Opportunities for expanded and higher value utilization of No. 3A Common hardwood lumber

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Abstract

The percentage of low-grade material composing the annual hardwood lumber production in the United States is on the rise. As a result, finding markets for low-grade and 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 determine specific conditions that can lead to optimal part yield when processing No. 3A Common (3AC), 4/4-thickness, kiln-dried red oak lumber in rip-first and crosscut-first rough mill operations. Results of the simulations indicated that cutting bills with narrow part widths and short part lengths are the most conducive to obtaining optimal part yield while processing 3AC lumber. Further, the results indicated that higher part yields can be obtained when processing short-length 3AC lumber (between 6 and 8 ft.) as opposed to longer length 3AC lumber. Part yields from short, 3AC lumber were from 3 to 6 percent higher than were the yields from long, 3AC lumber (between 14 and 16 ft.) in three of four simulation trials. The lumber length effect was more consistent in the rip-first processing trials than in the crosscut-first trials.

There are several major challenges facing the forest products industry as it enters the 21st century. One of these challenges is improving efficiency and resource utilization. Perhaps the largest opportunity area relates to improved utilization of low-grade lumber. More specifically, what can low-grade hardwood lumber be used for and how can it be produced and manufactured in an efficient and economically feasible manner?

In the 1996 Hardwood Symposium Proceedings, the National Hardwood Lumber Assosciation (NHLA) stated that out of 322 identified research needs of the industry "identifying and developing new and better markets for low-value, low-grade lumber and products, including smaller pieces was their number one priority" (NHLA 1996). Likewise, the Research Steering Committee for the Center for Forest Products Marketing and Management (2001) at Virginia Tech identified finding profitable markets for low-grade lumber as their number one priority. Cumbo et al. (2001) showed that the majority of the sawmills in the United States agree with these statements. Hardwood manufacturers need strong and reliable markets for their low-grade and low-value lumber. As the availability of higher grade hardwood lumber decreases, manufacturers will have to be able to sell their low-grade material to stay in business (Meyer 1996). New harvesting and manufacturing techniques will be required in order for the production of low-grade material to be economically feasible.

Furthermore, as low-grade hardwood lumber production volume rises (Cumbo et al. 2001), consumption numbers are holding steady, creating a surplus of low-grade lumber. Finding markets for

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Forest Prod. J. 54(9):77-85.

low-grade hardwood lumber will benefit both the forestry and forest products industries by improving efficiency and resource utilization and providing a broader spectrum of forest management options. The hardwood resource is changing and it is vital to companies processing hardwood lumber that they adapt to these changes. To facilitate this, we seek to provide information regarding the currently available raw material and its processing capabilities.

As a result of rising lumber prices, lower log quality (Serrano and Cassens 2000), and environmental constraints (Meeks 2001), the hardwood industry is being forced to look at nontraditional wood sources and processing methods (Gephart et al. 1995). 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, different composite materials, modified sawmilling operations, finger-jointing, and structural hardwood lumber (Lin et al. 1994, Wiedenbeck and Araman 1995, Youngquist and Hamilton 1999).

A large portion of the hardwood lumber harvested in the United States is processed in rough mills to create value-added products. In 1996, Wiedenbeck and Scheerer (1996) surveyed 38 different companies investigating rough mill yields. The majority of respondents reported overall yields from 50 to 59 percent. Based on these results, it is evident that many operations have room to improve product recovery efficiency.

Many manufacturing systems cannot be physically manipulated without causing significant disruption to the production process. A rough mill is one of these. Simulation modeling offers a good alternative to running an actual experiment in a rough mill (Wiedenbeck 1992). Numerous computer simulation programs have been used to simulate various aspects of rough mills including production impacts; 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) performed a study to determine the validity of ROMI-RIP results when simulating operations using 4/4 kiln-dried red oak. They compared the overall ripsaw and chopsaw yields derived from simulation-based processing with results from actual rough mill cut-up and found that ROMI-RIP 2.0 reasonably simulates actual rough mill production; 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 in order to facilitate efficient and profitable incorporation of this lumber grade into the mix of wood materials processed into high-value appearance products. In this first phase of what promises to be a multi-phase research project, two objectives were identified and addressed.

Objective 1 was to identify two feasible low-grade cutting bills, based on yield and sawing efficiency through a series of exploratory rip-first and cross cut-first simulation studies, using ROMI-RIP and ROMI-CROSS.

Objective 2 was to compare yields and sawing efficiencies for short (6 to 8 ft.), medium (10 to 12 ft.), and long-length (14 to 16 ft.) 3AC lumber using the two most feasible cutting bills to determine if there is any difference between length groups and, if a difference is detected, to determine which length group(s) offers the most favorable results.

Methods

Before conducting the simulations to address these two objectives, 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 that were then used in combination with the 3AC lumber in the 1998 Data Bank for Kiln-Dried Red Oak Lumber (Gatchell et al. 1998). In addition, cutting bills were collected from four rough mill operations for use in the simulations.

Objective 1 methodology

Our first study objective was to identify the two most productive 3AC cutting bills based on both part yield and sawing efficiency for each rough mill configuration (rip- and crosscut-first). Part yield is the ratio of the BF of parts produced to the BF of dry lumber input into the production process. Sawing efficiency comparisons were calculated by dividing the total number of cuts (both rip and crosscut) by the BF of parts produced. In this research, sawing efficiency was not a measure of machine utilization but rather a measure of the actual number of sawkerfs (sawlines) required to produce the parts specified by the cutting bills. 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 salvage parts produced from salvage operations were included. Many rough mill managers are focused principally on primary yields. Similarly, cutting efficiency was based only on the number of sawkerf lines used to produce the primary parts; salvage operations were not included.

For the simulations in this research, the clear two-face (C2F) part quality definition was applied to all parts in all cutting bills. This part quality definition allows no defects on the face or backside of the parts produced. This is the strictest part quality classification and leads to lower part yields than do quality standards that allow some defects (or character) on one or both part faces. Therefore, our simulated part yields represent the most conservative estimates of the yields that should be expected when processing 3AC lumber.

Four "low-grade" cutting bills were collected from industry operations for analysis with ROMI-RIP and ROMI-CROSS. In addition, the "easy" cutting bill used by Gatchell et al. (1999) was used (**Table 1**). Cutting Bill A was a dimension parts cutting bill. Cutting Bill B was Gatchell et al's. "easy" cutting bill. Cutting Bill C was a cabinet parts cutting bill. Cutting Bill D was a strip flooring cutting bill (strip lengths in this bill were quite long - 3 to 6 ft.). Cutting

Table 1. — Descriptions of cutting bills.

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

[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 do include panel parts in their calculations.

Table 2. — Part widths and arbor sequences for cutting bills.

Cutting bill	Kerf	Part widths	Arbor spacing sequence	Arbor width
	(in.)			
A	0.125	2.5	2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5	18.25
B	0.125	1.5, 1.87, 2.62, 3.87, 4.25	1.87, 1.87, 2.62, 1.87, 4.25, 3.87, 1.5, 2.62	21.37
C	0.125	2.31	2.31, 2.31, 2.31, 2.31, 2.31, 2.31	14.48
D	0.125	2.5, 2.25	2.5, 2.5, 2.25, 2.5, 2.5, 2.5, 2.25, 2.25, 2.25	22.5
E	0.125	2.125, 2.5, 3.0	2.5, 3.0, 2.125, 2.5, 2.125, 3.0, 2.5, 2.5	21.125

Bill E was a moulding/millwork cutting bill.

Cutting Bills A, B, C, and D required only part quantity modifications (so that the size of the cutting bill would fit the size of the lumber input file) for use with ROMI-RIP and ROMI-CROSS. Cutting Bill E, however, required the modification of several random-length part descriptions. Another challenge faced in simulating Cutting Bill E was caused by the presence of some very long parts in the cutting bill. These long parts were nearly impossible to acquire with the 3AC boards used in the simulation. To resolve this problem, the long random-length parts (45 to 96 in.) and the long fixed-length part (98 in.) were removed from the cutting bill. To bypass the random-length limitations of the ROMI-CROSS program, random-length parts were approximated by defining discrete lengths at 3-inch intervals over the range of acceptable lengths. This same cutting bill part length adjustment was used for Cutting Bill E in the rip-first simulations to simplify cutting bill comparisons.

Cutting Bills D and E were from rough mill operations that required a continual supply of the part sizes listed in their cutting bills; thus, no specified quantities were assigned to the defined parts. This is the case in an operation producing few or identical products continuously, such as flooring operations. Cutting Bill D required 10 different part sizes but had no required quantities. An equal quantity was assigned to all 10 parts. For Cutting Bill E, one part width (2.5 in.) was defined as the target width and the other two widths were defined as drop sizes. Drop sizes are parts to be cut only if the target size cannot be obtained. Quantities were assigned for the part requirements such that the target width required twice as many parts as the drop widths.

Saw blades in a circular-blade gang ripsaw like that simulated in ROMI-RIP (in this case 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 each of the cutting bills used in this research (**Table 2**).

For each of the five cutting bills, simulations were run using a 3AC board file created based on lumber sizes processed by industry (Wiedenbeck et al. 2003). **Table 2** shows a list of cutting bills, part widths, and optimal arbor designs based on the GRO results. Note that all of the total arbor widths given in the rightmost column of **Table 2** are less than 24 inches, a standard-width arbor used by rough mills.

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

- All cutting/processing sizes in inches to the nearest 1/16 inch;
- Primary strip yield optimized for best priority fit;
- Full strip scanned and optimized at once;
- Primary operations avoid producing orphan parts (more parts than are needed);
- Random-width strip parts acceptable in panel production;
- Part priorities continuously updated;
- Arbor type: fixed-blade-best-feed;
- Ripsaw kerf size: 2/16 inch;
- Left and right edger kerf sizes: 4/16 inch;
- Board cutup solution optimized at every 1/16-inch position on the arbor;
- End-trim allowance for each board end: 16/16 inch.

For the ROMI-CROSS simulations the processing and control options were set up as follows:

- All parts and processing measurements are in inches;

• Part lengths are specified;

• Primary operations avoid orphan parts;

• Crosscuts optimized for best length fitting to board features;

• Scanner optimized for entire board length;

• Boards will be trimmed 1 inch on both ends;

• Chopsaw kerf is 2/16 inch; ripsaw kerf is 2/16 inch;

• Primary parts are C2F.

An important parameter of the simulations is the part prioritization strategy (Thomas 1997). Part prioritization strategy refers to the priority weighting that is placed on the different sizes of parts as the simulation progresses. For this research, the Complex Dynamic Exponent (CDE) strategy was used; a detailed description of this strategy, including equations for weighting factors, is given in a previous publication (Thomas 1996). The CDE strategy prioritizes parts based on their length, width, and required quantity. The number of attained parts and the remaining quantity requirements are constantly analyzed and priorities are continually reassigned based on the progress up to that point. Thus, in three different runs using the same cutting bill, the same board may yield different parts depending on when it is cut and the part priorities at that time.

Before running the simulations in Objective 1, several preliminary steps had to be completed. Thomas' Makefile program (Thomas 1997, Gatchell et al. 1998, Thomas 1999a), was used to create several board data files containing 3AC red oak boards. The new board files derived from digitizing the 1,500 BF of 3AC red oak lumber that was collected for this research were used along with the pre-existing 3AC board files (Gatchell et al. 1998). The 4-foot lumber (not used in this research) was removed from the 3AC data files. As a result, the complete 3AC board source for this research consisted of 314 digitally mapped boards (1,627 BF).

The "Grade/size mix file creation" option in Makefile was used to create a 3AC board file according to the 3AC width distribution set forth by Wiedenbeck et al. (2003) (17% = 5 in.; 43% between 5 and 6.75 in.; 27% between 7 and 8.75 in.; 10% between 9 and 10.75 in.; and 3% between 11 and 14.75 in. wide). Past research has shown that a minimum of 150 boards is desirable for a ROMI simulation – stable yield results are obtained when this many boards are used (i.e., adding more boards to the input data file does not have a significant influence on the results of the simulation) (Buehlmann et al. 1998). As a result, simulations in this research were designed to process at least 150 boards per simulation to ensure accurate yield results. The simulation input file for Objective 1 contained 173 3AC red oak boards, randomly selected by Makefile, having a total volume of approximately 954 BF.

The Mix-Master program (Thomas 1999a), which also comes with the ROMI simulation software, was used to create two more board files containing the same boards in a different random order. Thus, all three files used in addressing Objective 1 had the same number of boards, the same BF volume, the same width and length distribution, and the same amount and distribution of crook. All variables surrounding the simulations were held constant as well, except for the actual part sizes and quantity requirements of the five cutting bills. This ensured that any differences in part yield or cutting efficiency between simulations were attributed only to the part sizes and their required quantities in the cutting bills.

Once the board files were created and the arbors for each of the cutting bills were designed, the part quantities for the cutting bills had to be adjusted so that all the requirements of the cutting bills could be met with the 173 boards contained in the 3AC board files. In addition, it was equally important that at least 150 boards be used to meet the requirements in order to obtain accurate part yield estimations (Buehlmann et al. 1998). This determination of suitable part quantity 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 Part A, 50 parts for Part B, and 30 parts for Part C, the adjusted quantities would still maintain this 10:5:3 ratio).

Each of the 3AC board files (3 files) was processed through Cutting Bills A through E (5 cutting bills) using both ROMI-RIP and ROMI-CROSS (2 simulation programs); thus, 30 simulations were conducted in addressing Objective 1 (3 × 5 × 2). Cutting Bills A through E were each run once with each of the newly created 3AC red oak lumber data files. As a result, each cutting bill was run three times for ROMI-RIP and three times for ROMI-CROSS. A total of 15 simulations were conducted with ROMI-RIP and 15 were conducted with ROMI-CROSS for a total of 30 simulations.

Objective 2 methodology

In this objective, part yields and sawing efficiencies were compared for three different length groups of 3AC lumber. The lumber length groupings were: short (6 to 8 ft.), medium (10 to 12 ft.), and long (14 to 16 ft.). These groups were evaluated using ROMI-RIP and ROMI-CROSS with the two best cutting bills identified in Objective 1. Cutting Bills C and E were used for ROMI-RIP and Cutting Bills A and E were used for ROMI-CROSS. In analyzing the effects of lumber length on yield and sawing efficiency, it was important that the width and crook distributions of the short, medium, and long 3AC lumber files be the same. The same arbor setups, chopsaw setups, salvage specifications, and overall processing and control options listed previously were used in addressing this objective. The only differences were in the board files used and the number of parts of each size required by the cutting bills.

As described previously, the cutting bills were modified to ensure at least 150 boards would be used in each simulation. The two best rip-first and the two best crosscut-first cutting bills from Objective 1 were modified for each lumber length test level. For example, from rip-first Cutting Bill C, Cutting Bills Cs (short length), Cm (medium length), and Cl (long length) were created by adjusting the required part quantities for each lumber length. In all, 12 modified cutting bills were constructed. The part quantities were adjusted so that all the required part quantities could be satisfied and at least 150 boards would be used when processing the lumber length board files. Every other aspect of the cutting bills remained exactly the same as in the original Cutting Bill C.

Because the short-, medium-, and long-length 3AC lumber files for Objective 2 all contained substantially fewer than 150 boards, the input files for the Objective 2 simulations utilized boards

Table 3. — Average part yields and sawing efficiencies for five low-grade cutting bills based on ROMI-RIP and ROMI-CROSS simulations.[a]

ROMI-RIP results			ROMI-CROSS results		
Rip-first bill	Yield	Efficiency	Crosscut-first bill	Yield	Efficiency
	(%)			(%)	
A	36.8	6.8	A	**31.4**	**7.6**
B	18.2	8.9	B	18.8	6.6
C	**38.4**	**7.8**	C	37.1	9.3
D	14.0	7.7	D	14.3	3.7
E	**37.2**	**6.2**	E	**36.4**	**6.4**

[a]Efficiency is defined as the total number of sawkerf lines per BF of parts produced; highlighted in bold are the best cutting bills in terms of yield and sawing efficiency.

repeatedly. For example, board file short 3a, containing 26 boards, was processed seven times per simulation (26 × 7 = 182 boards). Using the same board more than one time in an input file is feasible because of the continual adjustments that are made to the lumber cut-up algorithm when the CDE prioritization strategy is used (Thomas 1996).

Recent research conducted by Zuo and Buehlmann (2002) looked at the variability of yield results from ROMI-RIP simulations achieved when using the same boards more than once. Yields were obtained for input board data sets made up of 1,000 BF of lumber, 500 BF of lumber with each board used twice (for a total of 1,000 BF), 250 BF of lumber with each board used four times, 62.5 BF (approximately 10 boards) of lumber with each board used 16 times, and 31.25 BF of lumber (approximately 5 boards) with each board used 32 times to once again construct an input file comprised of 1,000 BF. Statistical analysis found that the part yield results were not statistically different until the number of No. 1 Common (1C) boards used dropped to five (31.25 BF). Since greater between-board variability is expected for 3AC lumber than for 1C lumber, the minimum number of boards that could be used in a repeating sequence in a simulation input file was projected to be 10.

For Objective 2, each of the 12 cutting bills (short/medium/long length × rip/crosscut-first × Cutting Bills C and E or A and E) was run 3 times (3 replications using different board files). Therefore, a total of 36 simulations were conducted.

Statistical methodology

In addressing the objectives, analysis of variance (ANOVA) tests were conducted on the part yield and sawing efficiency results for both the ROMI-RIP and ROMI-CROSS simulations (α = 0.05). In addressing both Objectives 1 and 2, there were two sets of statistical tests conducted, one set addressing the dependent variable yield and the other addressing the dependent variable sawing efficiency. So, one null hypothesis under each objective was that there was no detectable yield difference between classes and the second null hypothesis was that there was no detectable difference in sawing efficiency between classes.

Tukey's Honestly Significant Difference (HSD) multiple comparison tests (α = 0.05) were conducted in cases where differences were indicated by the ANOVAs. The Tukey 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. Three replications were performed in each cell for each trial. The Statistical Package for the Social Sciences (SPSS©) was used for the statistical analyses.

For Objective 1, a one-way fixed effects ANOVA was conducted for each of the dependent variables: yield and efficiency. The classification variable in these models was cutting bill. Separate statistical tests were conducted on the crosscut and rip-first results. Thus, four null hypotheses were tested under this objective.

For Objective 2, a two-way fixed effects ANOVA was conducted for the dependent variables: yield and efficiency. The class variables in these models were cutting bill and lumber length. There were six basic null hypotheses tested under this objective: 1) there is no effect of cutting bill on mean part yield; 2) there is no effect of lumber length on mean part yield; 3) there is no interaction of cutting bill and lumber length on mean part yield; 4) there is no effect of cutting bill on mean cutting efficiency; 5) there is no effect of lumber length on mean cutting efficiency; and 6) there is no interaction of cutting bill and lumber length on mean cutting efficiency. Each null hypothesis was tested using first the rip-first simulation results and then the crosscut-first results (12 null hypotheses in total).

Lumber length class was the principal main effect of interest. However, by conducting the two-way ANOVA, the significance of the interaction effect between cutting bill and lumber length class could be examined.

Results and discussion

Objective 1: Assessing 3AC's performance with five cutting bills

For the rip-first simulations, the one-way ANOVA test for differences in yield between cutting bills was significant (α = 0.05), therefore we rejected the null hypothesis that yields obtained in rip-first processing are the same for all five cutting bills. Tukey's HSD indicated that the part yields were different for all cutting bills except A and E. Cutting Bill C had the highest part yield at 38.4 percent (**Table 3**). A and E were tied for the second best part yield at 36.8 and 37.2 percent. Cutting Bills B and D had much lower part yields at approximately 18.2 and 14.0 percent, respectively.

The ANOVA test for differences in manufacturing efficiency between cutting bills also was significant for the rip-first simulations leading us to reject the null hypothesis that cutting efficiencies realized in rip-first processing are the same for all cutting bills. Tukey's HSD indicated that all the sawing effi-

Table 4. — The impact of lumber length on average part yield and sawing efficiency when cutting 3AC lumber (Objective 2) in rip-first and crosscut first simulations.

Cutting bill	Board length	Part yield and sig. group[a]	Sawing efficiency[b] and sig. group[a]
	(ft.)	(%)	
Rip-first with ROMI-RIP			
	6 to 8	44.97 A	8.65 C
C	10 to 12	41.79 B	7.56 B
	14 to 16	41.97 B	7.05 A
	6 to 8	41.18 A	7.09 C
E	10 to 12	39.80 A	5.87 B
	14 to 16	37.18 B	5.41 A
Crosscut-first with ROMI-CROSS			
	6 to 8	34.49 A	8.01 A
A	10 to 12	31.19 AB	7.68 A
	14 to 16	27.89 B	7.96 A
	6 to 8	36.09 A	6.86 A
AE	10 to 12	36.34 A	6.55 A
	14 to 16	35.76 A	6.57 A

[a]Statistically dissimilar simulation group means have different letters assigned to them with A assigned to the group having the most favorable result.
[b]Kerf lines per BF of parts produced.

ciencies were different except for D and C. Cutting Bill E was the most efficient in processing 3AC lumber, followed by A, C, D and B. Cutting Bill E required approximately 6.2 cuts per BF of parts produced, A required 6.8, C required 7.8, D required 7.7, and B required 8.9 (**Table 3**). Although Cutting Bills A and E exhibited no difference in part yields, E was a more efficient cutting bill to process. As a result, Cutting Bills C and E were selected as the two best rip-first cutting bills in terms of yield and sawing 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.

For the ROMI-CROSS simulations, the null hypothesis of no difference between mean part yields for the five cutting bills also was rejected. Tukey's HSD indicated that all the part yields were different except for those of Cutting Bills C and E. The highest part yield was shared by 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 3**).

Finally, the null hypothesis of no difference between mean sawing efficiencies for the five cutting bills in crosscut-first processing was rejected. Tukey's HSD indicated that the sawing efficiencies associated with the five cutting bills were all different. The most efficient-to-cut crosscut-first cutting bill was D, followed by E, B, A, and C. Cutting Bill D required 3.7 cuts per BF of parts produced, E required 6.4, B required 6.6, A required 7.6, and C required 9.3 (**Table 3**). Cutting Bills C and E exhibited no difference in their part yields, however E was much more efficiently processed. 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.

There was a fairly distinct division of part yields in both the rip-first and crosscut-first simulations. Cutting Bills A, C, and E had much higher part yields than B and D (**Table 3**). Looking for differences between these cutting bills, Cutting Bill B had several medium to long parts between 40 and 80 inches and the required quantities for these parts were higher than those for the shorter parts (**Table 1**). Cutting Bill B also had several parts over 3 inches wide. Cutting Bill D only had five different part lengths and they were all 3 feet in length or longer. Cutting Bills A, C, and E had the shortest average part lengths with very few part requirements longer than 40 inches (**Table 1**). Narrow part widths, 3 inches or less, an abundance of short part lengths, 24 inches or less, and a scarcity of part lengths longer than 40 inches were characteristic of the best cutting bills in terms of part yields and, to a lesser extent, sawing efficiencies (especially for rip-first processing).

One of the best rip-first cutting bills selected in this objective originated from a rough mill producing cabinet parts (Cutting Bill C). Both the cabinet and the furniture industries require many parts 3 inches wide or narrower and many parts less than 40 inches in length. According to Araman (1982), 83 percent of the parts used in the manufacture of kitchen cabinets are 36 inches in length or shorter and 48 percent are 24 inches or shorter! Furthermore, 54 percent of the parts used in the manufacture of kitchen cabinets are 3 inches wide or narrower. Looking at furniture, 75 percent of the parts that go into the production of upholstered furniture and 93 percent of the parts that go into recliners are 36 inches long or shorter (Araman 1982). In fact, 35 and 65 percent of the parts needed for upholstered furniture and recliners, respectively, are 24 inches or shorter in length. Since 3AC lumber must have a minimum of 33 percent of its surface area contained in clear-face cuttings that are at least 2 feet by 3 inches in size (NHLA 1998), it seems plausible that significant portions of the parts required for cabinets, recliners, and upholstered furniture can be obtained from 3AC.

Objective 2: The effects of lumber length on 3AC part yields

Table 4 contains a summary of the average part yields and sawing efficiencies resulting from simulations conducted in Objective 2. The lumber length class variable was the principal main effect of interest. However, by running the two-way ANOVA, the significance of the interaction effect between cutting bill and lumber length class could be determined. It should be noted that there were three minor inconsistencies while running the ROMI-CROSS simulations. It is possible that the failure to fulfill all part requirements (2 of 6 short lumber simulations) and using less than 150 boards (1 of 6 short lumber simulations) created minor inaccuracies in the prediction of yield and sawing efficiency in the crosscut-first simulations. In all three cases, these were very small deviations, thus their effect on the results are assumed to be unimportant.

Analysis of the rip-first (ROMI-RIP) simulation results indicated that both main effects and the interaction effect in the yield model were significant. The difference in yields when processing different lumber lengths was highly significant ($p < 0.0001$), while the interaction between cutting bill and lumber length had a p-value of 0.035. Tukey's HSD indicated that the medium and long length lumber had statistically similar mean part yields, while the short lumber produced a significantly different (higher) mean part yield. The variable influence of lumber length on part yields for the two cutting bills (indicated by the significant interaction term) is readily observed. For rip-first Cutting Bill C, the mean part yield cut from the medium-length lumber was only 0.2 percent higher than the yield cut from the long-length lumber. The mean yield from the short lumber was 3.0 percent higher than the yield from the medium-length lumber. However, for Cutting Bill E, the medium-length lumber's mean yield was considerably higher than the long-length lumber's – 2.6 percent. The difference in the mean yields between the short- and medium-length lumber groups was not as significant for this cutting bill – only 1.4 percent.

Two of the three Objective 2 hypotheses concerning sawing efficiencies (kerf lines per BF of parts produced) in rip-first processing were rejected. Only the hypothesis of no interaction of cutting bill and lumber length on mean part yield was accepted. Tukey's HSD indicated that sawing efficiency was different for all three lumber lengths. The best sawing efficiency was experienced while running the long-length lumber followed by the medium- and short-length lumber. The long, medium, and short lumber required an average of approximately 6.2, 6.7, and 7.9 sawlines per BF of parts produced, respectively, for the two cutting bills combined. Using the mean efficiency measure for long-length lumber as our index, the efficiency ratio for rip-first processing was 1:1.1:1.3.

Analysis of the crosscut-first (ROMI-CROSS) simulation results indicated that both main effects and the interaction effect in the yield model were significant. The p-value for the test on lumber length's influence on yield was 0.013, while the test on the interaction between cutting bill and lumber length had a p-value of 0.023. Tukey's HSD indicated that the short-, medium-, and long-length lumber produced statistically dissimilar mean part yields. The variable influence of lumber length on part yields for the two cutting bills (indicated by the significant interaction term) is readily observed. For crosscut-first Cutting Bill A the mean part yield cut from the medium-length lumber was 3.3 percent higher than the yield cut from the long-length lumber. The mean yield from the short lumber was another 3.3 percent higher than the yield from the medium-length lumber. In contrast, for Cutting Bill E, the medium-length lumber's mean yield was only slightly higher than the long-length lumber's – 0.6 percent. In contrast to the other yield models examined under this objective, the short lumber group's mean yield for Cutting Bill E was actually slightly lower (0.2% less) than the medium lumber group's mean yield.

For the sawing efficiency model, the outcomes of the two-factor ANOVA test conducted on the 3AC crosscut-first simulation results indicated that the main effects were significant but the interaction effect was not (cutting bill*lumber length). When the sawing efficiency (average sawlines required per BF of parts produced) results of the two cutting bills are combined, the relationship between the long-, medium-, and short-length lumber was 7.1, 7.3, and 7.4, respectively – a statistically significant but relatively small difference.

A feasible explanation for the yield and sawing efficiency differences between lumber length groups can be deduced from the NHLA's grade rules (1998). Although there are no limitations to the number of grading cuttings that can be used to meet the minimum required clear area in 3AC lumber (33-1/3%), there are limitations on the number of cuttings that can be used when trying to meet the clear area requirement for No. 2A Common (2AC) lumber. As is true for all grades above 3AC, fewer grading cuttings are permissible for smaller boards. For example, a board with a surface measure of 2 or 3 (e.g., a board that is 6 in. by 6 ft.) can have a cutting yield as high as 66-1/3 percent and still only qualify to be a 3AC board if the clear area yield is contained in more that one square cutting (NHLA 1998). Since any board that will not qualify for 2AC because its clear areas are contained in too many cuttings will qualify as a 3AC board, more of the smaller (narrower and shorter) 3AC boards have a higher percentage of clear cuttings. This analysis appears to be supported by yield percentages that are given in the 1998 Data Bank for Kiln-Dried Red Oak Lumber (Gatchell et al. 1998). For the 3AC boards in the data bank, the average clear area contained in grading cuttings for 6- to 8-foot-long 3AC boards was 46 percent. For 10- to 12-foot-long 3AC boards, the average clear area also was 46 percent. However, for the 14- to 16-foot-long boards, the average clear area was only 41 percent.

In addition, differences in part yields and sawing efficiencies between cutting bills could have been due to the percentage of smaller parts composing the cutting bill. In rip-first Cutting Bill C, approximately 92 percent of the part lengths were less than 30 inches compared to approximately 53 percent for Cutting Bill E. The high percentage of smaller parts could have allowed Cutting Bill C to better utilize certain clear areas in a board. For example, if there was a clear face section in a board that was 32 inches long, more of this wood could be used cutting two 15.5-inch parts from it than one 30-inch part. This could have helped Cutting Bill C to achieve better part yields than Cutting Bill E in some situations. Further, this would also have decreased the sawing efficiency of a cutting bill since it may take several small parts to produce the same area as one large part.

Summary and conclusions

The goal of this research was to evaluate potential utilization opportunities for 3AC lumber. In a series of three studies, the impacts of cutting bill and lumber length on the yield and processing efficiency of the rough mill when processing 3AC lumber were explored. Both rip-first and crosscut-first rough mills were studied. Optimum processing conditions were assumed. Red oak lumber was processed into C2F parts. The two best (out of five) rip-first cutting bills were C and E. Their part yields when processing mixed lumber lengths were approximately 38 and 37 percent, respectively. Cutting Bill C required 7.8 cuts (sawkerfs) per BF of parts produced and Cutting Bill E required 6.2. The two best (out of five) crosscut-first cutting bills were A and E. Their part yields when processing mixed lumber lengths were approximately 31 and 36 percent, respectively. Cutting Bill A required 7.6 cuts per BF of parts produced and Cutting Bill E required 6.4.

Characteristics shared by the best cutting bills were narrow part widths and short part lengths. More specifically, cutting bills that call for the manufacture of 3-inch-wide or narrower part widths to at least 10 different lengths less than 40 inches long will achieve optimal part yield when processing 3AC lumber into C2F parts. As a result, operations that have a good opportunity for achieving optimal part yield while processing 3AC lumber are those rough mills that produce dimension parts, parts for cabinets, parts for smaller dimension case goods, upholstered furniture parts, and parts that will allow finger-jointing. Finger-jointing operations provide a great opportunity for 3AC lumber since finger-jointers typically can utilize wood blocks as short as 5 inches.

The results of Objective 2 indicated that when processing 3AC lumber in rip-first and crosscut-first rough mills, the highest yields will be experienced when running short lumber between 6 and 8 feet in length. For rip-first Cutting Bill C, the part yield for the short-length lumber was approximately 3 percent higher than that of the medium- and long-length lumber. The short-length lumber required 1.1 additional sawlines per BF of parts produced compared to the medium-length lumber and the medium-length lumber required 0.5 additional sawlines compared to the long-length lumber. For rip-first Cutting Bill E, the part yield for the short- and medium-length lumber was approximately 3 percent higher than that of the long-length lumber. However, the short-length lumber required 1.2 additional sawlines per board foot of parts produced compared to the medium-length lumber and the medium-length lumber required 0.5 additional sawlines compared to the long-length lumber.

For the crosscut-first Cutting Bill A, the part yield for the short-length 3AC lumber was approximately 6.6 percent higher than the yield from long-length lumber. Depending on the cutting bill, part yields similar to that experienced when running short-length lumber may be experienced while running medium-length lumber (10 to 12 ft.). Unfortunately, rip-first rough mills running shorter 3AC lumber should expect a decrease in sawing efficiency and more wear and tear on their equipment. On the other hand, sawing efficiency in a crosscut-first rough mill can be expected to stay relatively the same regardless of the length of lumber being processed.

Overall, for three of the four simulations conducted to examine the effect of lumber length on yields and processing efficiency when cutting 3AC lumber, higher yields were obtained from the shortest lumber group. However, for two of the four simulations, lower efficiency was obtained when cutting the short lumber.

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. Although a limited number of cutting bills were examined in this study (five), the wide range of part yields (14% to 38%) and cutting efficiencies obtained from 3AC lumber demonstrates how important it is for rough mills to carefully consider how to incorporate a higher percentage of this grade into their lumber mix.

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