EFFECT OF CUTTING BILL REQUIREMENTS ON LUMBER YIELD IN A RIP-FIRST ROUGH MILL

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ABSTRACT

In recent years, producers of solid wood dimension parts have emphasized improvements in lumber yield, focusing primarily on lumber grade and cutting technology rather than cutting bill design. Yet, cutting bills have a significant impact on yield. Using rip-first rough mill simulation software, a data bank of red oak lumber samples, and a cutting bill that resembles those used in industry, we determined the effect of changes in part size within an existing cutting bill and the impact of part-quantity requirements on yield. The results indicated that cutting bill requirements have a large influence on yield when the shortest part length in the bill is changed. Medium-length part sizes also affect yield except when the cutting bill requires an unlimited number of small parts; in this case, yield always will be high. When an all-blades-movable arbor is used, length changes in the bill affect yield more than changes in width. This study reveals our current lack of understanding of the complex relationship between cutting bill and lumber yield, and points out the yield gains that are possible when properly designed cutting bills are used.

Keywords: Cutting bill requirements, lumber yield, rip-first rough mill, response surface, interaction between cutting bills and yield.

INTRODUCTION

Solid-wood dimension parts are rectangular pieces cut in the rough mills of furniture, cabinet, and dimension-parts plants according to a list of needed part sizes called a cutting bill. The objective of a rough mill is to produce dimension parts at the lowest overall cost within the quality and quantity parameters required by the cutting bill. Lumber yield is the most commonly used measure of efficiency in a rough mill. Yield is defined as the ratio of (part) output surface area to (lumber) input surface area (Gatchell 1985).

The cost of lumber accounts for about 70% of total direct processing costs (material and

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processing costs) incurred in a rough mill (Anonymous 2000; Wengert and Lamb 1994), and as much as half of the total production cost of a piece of furniture (Anonymous 2000; West and Hansen 1996; Anonymous 1984). A 1% savings in raw material (i.e., increasing yield by 1%) potentially saves 2% of total production costs (Kline et al. 1998; Wengert and Lamb 1994). Higher yield not only saves raw material but also can increase production capacity because fewer boards are needed to obtain the same output.

Producing dimension stock from lumber is a manufacturing step unknown in other industries (Anonymous 1979). Lumber must be cut in such a way as to obtain all of the parts listed in a cutting bill while simultaneously maximizing yield. This process is complicated because lumber is a heterogeneous raw material with unusable areas (e.g., character marks or defects) of varying size (Brunner et al. 1990). Mathematical solutions, which could provide optimum results and fast computing, exist only for simplified cases of the lumber cut-up problem (Carnieri et al. 1993). Owing to the lack of broadly applicable mathematical models to optimize lumber cut-up, computer simulation techniques are widely used (Wiedenbeck and Kline 1994). Computer simulations incorporate either exhaustive search methods or heuristic approaches (Brunner et al. 1990). Thomas (1999, 1997) and Harding and Steele (1997) developed the most widely used rough mill simulation models. These models allow researchers and practitioners to gain a better understanding of the complex relationships that govern lumber yield in rough mills.

Cutting bill requirements that have a major effect on yield include geometric, qualitative, and quantitative part parameters (BC Wood Specialties Group 1996; Buehlmann 1998; Buehlmann et al. 1999, 1998; Wengert and Lamb 1994). Specifically, they refer to part-quality requirements, the size of individual parts in a cutting bill, the distribution of these sizes, and the individual quantities of parts required.

Compared to other issues related to rough mill operations, the effect of cutting bill on yield is largely ignored. In fact, there are no studies on the relationship between cutting bill requirements and lumber yield. An exception is the work on yield nomograms by Thomas (1965), Englerth and Schuman (1969), Dunmire (1971), Hallock (1980), and Manalan et al. (1980). However, these researchers did not focus on understanding the relationships between cutting bill requirements and yield, but instead on estimating lumber yield for cutting bills based largely on the part dimensions included in the cutting bills.

Buehlmann et al. (1998) researched potential yield increases due to the inclusion of character marks in furniture parts and found that different cutting bill requirements used in industry can lead to yield differences greater than 15% in a rip-first rough mill. Cutting bill factors hypothesized to explain such varied yield results include the number of different part sizes, quantity of each part size, and distribution of part lengths and widths including their interaction. The importance of the different factors affecting yield outcomes and how they interact is poorly understood.

Clearly, cutting bill yields are determined by more than one factor. By gaining a better understanding of the relationship between cutting bill requirements and yield, producers will be able to better predict, control, and increase lumber yield. Currently, questions such as ‘‘Are there ways to increase lumber yield by combining specific parts into the same cutting bill?’’ or ‘‘Should a producer reject certain parts that will decrease a mill’s yield?’’ cannot be answered with a high degree of confidence. The purpose of this study was to determine the effect of both part size and part-quantity requirements on the yield of rough parts from lumber.

METHODS

We used rip-first rough mill simulation software and a data bank of red oak boards to mimic real operations. For the entire test series, all operating parameters, except for cut-

TABLE 1. *Setup of ROMI-RIP simulation input: a ''C'' in the left margin indicates a parameter that was constant for all simulations, a ''V'' indicates a parameter that was varied between simulations.*

Part Definitions					
V	Part Lengths (in.)				
	13.00	29.00	45.00	61.00	77.00
V	Part Widths (in.)				
	1.50	2.25	3.25	4.25	
C	Primary Operations Avoid Orphan Parts				
Arbor Setup					
C	Arbor type is All-Blades Movable				
C	Arbor has 15 spacings defined				
C	Processing board from Right edge of board to Left edge				
Trimming					
C	Boards will be edged 0.25 inch on both sides				
C	Boards will be trimmed 0.25 on both ends				
Salvage					
C	Salvage uses primary widths				
C	Salvage uses primary lengths				

ting bill requirements, were held constant to obtain unbiased information on the effect of cutting bill on lumber yield.

Rip-first rough mill yield simulation

We used version 1.0 of the ROMI-RIP rough mill yield simulation program (Thomas 1995a, b). The ROMI-RIP setup was the same as that for an earlier study (Buehlmann et al. 1998) and is shown in Table 1. To avoid bias owing to sub-optimal arbor set-ups and arbor spacing-part size-board size influences, we used the all-blades movable arbor set-up option available in ROMI-RIP. All yield figures reported are absolute values and consist of primary and smart salvage yields reported in ROMI-RIP. Fingerjointed or glued-up parts were excluded and only clear-two-face (C2F) parts were produced.

Lumber

Red oak is one of the most important species used for furniture in the United States (Hansen et al. 1995; Meyer et al. 1992; Vlosky 1996). No. 1 Common lumber is the grade most widely used by furniture, kitchen, and dimension producers, although 2A Common and 3A Common grades are gaining in importance.

No. 1 Common red oak boards from the ''1998 Data Bank for Red Oak Lumber'' (Gatchell et al. 1998) were used for this study. The lumber samples were selected randomly from the boards available in Gatchell et al.'s (1998) data bank using the ''CUSTOM DATAFILE CREATION'' feature of ROMI-RIP. Our cutting bill requirements were set up so that at least 150 boards were needed to obtain all parts. This minimum lumber sample size was used to reduce bias (see Buehlmann et al. (1998) for a complete explanation).

Cutting bills

To determine the effect of part size on yield, cutting bill part sizes were changed systematically and incrementally. For these tests, we limited usable part sizes to lengths ranging from 5 to 85 inches and widths from 1.00 to 4.75 inches. A prior analysis of 40 cutting bills showed that more than 90% of all nonglued, nonfingerjointed part sizes were within these part size limits (Buehlmann 1998). We created a ''cutting-bill-part-size space'' with two dimensions (Fig. 1) by assigning length to the

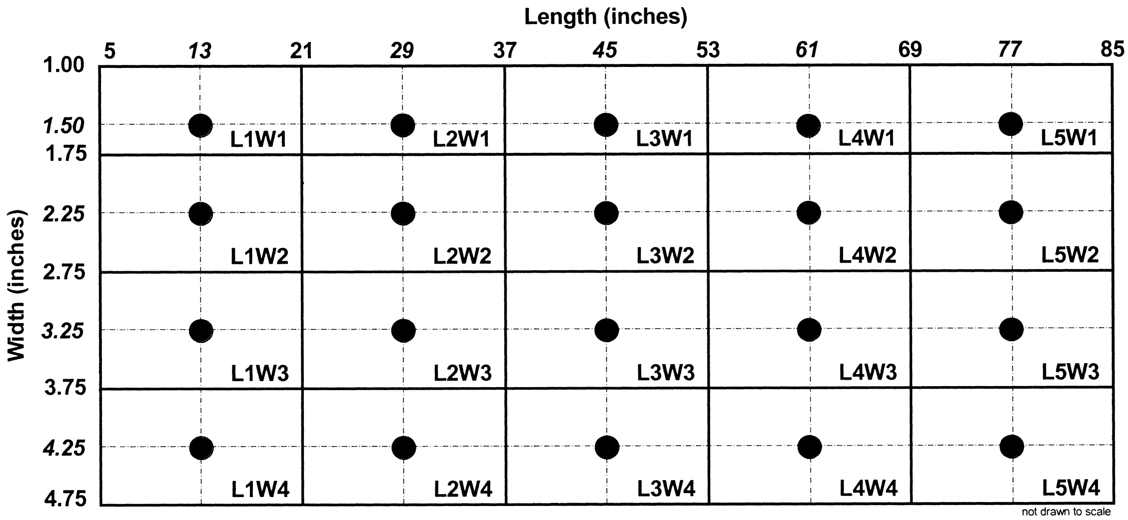

FIG. 1. Cutting bill-part size space ranging in length from 5 to 85 inches and in width from 1.00 to 4.75 inches.

X-axis and width to the Y-axis of a graph. The space was then divided evenly into five length and four width groups. The geometric midpoint of each of these groups was assigned the notation L_x for length and W_y for width, where $x = 1, 2, 3, 4, 5$ and $y = 1, 2, 3, 4$. The smaller number denotes smaller part sizes. For example, the largest part group, denoted L_5W_4, describes parts ranging in length from 69 to 85 inches and in width from 3.75 to 4.75 inches. The geometric midpoint of part group L_5W_4 is 77 inches long and 4.25 inches wide. The 20 geometric midpoints shown in Fig. 1 form the standard cutting bill for the tests. This cutting bill is given in Table 2.

TABLE 2. *Cutting-bills and part quantities used.*

Part no.	Standard part length (inches) Part name	Length	Width	Quantity used (number) Araman	Unlimited[a]	Even
1	L_1W_1	13	1.50	172		50
2	L_2W_1	29	1.50	154		50
3	L_3W_1	45	1.50	57		50
4	L_4W_1	61	1.50	30		50
5	L_5W_1	77	1.50	19		50
6	L_1W_2	13	2.25	336		50
7	L_2W_2	29	2.25	283		50
8	L_3W_2	45	2.25	108		50
9	L_4W_2	61	2.25	68		50
10	L_5W_2	77	2.25	32		50
11	L_1W_3	13	3.25	136		50
12	L_2W_3	29	3.25	140		50
13	L_3W_3	45	3.25	58		50
14	L_4W_3	61	3.25	40		50
15	L_5W_3	77	3.25	23		50
16	L_1W_4	13	4.25	92		50
17	L_2W_4	29	4.25	93		50
18	L_3W_4	45	4.25	36		50
19	L_4W_4	61	4.25	10		50
20	L_5W_4	77	4.25	13		50

[a] Unlimited quantity.

From Fig. 1 it can be observed that the midpoints for the four cells in the smallest width group (i.e., part groups L_1W_1, L_2W_1, L_3W_1, and L_4W_1) are not at the geometric midpoints (which would be at 1.375 inches) but instead are set at 1.50 inches because ROMI-RIP rounds all measurements to the nearest quarter inch. However, since this higher width is applied to all tests, it did not affect our comparative results.

The first series of tests were designed to detect the effect of changes in part size within a given cutting bill on part yield. To do this, we altered only one part-size dimension at a time. We began by altering part lengths while maintaining part widths at their midpoint levels. For example, to observe how yield varied when the third part-length (described by L_3W_y) changed from 45 inches to another val-

TABLE 3. *Example of the nine tests for length-group 3 (in inches).*

	Standard part sizes			Test for L_3W_y								
No.	Part name	Length	Width	L_3-test 1	L_3-test 2	L_3-test 3	L_3-test 4	L_3-test 5	L_3-test 6	L_3-test 7	L_3-test 8	L_3-test 9
1	L_1W_1	13	1.50	13	13	13	13	13	13	13	13	13
2	L_2W_1	29	1.50	29	29	29	29	29	29	29	29	29
3	L_3W_1	45	1.50	37[a,b]	39[a]	41[a,b]	43[a]	45[a,b]	47[a]	49[a,b]	51[a]	53[a,b]
4	L_4W_1	61	1.50	61	61	61	61	61	61	61	61	61
5	L_5W_1	77	1.50	77	77	77	77	77	77	77	77	77
6	L_1W_2	13	2.25	13	13	13	13	13	13	13	13	13
7	L_2W_2	29	2.25	29	29	29	29	29	29	29	29	29
8	L_3W_2	45	2.25	37[a,b]	39[a]	41[a,b]	43[a]	45[a,b]	47[a]	49[a,b]	51[a]	53[a,b]
9	L_4W_2	61	2.25	61	61	61	61	61	61	61	61	61
10	L_5W_2	77	2.25	77	77	77	77	77	77	77	77	77
11	L_1W_3	13	3.25	13	13	13	13	13	13	13	13	13
12	L_2W_3	29	3.25	29	29	29	29	29	29	29	29	29
13	L_3W_3	45	3.25	37[a,b]	39[a]	41[a,b]	43[a]	45[a,b]	47[a]	49[a,b]	51[a]	53[a,b]
14	L_4W_3	61	3.25	61	61	61	61	61	61	61	61	61
15	L_5W_3	77	3.25	77	77	77	77	77	77	77	77	77
16	L_1W_4	13	4.25	13	13	13	13	13	13	13	13	13
17	L_2W_4	29	4.25	29	29	29	29	29	29	29	29	29
18	L_3W_4	45	4.25	37[a,b]	39[a]	41[a,b]	43[a]	45[a,b]	47[a]	49[a,b]	51[a]	53[a,b]
19	L_4W_4	61	4.25	61	61	61	61	61	61	61	61	61
20	L_5W_4	77	4.25	77	77	77	77	77	77	77	77	77

[a] Denotes part lengths that changed for the tests described.
[b] Denotes part lengths used in the 2nd series of tests.

ue, we simultaneously adjusted the length of all parts in the cutting bill whose standard length was 45 inches (parts L_3W_1, L_3W_2, L_3W_3, and L_3W_4). To observe the effect of changing this length over the entire range represented by the 45-inch-long parts (from 37 to 53 inches), we first altered the standard length for all parts from 45 to 37 inches (the lower boundary of the L_3 group). After testing yield using this cutting bill configuration (with $L_3 =$ 37 inches), we tested $L_3 = 39$ inches, then $L_3 = 41$ inches and so forth until we reached $L_3 = 53$ inches. Note that lengths in the other length groups were held constant, as was width for all length groups. This resulted in nine cutting bills ($L_3 = 37$, 39, 41, 43, 45, 47, 49, 51, and 53 inches) for length group L_3 (Table 3). This procedure was repeated for the other four length groups resulting in a total of five separate length-group experiments (L_1, L_2, L_3, L_4, L_5). There were three replicates for each cutting bill.

Similarly, to observe the influence of changing part widths over the standard width range represented by the second part-width group (W_2 widths ranging from 1.75 to 2.75 inches in width, with midpoint at 2.25 inches), we altered the standard width for all W_2 parts. During these width tests, length was held constant at each part's standard length. This resulted in five tests or levels for width group W_2 (W_2 = 1.75, 2.00, 2.25, 2.50, and 2.75 inches). Four separate width group-experiments were carried out (W_1, W_2, W_3, W_4). The cutting bills for the width tests for group W_2 are included in Table 4. Again, there were three replicates for each cutting bill.

Using this methodology, we created 64 cutting bills, 45 for length (5 tests $\times$ 9 levels) and 19 for width (3 tests $\times$ 5 levels + 1 test $\times$ 4 levels; only 4, ¼-inch increments were possible for W_1). Since there were three replicates for each of the 64 cutting bills, a total of 192 tests were conducted.

To learn how part quantities affect yield for different cutting bills, we added three part-quantity assignment systems (schedules) to these tests. Having specified the part sizes for each test, part-quantity requirements were assigned to the 20 part groups within the 64 cut-

TABLE 4. *Example of the five tests for width-group 2 (in inches).*

		Standard part size		Tests for L_xW_2				
No.	Name	Part length	Width	W_2-test 1	W_2-test 2	W_2-test 3	W_2-test 4	W_2-test 5
1	L_1W_1	13	1.50	1.50	1.50	1.50	1.50	1.50
2	L_2W_1	29	1.50	1.50	1.50	1.50	1.50	1.50
3	L_3W_1	45	1.50	1.50	1.50	1.50	1.50	1.50
4	L_4W_1	61	1.50	1.50	1.50	1.50	1.50	1.50
5	L_5W_1	77	1.50	1.50	1.50	1.50	1.50	1.50
6	L_1W_2	13	2.25	1.75[a]	2.00[a]	2.25[a]	2.50[a]	2.75[a]
7	L_2W_2	29	2.25	1.75[a]	2.00[a]	2.25[a]	2.50[a]	2.75[a]
8	L_3W_2	45	2.25	1.75[a]	2.00[a]	2.25[a]	2.50[a]	2.75[a]
9	L_4W_2	61	2.25	1.75[a]	2.00[a]	2.25[a]	2.50[a]	2.75[a]
10	L_5W_2	77	2.25	1.75[a]	2.00[a]	2.25[a]	2.50[a]	2.75[a]
11	L_1W_3	13	3.25	3.25	3.25	3.25	3.25	3.25
12	L_2W_3	29	3.25	3.25	3.25	3.25	3.25	3.25
13	L_3W_3	45	3.25	3.25	3.25	3.25	3.25	3.25
14	L_4W_3	61	3.25	3.25	3.25	3.25	3.25	3.25
15	L_5W_3	77	3.25	3.25	3.25	3.25	3.25	3.25
16	L_1W_4	13	4.25	4.25	4.25	4.25	4.25	4.25
17	L_2W_4	29	4.25	4.25	4.25	4.25	4.25	4.25
18	L_3W_4	45	4.25	4.25	4.25	4.25	4.25	4.25
19	L_4W_4	61	4.25	4.25	4.25	4.25	4.25	4.25
20	L_5W_4	77	4.25	4.25	4.25	4.25	4.25	4.25

[a] Denotes part widths that changed for the tests described.

ting bills. This allowed us to observe the interactions between part sizes and part quantities. The following schedules were used:

1. We derived individual-part quantities based on the results by Araman et al. (Araman et al. 1982), which gave cutting bill requirements for different dimension part-producing sectors of the secondary wood industry. Our part-quantity requirements for individual parts were determined by overlaying our cutting bill-part size space onto the results in Araman's work. The sum of part quantities within each individual part group was taken as the required part quantity for each of the 20 part groups, respectively. Sizes beyond our cutting bill-part size space were discarded. The actual number of required parts was set so that for all tests, a minimum of 150 boards was needed to fulfill the cutting bill requirements (Table 2).
2. We did not set a limit on the number of parts of each size to be cut. For each part, we entered an artificially high number (32,000) as the required quantity so that the prioritization strategy of ROMI-RIP would not influence which parts were cut (Table 2). This system forces ROMI-RIP to cut for maximum yield.
3. We specified the same quantity of all parts (50 parts of each), indicating that we wanted to obtain the same number of parts for all sizes. Although this system is not realistic, it allowed us to compare the impact of changes in part-quantity requirements (Table 2).

Using these three schedules, we tested each of the 64 cutting bills with three replications of each (total: 576 test runs). Thus, there were two factors in each experiment, namely, dimension (length or width) and schedule. We conducted an ANOVA to test for factor effects in the two types of experiments. Interaction terms were included initially for each experiment. Interaction terms that were not significant ($\alpha = 0.05$) were removed from the model. Homogeneity of variance and normality of the error terms were evaluated. The generalized model for the length experiments is as follows:

$$\text{Yield} = f(\text{length, schedule, length} \times \text{schedule}) \quad (1)$$

and for the width experiments is as follows:

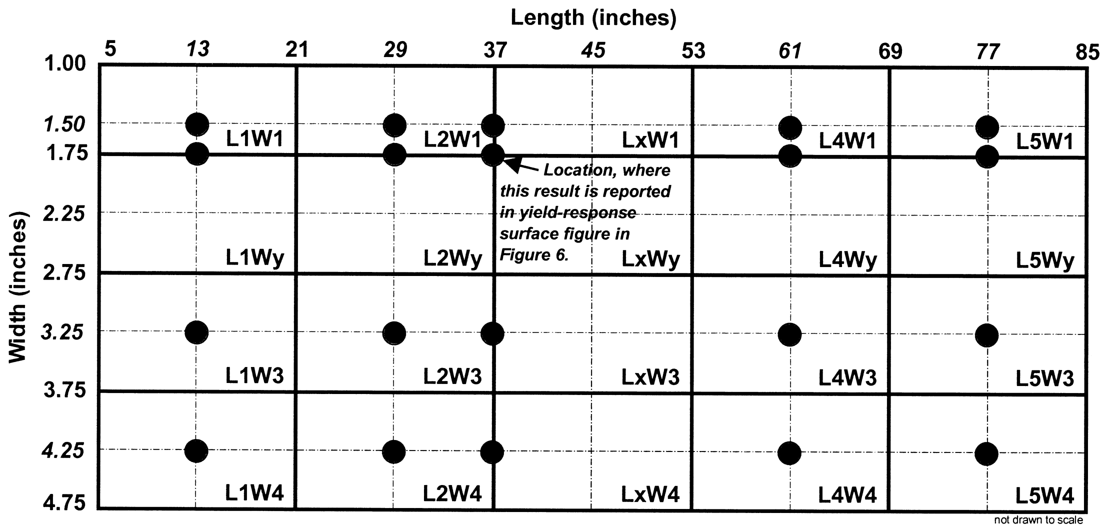

FIG. 2. Cutting bill-part size space with sizes for the L_xW_y case indicated by dots.

$$\text{Yield} = f(\text{width, schedule, width} \times \text{schedule}) \quad (2)$$

For factors that were significant, pairwise comparisons of the factor levels were conducted using a Tukey adjustment for multiple comparisons. Thus the experiment-wise level of significance was held constant at the 0.05 level.

TABLE 5. *Cutting bill for the L_xW_y case (in inches).*

	Standard part sizes			Part sizes for L_XW_Y		
No.	Part name	Length	Width	Part name	Length	Width
1	L_1W_1	13	1.50	L_1W_1	13	1.50
2	L_2W_1	29	1.50	L_2W_1	29	1.50
3	L_3W_1	45	1.50	L_XW_1	37[a]	1.50
4	L_4W_1	61	1.50	L_4W_1	61	1.50
5	L_5W_1	77	1.50	L_5W_1	77	1.50
6	L_1W_2	13	2.25	L_1W_2	13	1.75[b]
7	L_2W_2	29	2.25	L_2W_2	29	1.75[b]
8	L_3W_2	45	2.25	L_XW_2	37[a]	1.75[b]
9	L_4W_2	61	2.25	L_4W_2	61	1.75[b]
10	L_5W_2	77	2.25	L_5W_2	77	1.75[b]
11	L_1W_3	13	3.25	L_1W_Y	13	3.25
12	L_2W_3	29	3.25	L_2W_Y	29	3.25
13	L_3W_3	45	3.25	L_XW_Y	37[a]	3.25
14	L_4W_3	61	3.25	L_4W_Y	61	3.25
15	L_5W_3	77	3.25	L_5W_Y	77	3.25
16	L_1W_4	13	4.25	L_1W_4	13	4.25
17	L_2W_4	29	4.25	L_2W_4	29	4.25
18	L_3W_4	45	4.25	L_XW_4	37[a]	4.25
19	L_4W_4	61	4.25	L_4W_4	61	4.25
20	L_5W_4	77	4.25	L_5W_4	77	4.25

[a] Denotes part lengths that changed for tests described.
[b] Denotes part widths that changed for tests described.

In the second series of tests, we sought to assure that the yield results detected in the first test series represented the entire cutting bill space shown in Fig. 1. We performed yield tests for the case when both length and width were changed simultaneously for each length and width group. For example, when part length L_3 was set at 37 inches (from 45 inches), we simultaneously set part width W_2 at 1.75 inches (from 2.25 inches). Thus, parts 3, 8, 13, and 18 were set to a length of 37 inches (instead of 45 inches) and part numbers 6, 7, 8, 9, and 10 to 1.75 inches in width (instead of 2.25 inches). All the other lengths and widths in the standard cutting bill remained unchanged. Figure 2 and Table 5 show this new cutting bill; the yield result is reported at the point on the matrix given by the coordinates 37 × 2.75 inches. These tests were performed at length increments of 4 rather than 2-inch increments (i.e., 5, 9, 13, 17, . . . , 77, 81, and 85 inch lengths) and quarter-inch width increments. The Araman part quantity distribution was used for these tests. Thus, 475 tests (19 width combinations × 25 length

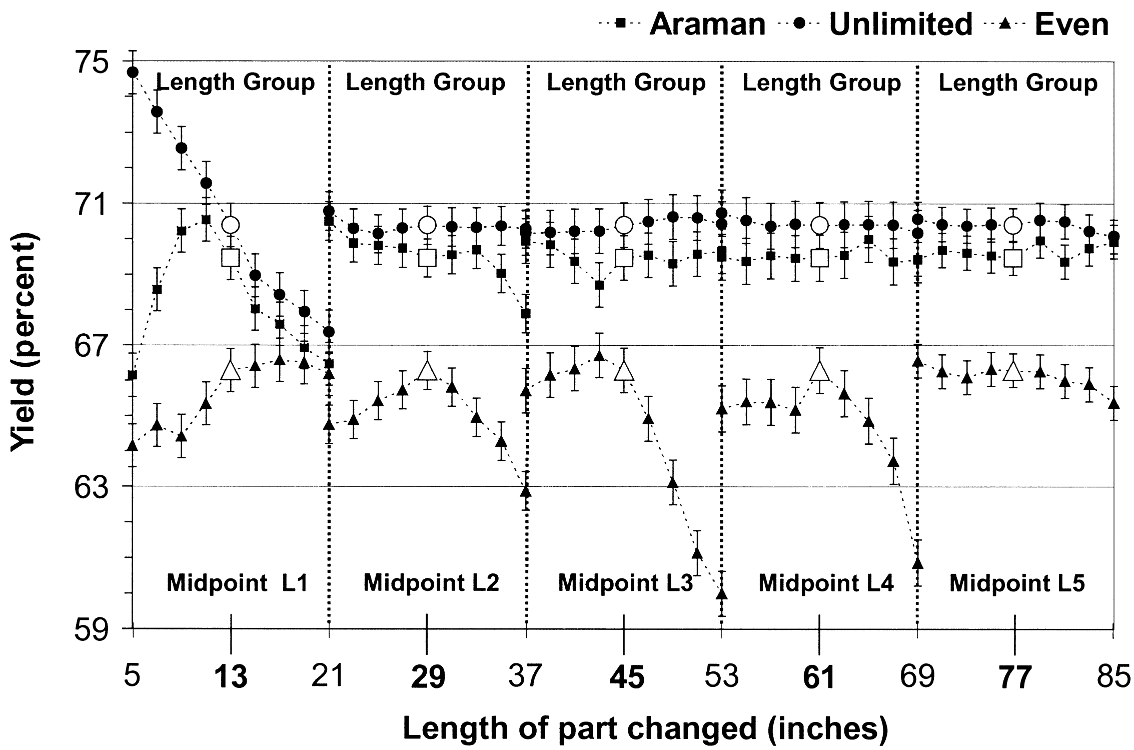

FIG. 3. Effect of length on yield for three part-quantity requirements.

combinations) with 3 replications for each (1,425 simulation runs) were performed.

RESULTS AND DISCUSSION

Effect of cutting bill length

The effect of systematic, incremental changes in part length on rough mill part yield based on the first series of tests is shown in Fig. 3. For the length range and the board length distribution examined in these tests, the maximum observed yield ranges were 4.4, 7.3, and 6.7%, respectively, for the Araman, Unlimited, and Even schedules.

Analysis of the yield results of each of the five length-group experiments revealed interaction effects between length and schedule. For each length group, the effects of length are dependent on the schedule that is used when processing boards. Thus, for all length groups, the following model applies:

$$\text{Yield} = f(\text{length, schedule, length} \times \text{schedule}) \quad (3)$$

The three schedules are shown in Fig. 3 for visual comparisons. Figure 3 also shows cutting yields for simulation experiments in which the targeted standard-length groups are changed to the lengths indicated on the X-axis. For example, when the observations for group L_1 were made, only the lengths for parts with the midpoint at 13 inches (parts 1, 6, 11, and 16 from Table 2) were changed to 5 inches. The other 16 part lengths remained at their midpoints (29, 45, 61, and 77 inches). Widths remained unchanged during all tests for length. The variations within and between the yield curves for each of the part quantity assignment systems are discussed below.

Case 1: Effect of changes in cutting bill lengths using industry-based (Araman) part quantities.—Given a cutting bill with part quantities required according to Araman et al. (1982), there exists an optimum length for L_1 for maximizing yield (Fig. 3). Interestingly, test results indicated that maximum yield was not obtained when L_1 was shortest (5 inches) but rather when it was 11 inches. Yields were 4.4 and 4.1% lower for shorter and longer L_1 parts, respectively. Strip area was used most effectively by 11-inch-long parts. When L_1 was set to a shorter length, the shorter parts were so easily obtained that their quantity limit was reached before that of other parts on the cutting bill. Longer parts were not as easily obtained as 11-inch and shorter parts due to the limited length of remaining clear areas. The optimum value for the shortest part length in a given cutting bill will fluctuate according to the length of the other parts required, the schedule, and the lumber characteristics.

When the second shortest part group (L_2) is changed and the other groups are maintained at their representative midpoints, the yield is high when group L_2 is set at its shortest length (21 inches). As L_2's length increases, however, yield is reduced and reaches a minimum when set at 37 inches, the longest length tested for group L_2. When the L_2 parts were 37 inches long, yield was 2.6% below that recorded for the test when L_2 was only 21 inches. This result highlights the importance of having more than one shorter cutting length in sufficient quantity in a cutting bill to obtain a high yield, given restricted quantity requirements.

When part lengths within the longer length groups (L_3, L_4, and L_5) are changed, the impact on yield is less pronounced because the Araman cutting bill requires sufficient short parts (74% of all parts are in groups L_1 and L_2) such that the impact on yield from changing longer lengths is relatively small. This supports the theory that when there are enough short parts required by a cutting bill, the longer parts have little effect on yield.

Case 2: Effect of changes in cutting bill lengths using unlimited part quantities.—The Unlimited part-quantity studies also lend support to the theory that given a cutting bill with an adequate number of short parts, changes in the length of longer parts have a minimal effect on yield. In this case, the only length that affected yield to a large degree was the shortest length in the cutting bill. Variations in the other lengths have little impact on yield because an unlimited quantity of short parts can be cut from any remaining clear area of a board. Thus, no unused, clear lumber will accumulate that is longer than the shortest part required. This sheds light on why producing fingerjointed parts can dramatically improve rough mill yield. Since fingerjointers require an essentially unlimited quantity of clear-wood feedstock in lengths as short as 4 to 5 inches, the results for the unlimited schedule are applicable. Under certain circumstances, a mill with a minimum cutting length of 13 inches that introduces fingerjointing can increase yield by as much as 6% (Fig. 3). However, since primary parts are more highly valued, rough mills with fingerjointing capacity should maintain vigilance to ensure optimal primary cutting yields.

For length groups 2 through 5, there is substantial overlap of mean yield confidence intervals between the Araman and Unlimited schedules for the different length levels. Overlap indicates a lack of significant differences between the part-scheduling systems (Fig. 3).

Case 3: Effect of changes in cutting bill lengths using even part quantities.—The yield curves for the scenario in which we specified even part quantity requirements for all parts (50 parts of each) are more difficult to interpret (Fig. 3). Since short parts accumulate at a much faster rate during cut-up than longer ones (i.e., they are easier to obtain), yield suffers when the cutting bill calls for a relatively small quantity of short parts. This is the primary reason why the Even yield curves in Fig. 3 have generally lower yield outcomes than the Araman and Unlimited schedules (cases 1 and 2).

When the quantity of shorter parts is limited, cutting longer lengths in length groups L_2, L_3, and L_4 begins to have a negative effect on yield. Differences in length groups 2 through 4 for the Even schedule are significant owing to different yields between the midpoint length's result (which is higher) and the yield result for the case where the length for the group is set at its longest length. For example, when the length of parts in group L_3 changes from 43 to 53 inches (with all other part sizes remaining constant), yield drops by 6.7%.

The longest-length group (L_5), with a range of 69 to 85 inches, apparently has little effect on yield even when short parts are less dominant. The only statistically significant difference in yield for this length group was between the shortest and longest lengths in the group. These longer parts are so difficult to obtain that an incremental increase in length has a minimal effect on yield.

The form of the yield curves for individual parts (except for the L_5 curve) for the Even schedule is similar to that of the curve of the shortest group (L_1) for Case 1 (industry-based part quantity assignment system). Two of the interpretations cited in the discussion of how changes in L_1 affect yield under Case 1 would seem to apply to the Case 3 curves. Because there are clear areas available from which to obtain the midrange part lengths within each group, recovering the midrange lengths rather than the shorter lengths in these groups produces higher yield (since the number of board feet per part will be higher for the longer part lengths). However, when the cutting bill length for the groups is at the longer end of the group range, shorter clear areas on the boards cannot be used and cuttings must be obtained from areas that otherwise would yield one or more of the longer part lengths.

Comparison of cases

Yield results for length group L_1 for the three cases (representing the three different part scheduling systems) are of particular interest since they demonstrated substantial within and between schedule differences for the different levels of length. For the Unlimited schedule, mean yield decreased with increases in length. For this case, when L_1 was short, the remaining clear areas were used effectively and little waste was created. When L_1 was longer, larger board sections went unused because even the shortest part would not fit. When an unlimited number of short parts can be produced, yield will always be higher for cutting bills with shorter L_1 parts.

In contrast, there was a trend toward increased yield when L_1 part lengths increased for the Even schedule. Since only a limited quantity of L_1 parts could be produced, yield increased with increasing length since those parts that were cut contained more area.

The Araman (industry-based) schedule produced maximum yields when L_1 was near the midpoint of the length group. In this scenario, when parts were very short, they were quickly obtained, after which there remained no options for using shorter board sections. When the shortest part requirement was too long, shorter, clear board sections were wasted throughout the production run.

Effect of cutting bill width

Cutting bill width, at least over the width range and for the distribution of board widths examined in these tests, does not seem to have the same effect on yield as length. The maximum observed yield range for tests of width was 2.2, 1.8, and 2.4%, respectively for Araman, Unlimited, and Even quantities. For length, these values were 4.4, 7.3, and 6.7%. These simulation results confirm that yield variability due to changes in width are less pronounced than for length (Fig. 4). This finding is supported statistically in that there were significant interaction effects ($\alpha = 0.05$) only for width groups 2 and 4. The model for these two groups is as follows:

$$\text{Yield} = f(\text{width, schedule, width} \times \text{schedule}). \quad (4)$$

There were no statistically significant interaction effects for width groups 1 and 3 ($\alpha = 0.05$). There were, however, width effects and schedule effects for both groups as can be seen in Fig. 4. The model for these two width groups is as follows:

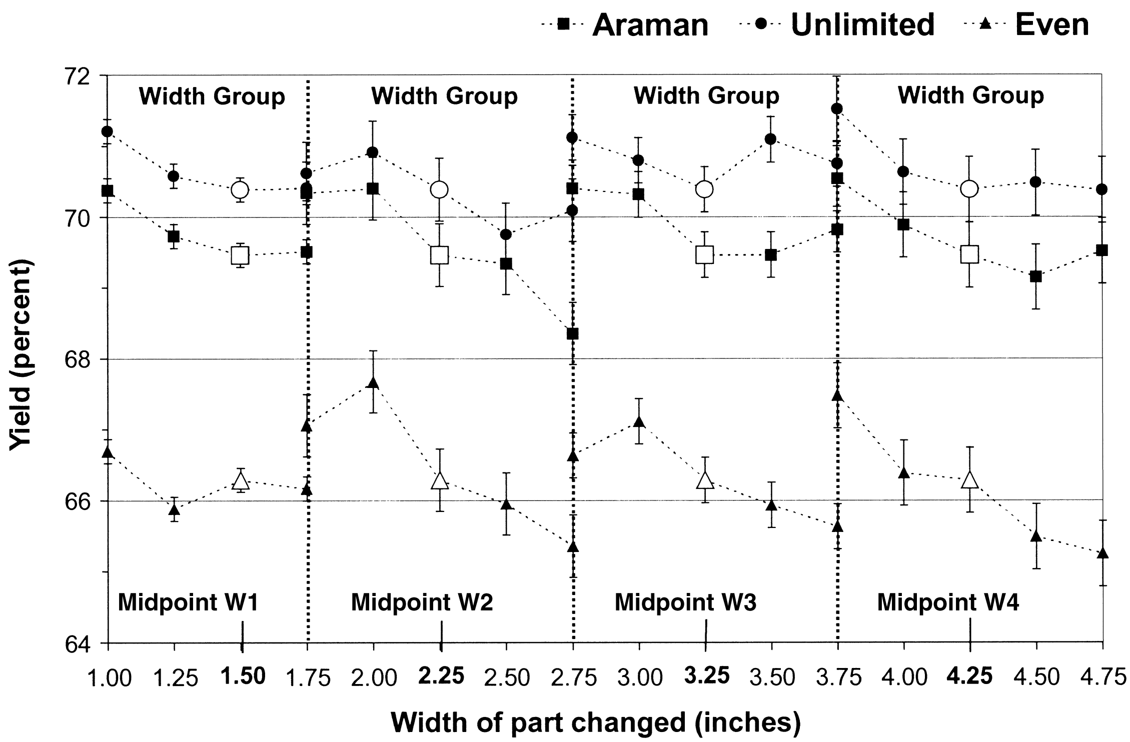

FIG. 4. Effect of width on yield for three part-quantity requirements.

$$\text{Yield} = \text{f(width, schedule)}. \quad (5)$$

For width groups W_1 and W_3, mean yields were greater for the narrowest than for the widest width across all schedules. Within groups W_1 and W_3, there was a consistent ordering of the yield outcomes (from smallest to largest) by schedule. The Even schedule had the lowest yield, the Araman schedule had a statistically higher yield, and the Unlimited schedule produced a slightly higher (significant) yield than the Araman schedule (Fig. 4). The mean yield for the Even schedule was more than 3% below that obtained when processing lumber using the Araman schedule!

The yield results from cutting bill width-change tests were similar to those for the length-change tests, specifically, yield was highest when an Unlimited quantity of any part size was cut and lowest when an Even quantity of parts was produced.

When the Araman requirements were tested, yield generally was higher for the narrower width parts within each part group than for the mid- and wide-width part-size settings. This indicates that the smaller the widths in any width group, the higher the yield, given an all-blades movable arbor. The reverse is true for length, however. As long as there are sufficient shorter parts required by the cutting bill, longer lengths seem to have little effect on yield. Accordingly, the width of the narrowest part on the cutting bill does not affect yield as much as the length of the shortest part on the cutting bill, given a typical spread of cutting-size and quantity requirements.

This knowledge should be incorporated into the planning and decision-making process when designing furniture. Designers need to be aware that increasing the length dimensions of a part, especially of a short part, can affect yield in the rough mill by up to 4%.

Yield-response surface

The yield-response surface shown in Fig. 5 represents the results of the second series of

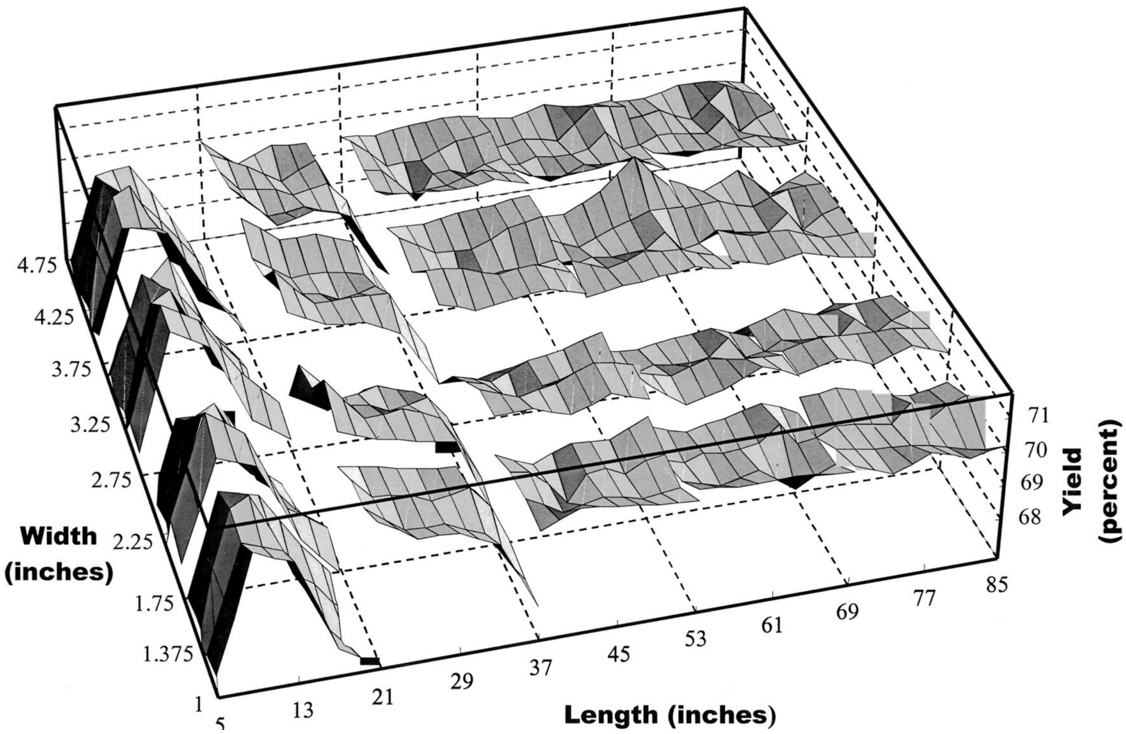

FIG. 5. Yield-response surface over the entire cutting bill space when using the Araman schedule.

simulation experiments in which one length group and one width group were changed simultaneously. For this series of tests, only the Araman schedule was used. The entire cutting bill space, with lengths ranging from 5 to 85 inches and widths ranging from 1.00 to 4.75 inches, is included in the yield-response surface.

The relationship between cutting bill requirements and yield was consistent with that observed in the first series of tests. No unexpected length nor any width interactions were observed. Figure 5 illustrates that the results presented in Figs. 3 and 4 are good approximations of what can be expected over the entire cutting bill space. It also illustrates the importance of short length parts in a cutting bill, which is manifested by the highly variable yield results at the lower end (i.e., the shorter end) of the length space. By contrast, the results for width are less variable with fewer drastic yield changes when widths are shifted incrementally.

All of the yield differences observed in Fig. 5 result from changes in part size. The widths and lengths of all parts in a particular size class were shifted to the new part size (Fig. 2 and Table 5). Had we changed only the size of the part labeled L_xW_y, but not the other lengths (L_xW_1, L_xW_3, and L_xW_4) and widths (L_1W_y, L_2W_y, L_4W_y, and L_5W_y), then an additional length and width would have been added to the cutting bill. In this case, the yield changes could not have been clearly assigned to the part-size change because the introduction of the additional cutting size also might have affected yield.

The yield response surface demonstrates the yield variability when one (length or width) or two dimensions (length and width) of a piece of furniture are redesigned to different size specifications. An example of this is a standard bookcase with non-glued up top and side faces that is redesigned to have a profile that is 2 inches shallower and 2 inches narrower.

SUMMARY AND CONCLUSIONS

Understanding the complex relationship between cutting bill requirements and lumber yield was the focus of this study. The importance of part length for high yield was demonstrated clearly when using Araman's (industry-based) or Even part quantities. For these cutting-bill part requirements, lengths below 20 inches have a particularly significant influence on yield—with only minor changes in the length of these shortest length parts, cutting bill yields can vary by as much as 3%. For the Araman (industry-based) and Unlimited part quantity cutting bill scenarios, longer lengths have a relatively minor impact on yield, unlike the Even part quantity cutting bill scenario. Given Even part quantity requirements, a change in length of the medium-length parts from 43 to 53 inches, can trigger a yield drop of almost 7%.

Width does not have as much of an impact on yield as does length. The maximum yield changes due to width changes were below 2.5% for all cutting bill scenarios tested, versus up to 7.3% for length. In general, we observed that smaller part widths resulted in higher yield when using an all-blades movable arbor.

The study showed the beneficial influence that fingerjointing can have on yield. Yield increases of 6% can be achieved under certain circumstances when adding short lengths of 4 to 5 inches to a cutting bill that requires parts no shorter than 13 inches. Similar yield gains might also be possible if an underlying knowledge of the cutting bill–yield relationship is employed when designing furniture. By appreciating the benefits of shorter and narrower parts, designers may design parts that help achieve higher yield and thus lead to lower production costs. In the end, smart software should be developed for designers that can be linked to production planning in order to create the individual cutting bills according to part requirements, due dates, and yield interactions.

Future research should be focused on a) further explaining the influence of the part-size distribution on yield, b) developing ways to make cutting bills less complex (i.e., reducing the possible part combinations to a manageable number, c) defining the marginal contributions to yield of different part sizes, and d) testing the validity of existing yield prediction models (e.g., FPL 118 (Englerth and Schumann 1969)) and, if indicated by the tests, devising more accurate and versatile yield prediction models.

By better understanding the relationship between cutting bill requirements and lumber yield, mill operators could save thousands of dollars per year (Kline et al. 1998). Furthermore, better knowledge of cutting bill and yield relationships can help to reduce pressure on the timber resource required to satisfy the demand for solid-wood dimension parts.

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