A efficiency = −0.9	

[a] Cutting efficiency for the crosscut-first studies was calculated by dividing *the sum of the crosscut AND ripsaw cuts* by the board footage of parts produced. Within each cutting bill, means with the same capital letter are not significantly different (5% level).

Discussion

Factors in cutting efficiency

The decrease in cutting efficiency when processing 3AC lumber compared to 2AC is directly related to the NHLA hardwood lumber grading rules. 2AC lumber is limited to a maximum number of cuttings (based on board size) to obtain its required minimum clear-face area (50%) while the 3AC lumber is allowed an unlimited number of cuttings. In fact, it is possible for a 3AC board to have a higher percentage of clear area than a 2AC board. For example, of 239 3AC boards in the *1998 Data Bank for Kiln-Dried Red Oak Lumber* (Gatchell et al. 1998), 4 percent have grading cutting yields of more than 60 percent and another 10 percent have yields between 50 and 60 percent. Of the 925 2AC boards in the same data bank (Gatchell et al. 1998), 14 percent have grading yields below 60 percent! These 2AC and 3AC boards have similar clear area yields but the clear area in 3AC boards is contained in a larger number of cuttings (which typically have a smaller average size). Therefore, it is expected that more cuts are required to remove clear-face cuttings from 3AC boards than from 2AC boards. Also, a 3AC board, on average, will produce smaller parts.

In both the rip-first and the crosscut-first simulations and for all three grade mixes, the majority of the sawlines were made in the second cut-up stage (the crosscut stage in the rip-first simulations and the ripping stage in the crosscut-first simulations). The second cut-up stage was also where the majority of the differences between grades in the number of required sawlines occurred. These crosscut-first cutting efficiency results do not differ between grades as much as those measured in the crosscut-first simulation experiments conducted by Steele et al. (1999). In that research, three cutting bills of varying difficulty were evaluated. Sawing efficiency ratios for 2AC versus 3AC lumber were calculated for both studies using the sawline results provided by ROMI-CROSS. For Steele et al's. (1999) three cutting bills, the 2AC:3AC processing ratios were 1:1.4, 1:1.9, and 1:1.5. The cutting bills used in the current study were more efficiently cut out of 3AC lumber than were any of the cutting bills in Steele et al.'s (1999) study with 2AC:3AC ratios of 1:1.1 and 1:1.2 for crosscut-first cutting bills A and E, respectively.

Whereas the average widths/lengths of cutting bills A and E were 2.5/23.4 and 2.5/28.0 inches in this study, the average part width and length for the cutting bill which was the most efficiently produced in Steele et al.'s study (1999) was 2.1/21.5 inches. Steele et al.'s average sizes were smaller. This is a case where averages do not tell the whole story. Neither do differences in part size distributions explain the differences in cutting efficiency between these two studies. The fact that Steele et al.'s cutting operations were conducted by limiting the number of part sizes that could be cut on any given saw while this study simulated a case where all sizes could be cut on each saw (i.e., the crosscut saws were not limited to a subset of the lengths) explains much of the difference in cutting efficiency. Since clear areas tend to be smaller and more scattered in 3AC compared to 2AC lumber, 3AC yields and cutting efficiencies show greater improvement by having a larger assortment of part size options available than do yields and efficiencies for 2AC lumber.

Estimated price difference between lumber grades for 3AC to be economically feasible

Based on the primary part yield results obtained in this research, the raw material cost to produce 1,000 BF of parts from 3AC lumber to the raw material cost to produce the same amount of parts from 2AC lumber for each cutting bill were compared. The price assigned to 3AC lumber was $485 per thousand board feet (MBF) and the price assigned to 2AC lumber was $545 MBF, based on Appalachian Hardwood prices from November 17, 2002 (Hardwood Market Report 2002). For both rip-first cutting bills and both crosscut-first cutting bills, the raw material cost for producing 1,000 BF of parts was less expensive using the 2AC lumber. For rip-first cutting bills C and E, the lumber cost to produce 1,000 BF of parts was $146.65 and $276.30 less when processing 2AC lumber compared to 3AC lumber. Likewise, for crosscut-first cutting bills A and E, the lumber cost associated with processing the 2AC lumber was $359.65 and $321.85 less compared to the cost when processing the 3AC lumber.

Raw material cost is only one of the direct cost components that needs to be carefully considered in weighing lumber grade mix options. Another significant manufacturing cost component is labor. If the cutting efficiency results are used as a surrogate for manufacturing (labor) efficiency, the ratios for 2AC versus 3AC can be used to produce an estimate of the increased manufacturing cost associated with processing 3AC lumber. By using the most extreme 2AC versus 3AC cutting efficiency ratio measured in this study (1:1.2). The most extreme estimate of the manufacturing cost difference between the two lumber grades was obtained.

Assuming (based on experience) that the average component part (rough dimension) manufacturing cost in a rough mill ranges from $1.75 to $2.05 per BF of parts produced (including the cost of lumber), then the lumber cost fraction of this amount ranges from $1.38 and $1.63 per BF for 2AC and 3AC Appalachian red oak lumber (obtained by adding $200/MBF kiln drying cost to the 2AC and 3AC green lumber prices and dividing these figures by the respective average yields obtained in this study). If it is assumed that the residual direct manufacturing cost is made up of labor costs (Mitchell 2001) and other costs that are affected by lumber grade, then the manufacturing cost per BF of parts produced will range from $0.37 to $0.67 per BF for 2AC lumber (e.g., $1.75/BF total manufacturing cost − $1.38/BF dry lumber cost = $0.37/BF manufacturing cost). The final step in estimating the variable cost associated with processing 3AC lumber instead of 2AC lumber is to apply an appropriate manufacturing cost inflation factor for 3AC processing (recall the 2AC:3AC cutting efficiency ratio was 1:1.2). The estimated 3AC manufacturing cost range is determined by multiplying $0.37 and $0.67 (the residual cost range for 2AC lumber after subtracting lumber cost) by 1.2, this study's inflation factor. Thus, the 3AC manufacturing cost range is $0.44 to $0.80 per BF.

The difference between these estimated 2AC and 3AC manufacturing cost figures is $0.07/BF for the low end of the range ($0.44 to $0.37) and $0.13/BF for the upper end of the range ($0.80 to $0.67) or $70 and $130 per MBF of parts produced. This difference, when added to the yield-based raw material cost difference discussed earlier (e.g., $147/MBF for rip-first cutting bill C), gives a less specific but more comprehensive estimate of the price difference that needs to exist between 2AC and 3AC lumber if 3AC is to be a viable raw material alternative. When the lumber price difference between 2AC and 3AC lumber exceeds $217 per MBF ($70 + $147), the 3AC alternative becomes worth evaluating and when the difference approaches $277 per MBF ($130 + $147), a strong case can be made for using 3AC lumber to fill appropriate low-grade cutting bills. However, the manufacturing costs used in this analysis may not be reflective of the costs for all rough mills, in which case the same approach should be used to calculate an alternate break-even range for 3AC lumber.

While Appalachian area red oak prices do not favor 3AC lumber as a raw material for these cutting bills, northern area red oak prices do. Currently, there is an average $245/MBF price difference between 2AC and 3AC red oak lumber in the northern area (Hardwood Market Report 2002). Based on these prices and our part yield results, 3AC lumber is a viable raw material alternative compared to 2AC lumber. Furthermore, since the same NHLA grade rules apply to most hardwood lumber manufactured in the United States, similar part yield results to those measured in this study for 3AC red oak can be expected when processing 3AC white oak, maple, cherry, and other species. Because red oak is a popular flooring species and some 3AC lumber is used by many strip flooring rough-mill operations, the price gap between 2AC and 3AC lumber is not as large as it is for many other species. For these other species, 3AC lumber may be a less expensive raw material to process compared to 2AC lumber (e.g., cherry and hard maple).

Based on the part yield results of this study for these three cutting bills and current Appalachian region market prices, 3AC lumber is not a cost effective raw material alternative compared to 2AC lumber. However, for cutting bills with smaller differences between their 2AC and 3AC part yields, using 3AC lumber can reduce raw material cost. Also, as the price difference increases between 2AC and 3AC lumber, 3AC becomes a more viable raw material option, especially in rip-first operations.

Summary and conclusions

The objective of this study was to compare part yields and cutting efficiencies obtained when cutting 3AC lumber with those obtained when processing 2AC or a 50/50 mix of 2AC and 3AC lumber. Both rip- and crosscut-first rough-mill processing experiments were conducted in a series of computer simulations. Two feasible low-grade lumber cutting bills were used for each simulation experiment. Optimum processing conditions were assumed. Red oak lumber was processed into clear two-face parts.

In both the rip-first and crosscut-first simulations, the results of the lumber grade mix yield simulations indicated that part yield decreased as the percentage of 3AC lumber in the grade mix increased. For rip-first cutting bill C, there was a 5.7 percent average difference in part yield between the 2AC grade mix and the 50/50 mix and a 6.4 percent average difference in part yield between the 50/50 mix and the 3AC grade mix which adds to a 12.1 percent average difference in primary part yield between the 2AC and 3AC grade mixes. The 50/50 grade mix required 0.3 additional sawlines (chopsaw lines only) per board foot of parts produced compared to the 2AC lumber and the 3AC lumber required 0.4 additional sawlines per board foot of parts produced compared to the 50/50 mix. For rip-first cutting bill E, there was an 8.9 percent average difference in part yield between the 2AC and 50/50 grade mixes, a 10.8 percent average difference in part yield between the 50/50 and 3AC grade mixes, and a 19.7 percent average difference in part yield between the 2AC and 3AC grade mixes. The 50/50 mix required 0.1 additional sawlines per board foot of parts produced compared to the 2AC grade mix and the 3AC grade mix required 0.2 additional sawlines per board foot of parts produced compared to the 50/50 mix.

For crosscut-first cutting bill A, there was a 6.9 percent average difference in part yield between the 2AC and 50/50 grade mixes, a 7.7 percent average difference between the 50/50 and 3AC grade mixes, and an average difference between the 2AC and 3AC grade mixes of 14.6 percent. The 50/50 mix required 0.2 additional sawlines (crosscut and ripsaw lines) per board foot of parts produced compared to the 2AC grade mix, and the 3AC grade mix required 0.7 additional sawlines per board foot of parts produced compared to the 50/50 grade mix. For crosscut-first cutting bill E, there was a 7.9 percent difference in part yield between the 2AC and 50/50 grade mixes and a 10.0 percent difference in part yield between the 50/50 and 3AC grade mixes. The 50/50 mix required 0.4 additional sawlines per board foot of parts produced compared to the 2AC lumber and the 3AC lumber required 0.5 additional sawlines per board foot of parts produced compared to the 50/50 mix.

When changing grade mixes, differences in part yields were highly dependent on the cutting bill. Part yield differences between grade mixes were inconsistent not only between cutting bills but also within cutting bills. Similarly, changes in cutting efficiencies were also variable between cutting bills when altering the grade mix. Rough-mill managers should develop awareness of the part yield that can be achieved when processing 3AC lumber alone and in combination with other lumber grades. Rough-mill operations processing cutting bills that experience only small differences in yield (less then 6% based on current lumber prices) when processing 3AC compared to 2AC lumber should consider increasing the percentage of 3AC lumber utilized when processing these cutting bills. Based on cutting bill A, which produced the best relative yield for 3AC compared to 2AC (12% to 14% lower yield for 3AC), replacing 2AC with 3AC becomes viable from a total manufacturing cost perspective when the cost difference between 2AC and 3AC approaches $220/MBF.

The NHLA standard grade rules apply to most hardwood lumber manufactured in the United States. Thus, the part yield results for 3AC lumber obtained in these red oak lumber cut-up simulations should be parallel to the results that would be expected when processing 3AC white oak, maple, cherry, and other species. The price difference between 2AC and 3AC lumber for most of these species is greater than the price difference for red oak. Therefore, 3AC lumber may be a less expensive raw material to process compared to 2AC lumber for some of these species.

The information derived from this research on potential utilization opportunities for 3AC lumber can help value-added solid wood products manufacturing companies better identify part sizes and cutting bills that can be profitably cut from this portion of the lumber resource which heretofore has been poorly utilized.

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