VALIDATION OF THE STANDARDIZED AND SIMPLIFIED CUTTING BILL

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Abstract. This research validated the framework for the standardized and simplified cutting bill presented in an earlier paper. The cutting bill validation was carried out in two ways. First, all 20 of the cutting bill's part groups were examined to determine if significant yield influences resulted from changing specific part sizes within the boundaries of a given part group. Second, five cutting bills from industrial operations were fit into the framework of the cutting bill, and the simulated yields from these industrial cutting bills were compared with the fitted cutting bills. Yield differences between the two were calculated and tested for significance. Tests revealed that the standardized and simplified cutting bill framework performed as designed. The maximum yield difference observed was 2% and the average less than 1%. Clustering the industrial cutting bill part requirements according to the cutting bill framework led to an average absolute yield deviation between the original cutting bills and the clustered cutting bills of 3.25%. These results show while cutting bill part-size requirements can be clustered into part groups, yield differences of a certain magnitude are introduced by so doing.

Keywords: Cutting-bill requirements, lumber yield, rip-first rough mill, fractional-factorial design, standardized, simplified Buehlmann cutting bill, model validation.

INTRODUCTION

Buehlmann (1998) introduced the concept of part groups, a theoretical concept describing cutting bills in a standardized, simplified format. The concept is intended to facilitate analyses of the relationships between cutting bill requirements (eg part sizes [length, width] and part quantities) and lumber yield in rough mills. It may also lead to the creation of a yield estimator that does not rely on computer simulation or yield nomograms. A yield estimator not based on simulation could potentially reduce the need

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of computing power and allow for more exhaustive cutting bill composition optimization efforts.

The relationship between cutting bill requirements and lumber yield is complex (Buehlmann et al 1998, 1999, 2003, 2008; Hamilton et al 2002; Buehlmann 1998; BC Wood Specialties Group 1996; Wengert and Lamb 1994) and has been barely researched (Buehlmann 1998; Buehlmann et al 2003, 2008). Yet, given the large influence of cutting bill requirements on lumber yield, a better understanding of this relationship would permit increased yield in rough mills, thereby decreasing product costs and save scarce raw materials.

Buehlmann et al (1998, 1999), BC Wood Specialties Group (1996), Wengert and Lamb (1994), and others provided limited insights into the relationship between cutting bill requirements and yield. Buehlmann (1998) and Buehlmann et al (2003, 2008) were the first to focus their research specifically on understanding this relationship. They simplified the complexity of the cutting bill requirements - lumber yield relationship. Principles from group technology combined with clustering techniques suggested the utility of forming part groups. Part groups are defined areas of the cutting bill length and width space where the entire space encompasses all part sizes (length and width), from minimum to maximum, eg 127−2159 mm in length and 25−121 mm in width, in this case. This cutting bill size range was partitioned into 5 length- and 4 width-groups, which formed a 5 by 4 part-group matrix. Individual part requirements of a given cutting bill (quantity, length, width) are clustered into these defined part groups and represented by one standardized size (referred to as the "midpoint" throughout this study) for each group. Each part-group size was set such that only a limited change in yield due to clustering would occur (Buehlmann 1998; Buehlmann et al 2008). Required quantities of all parts falling within a particular part group are summed to arrive at the quantity requirement for the part-group midpoint. Thus, the part-group midpoint is used as a representative of all parts that fall within a particular part-group size range. Using statistical methods, it was found that 20 such groups were needed to limit the change in yield due to clustering. Figure 1 shows the concept of part groups graphically.

In Fig 1, part-group midpoints are represented by dots in the middle of each cell. Part-group notations are shown in the bottom right portion

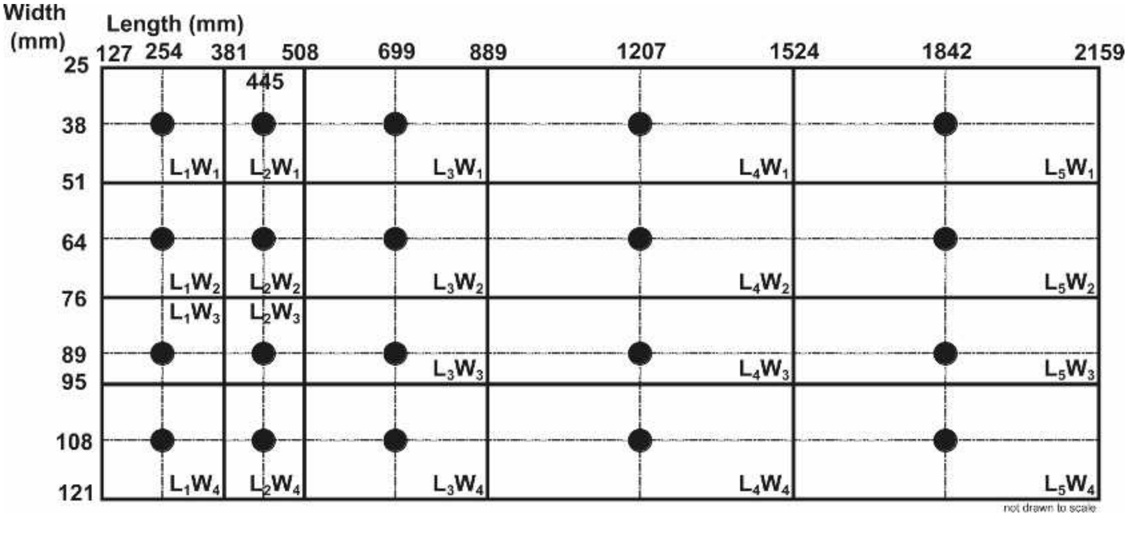

FIGURE 1. Semantic view of the 5 by 4 cutting bill space (part-group) matrix with dots indicating the part-size midpoint representing each part group.

of each cell with the exception of groups L_1W_3 and L_2W_3. The notation for these 2 groups is shifted to the top due to space limitations. The top x-axis shows the part-length boundaries and the midpoint position of individual part groups, while the left y-axis shows the same information for width. Araman et al (1982) information on part quantity requirements for solid wood dimension used by the furniture industry was employed to determine part quantities for each part group. Part quantity details are presented in Buehlmann et al (2008; Table 2).

For such a standardized, simplified cutting bill to be useful for analytical purposes, it is imperative that parts clustered within part groups and part sizes, reset to the part-group midpoints, do not exert too large a bias on lumber yield relative to the other part groups. Iterative tests involving statistical methods described in Buehlmann et al (2008) helped minimize this bias. These tests assured that the influence on yield when resetting the size of any part within a part group to the midpoint was similar for all groups, thus minimizing the difference occurring due to the clustering of parts within a part-group range.

The established part-group sizes differed widely in length, ranging 127–635 mm. The shorter part ranges, ie group L_1, L_2, and L_3, which, as Buehlmann et al (2003) showed, have a more pronounced influence on yield than do longer parts, spanned length ranges not exceeding 381 mm. The longer and less influential part ranges, ie groups L_4 and L_5, both had length ranges of 635 mm. Group L_2, however, had a length range of only 127 mm, emphasizing the large influence of this length range on yield.

Part width influences yield less than does length, at least for the width range of 25–121 mm considered in the Buehlmann et al (2008) study. To assure that the effect of individual part widths being reset to their respective part-group midpoint stayed below the threshold set forth in Buehlmann et al (2008), 4 width-groups were necessary. As shown in Fig 1, 3 width-groups were determined to be 25 mm (W_1, W_2, W_4), whereas the fourth spanned a width-range of 19 mm (W_3).

The statistical methodology described in Buehlmann et al (2008) to establish the part-group sizes shown in Fig 1 tested individual part groups for their influence on yield sequentially. First, length group 1 (L_1) was established, followed by L_2, L_3, L_4, and L_5. Once the length of individual part groups was set, width was next set starting with W_4, W_3, W_2, and W_1. In this way, the difference due to the clustering of parts within each part-group range was made smaller than required.

The objective of this study was the validation of this newly composed cutting bill, referred to as the “Buehlmann cutting bill” (BCB) (Buehlmann 1998). Recently, this cutting bill has been employed for several studies (Zuo et al 2004, 2008; Buehlmann et al 2003, 2004); thus, there is a need to know more about its characteristics. Among the questions that need to be answered are: a) what is the influence of changing only 1 part-group size (midpoint) to the extreme positions of its range, while leaving the other 19 part-group sizes unchanged at their midpoints (the original test procedures did reset all sizes on the same row and column to the same value (Buehlmann et al 2008); b) what is the yield influence of part clustering when using cutting bills from industry; and c) what is the influence of the number of different part sizes (eg the number of part groups), since recent studies indicate this may have an important effect on yield (Buehlmann 1998; Thomas and Brown 2003).

METHODS

The methods used in this research followed closely the ones outlined in Buehlmann et al (2008).

Rip-first rough mill yield simulation

Lumber cut-up simulation was performed using ROMI-RIP 1.0 (Thomas 1995a, 1995b). Settings included: 1) all-blades movable arbor, 2) dynamic exponential cutting bill part prioritization

(Thomas 1996b), 3) smart and unlimited salvage operation (Thomas 1996a, Anderson et al 1992), 4) no random width and no random length parts, 5) no fingerjointed or glued-up parts, 6) continuous updating of part counts, 7) end and side trim set at 6 mm on both sides, and 8) only clear-two-side (C2F) parts (Thomas 1995a and 1995b). Two replicates were used in the part-group yield influence tests and 3 were used in the tests of industrial cutting bills. Different lumber files compositions using the same lumber grades, but the same cutting bills and simulation settings were used to create replicates. Yields are reported in absolute terms and include both primary and smart salvage yield, unless specified otherwise.

Lumber

Gatchell et al (1998) kiln-dried red oak data bank was used for this research. Input data files were comprised exclusively of No. 1 Common lumber and were prepared using the "custom datafile creation" feature of ROMI-RIP (Thomas 1995a and 1995b). The simulation runs were set up such that each run would require at least 150 boards to fulfill the cutting requirements; this assured no bias due to between-board yield variations (Buehlmann et al 1998). The board quality and size distribution published by Wiedenbeck et al (2003) were used for the creation of the lumber data set.

Cutting bills

This study used the BCB as described in Buehlmann (1998) and Buehlmann et al (2008). To investigate the feasibility of using the BCB to represent cutting bills used in industry, 5 cutting bills from industrial operations that covered a wide range of product size and quantity requirements were used. Details of these 5 cutting bills are given in Table 1 and in Buehlmann (1998; Appendix G, Table A-8, pp. 213–214 [original bills] and Appendix H, Table A-9, pp. 215 [clustered bills]).

TABLE 1. *Cutting bill requirements of 5 cutting bills used to validate the part-group methodology.*

		Cutting bill	units	Original cutting bill					Clustered and scaled cutting bill				
				A	B	C	D	E	A	B	C	D	E
Distribution		Cutting sizes in cutting bill	# of	7	12	36	8	36	6	7	7	7	15
		Total parts	# of	840	2000	1362	6840	1080	668	1827	2235	1543	1893
Geometry	Length	Min.	mm	146	368	470	457	311	254	254	445	445	254
		Max.	mm	1962	1918	2064	1829	1746	1842	1842	1842	1842	1842
		Average	mm	867	784	934	959	729	857	907	971	1134	720
		Weighted average	mm	656	691	853	897	581	676	736	852	1014	582
	Width	Min.	mm	25	51	38	38	32	38	64	38	38	38
		Max.	mm	83	89	83	76	121	89	89	89	89	108
		Average	mm	53	68	53	52	73	55	71	67	60	78
		Weighted average	mm	65	69	55	52	68	67	71	63	56	71
	Area	Min.	mm^2	10202	23226	20323	17419	10887	16129	16129	26613	16935	9677
		Max.	mm^2	87218	121774	131048	116129	177419	70161	116935	116935	163709	198790
		Total area demanded	m^2	31	95	66	319	45	N/A	N/A	N/A	N/A	N/A
		Total area demanded (clustered)	m^2	N/A	N/A	N/A	N/A	N/A	33	107	74	410	47
		Average part area	mm^2	39718	52648	50792	50564	55683	40457	64516	66014	70392	60484
		Weighted average part area	mm^2	37456	47433	48654	46655	41867	38926	53381	54055	59989	44309

Control of individual part groups on yield

While creating the BCB, part-group sizes were tested and adjusted sequentially (Buehlmann et al 2008). In these tests, when the part size representing a given part group was shifted from its midpoint to an extreme corner of the part group, the lengths and widths of all other parts with the same length or width dimension also were shifted to the same size as that of the group under investigation. Finally, tests were conducted using the part-group midpoint to test for part-group curvature (Buehlmann et al 2003, 2008).

Using the methodology referred to above, the sizes of 8 parts were changed for each test. These tests did not assess the influence of changing only 1 part-group size to the extreme position while leaving all other 19 part-group sizes unchanged at the midpoint. The individual influence of a particular part group on yield was not heretofore established. For the first series of tests in the current validation study, only 1 part-group part size was changed, while all the remaining 19 part-group sizes remained fixed. Two replicates of each test were run. The results were fit to the general linear model described in Buehlmann et al (2008) and tested for statistical significance ($\alpha = 0.01$). Figure 2 gives a schematic view of the positions of each part-group midpoint when testing the influence on yield of part-group L_1W_1.

These tests also were used to examine the maximum yield difference between any 2 of the 5 observation points tested for each individual part group. The term "yield span" is used to denote this maximum absolute yield difference for each part-group test.

Control of influence on yield when using industrial cutting bills

Testing the influence on yield of changing the part-group midpoint location as described above shows the sensitivity of the BCB to limited and controlled part size changes. A second test was undertaken to address concerns about the applicability of these results to real-world situations. In this test, yields from cutting bills obtained from industry were compared with yields obtained when the same cutting-bill parts were clustered using the part groups established in the BCB. Paired t-tests were used to test for the significance of the differences observed. Three replicates using the same cutting bill require-

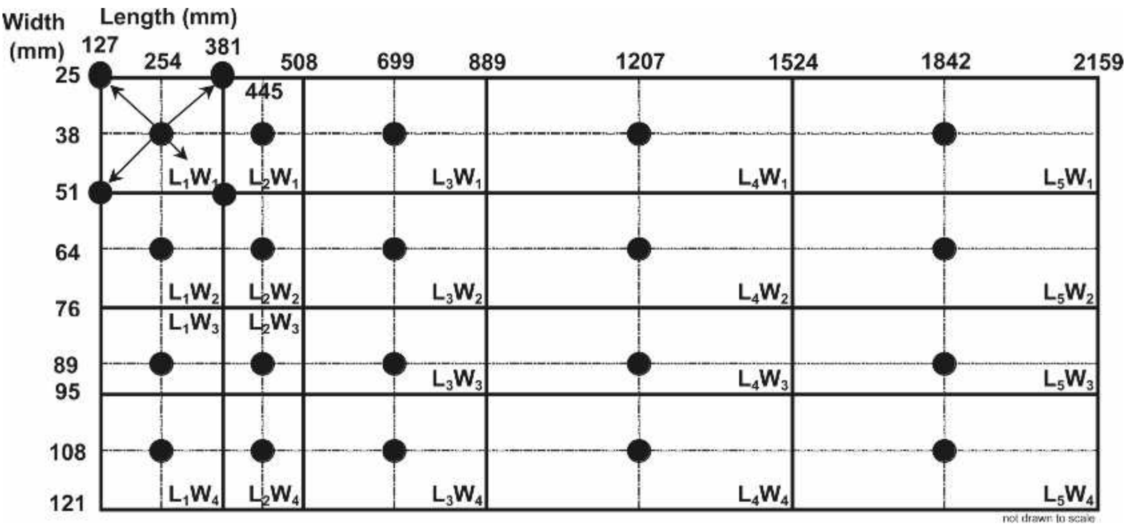

FIGURE 2. Procedure to test part-group L_1W_1 for its influence on yield.

ments and rough mill simulation set-up, but different sets of lumber were performed.

RESULTS

Two types of validation tests were conducted on the BCB framework. First, the existing framework comprised of 20 part groups was validated by changing one part-group size. Second, 5 cutting bills obtained from industrial operations were subjected to the framework of the BCB to see how well the standardized BCB represented industrial cutting bills.

Comprehensive testing of yield influence of individual part groups

In the first tests, only the midpoint of the part group under consideration was changed. Therefore, the change in yield was expected to be lower than that found when creating the BCB. It was hypothesized that the yield differences brought about by these changes were not found to be significant in tests conducted at the 99% of significance level ($\alpha = 0.01$). This hypothesis was found to be true. None of the part groups violated the significance level ($\alpha = 0.01$) requirement. Table 2 shows the levels of significance for each part group tested (length, width, interaction, curvature) and the yield span.

The minimum level of significance observed for length was 0.02 for part-group L_4W_2, whereas the average for all 20 length observations was 0.56. For width, the minimum significance was observed for part-group L_3W_4, only slightly higher than 0.01. The average significance for width was 0.39. The levels of all observations for the interaction term and the curvature terms were considerably higher than 0.01. Therefore, the standardized BCB, ie the part-group configuration shown in Fig 1, was accepted.

The yield span (the maximum absolute yield deviation between any 2 of the 5 tests done for each part group Table 2) averaged 0.86% (absolute percentage) for all 20 tests. The maximum average yield span for a single group was 1.99% for part-group L_5W_2 (Table 2). Seven of the 20 part groups had average yield spans larger than 1.00% (part-groups L_2W_1, L_3W_1, L_3W_2, L_4W_2, L_5W_2, L_5W_3, L_3W_4). Thus, although the BCB was derived to minimize yield influences when changing part sizes within part groups, changing the location of the part-group midpoint (eg changing the representative part size) appears to exert an influence on yield in these few cases. As pointed out previously, none of these results were found to be significant at the 99% of significance level. However, these tests were conducted under the most severe assumptions (ie part-group midpoints were set at the extreme corners of each part group). In reality, such extreme shifts in dimensions should rarely occur.

TABLE 2. *Summary of results when testing individual part groups for compliance with the requirements.*

	Test for				
Part group	Length	Width	Interaction	Curve	Yield-span
L1W1	0.8810	0.9007	0.9900	0.9777	0.11%
L2W1	0.8093	0.5068	0.1461	0.0836	1.01%
L3W1	0.3239	0.0435	0.8069	0.2590	1.65%
L4W1	0.2635	0.0635	0.3490	0.6822	0.93%
L5W1	0.2255	0.1869	0.9261	0.8737	0.89%
L1W2	0.9494	0.4962	0.3516	0.3865	0.66%
L2W2	0.7002	0.1310	0.3824	0.0510	0.88%
L3W2	0.4924	0.2874	0.3621	0.6840	1.17%
L4W2	0.0198	0.0832	0.6966	0.1963	1.05%
L5W2	0.1697	0.1167	0.2546	0.3344	1.99%
L1W3	0.8679	0.8431	0.5295	0.2523	0.27%
L2W3	0.7978	0.9152	0.5198	0.5867	0.37%
L3W3	0.6886	0.3885	0.5380	0.2367	0.51%
L4W3	0.9081	0.7305	0.8409	0.8890	0.43%
L5W3	0.1056	0.2409	0.2661	0.6299	1.26%
L1W4	0.5694	0.6180	0.3248	0.2502	0.44%
L2W4	0.9873	0.1354	0.2085	0.4505	0.96%
L3W4	0.4469	0.0125	0.2823	0.8995	1.52%
L4W4	0.4038	0.7330	0.4922	0.6047	0.48%
L5W4	0.5590	0.4069	0.7718	0.5630	0.57%
Average	0.5585	0.3920	0.5020	0.4945	0.86%
Std. Dev.	0.3040	0.3075	0.2542	0.2852	0.49%
Max.	0.9873	0.9152	0.9900	0.9777	1.99%
Min.	0.0198	0.0125	0.1461	0.0510	0.11%

Testing of industrial cutting bills

Clustering of parts required by industrial cutting bills into the part groups set by the BCB changed yield in all 5 cases tested. Clustering led to an average yield difference of 1.82% for the 5 bills tested. However, since cutting bill A resulted in higher yield when clustered (the remaining 4 cutting bills resulted in lower yields when clustered, Table 3), the average difference of 1.82% understates the real difference from clustering. The absolute average difference from clustering was 3.25% with a standard deviation of 3.12%. Table 3 displays the yields obtained for each industrial cutting bill and its clustered approximation. The cutting bills are ordered such that the one with the smallest yield difference between actual and approximated part composition (E) appears first, whereas the one with the largest difference (C) appears last. Also shown are the number of different part sizes, the total number of parts required by the cutting bill, and the number of different part groups into which the parts belonged when clustered.

DISCUSSION

The results from the 2 tests show that the concept of using a standardized cutting bill to represent cutting bills used in industrial settings as realized with the BCB has limitations. Whereas the influence on yield when changing one part group's size is limited, larger yield differences occur when clustering industrial cutting bills using the part groups developed.

Comprehensive testing of yield influence of individual part groups

While a considerable effort was made to minimize the influence on yield associated with changing the position of the midpoint within a part group (eg changing the size used to represent the part group), yield was still affected for some groups. Despite conforming to the rules laid out to create the part groups (significance level for tests of the effect of part size changes on yield below 0.99), the yield span was, on average for the 20 part groups, 0.86% (Table 2). The maximum within part-group yield difference (eg the maximum yield span) found was for part-group L_5W_2, where a yield difference of 1.99% between the 2 extreme yield values was observed. This large yield span occurred when the length of the parts to be cut for part-group L_5W_2 was increased from 1524–2159 mm. The only way to decrease the high yield spans would be to make the part groups smaller. However, enlarging the number of part groups used would make the cutting bill more complex, which was contrary to the goal of creating the standardized and simplified BCB.

Testing of industrial cutting bills

The average yield difference due to clustering parts when comparing yields from industrial cutting bills with yields from the same industrial cutting bills whose parts were clustered according to the BCB, was found to be 1.82%. The maximum yield difference observed was 4.48% (Table 3).

These yield differences can be attributed to 3 factors, namely, the change of size of clustered parts, the changing number of part sizes to be cut, and the differences in part quantities required between the original framework of the model and the actual quantities demanded.

TABLE 3. *Yield estimation differences due to clustering, number of part sizes, total parts required, and part groups used for the 5 industry cutting bills tested.*

Cutting bill	Yield of "real" cutting bill	Yield of clustered cutting bill	Error due to clustering	# of parts required	# of part sizes	# of part groups used
E	72.39%	70.16%	2.23%*	1080	36	16
D	65.47%	62.64%	2.82%**	6840	8	7
B	67.34%	64.18%	3.16%**	2000	12	7
A	64.40%	67.97%	−3.57%**	840	7	6
C	68.48%	64.00%	4.48%**	1362	36	7

notation:
* = significant at 95% level
** = significant at 99% level

These 3 sources are discussed in more detail below.

The first factor that affects the yield variance when clustering an industry cutting bill to the BCB, the size of individual parts to be cut, changes because the original part size (as required by the industrial cutting bill) is reset to the respective part-group midpoint of the BCB (Buehlmann 1998; Buehlmann et al 2008). The impact on yield of changes in the size of parts that have been reset to the part-group midpoint can be broken down into two components: the difference resulting from cutting the true part lengths as given by the industrial cutting bill vs the lengths that the parts assume when clustered to the midpoints of their respective part groups; and the differences owing to the width changes between the parts described in the industrial cutting bill and the parts when clustered. Because these cutting bills were not specifically designed to allow the separation of the yield difference (ie orthogonal design in respect to the differences under consideration), the exact magnitude of the component differences cannot be derived from this study.

Table 4 shows 2 measures for the deviation of part length (in millimeters) from the original industry cutting bill to the part length when clustered. The first measure, the absolute average deviation per part, quantifies the difference between the actual part length and the clustered lengths for all parts in each length group. Thus, what is shown under the heading "*average absolute deviation per part*" in Table 4 is the average of the absolute deviation in length (ie $|L_{original} - L_{clustered}|$) for each part within a part group, weighted by its quantity requirement. Results are shown for all 5 cutting bills tested. The cutting bills are listed in ascending order of yield deviation for the industrial vs clustered cutting bill as shown in Table 3.

The second measure shown in Table 4 is the "*average real deviation per part*." This measure shows the difference in part length between the actual industry cutting bill part-length requirements and the clustered part-length requirements. Thus, this measurement is similar to the first one, but is not an absolute measure. Hence, if there are both shorter and longer parts in the original cutting bill than the part-group midpoint to which the parts are clustered, the differences can cancel each other. This calculation gives information about the spread of the real part lengths around the length group midpoints. For example, when the average absolute deviation is high but the average deviation is low, then the parts are spread quite evenly on both sides of the length group midpoints. Length group L_3 of cutting bill C is an example of such a case. The average absolute deviation per part is 105 mm, but the average real deviation is only 5 mm per part because differences cancel.

Also given in Table 4 are the total absolute and the total real length deviations for all parts for all

TABLE 4. *Deviations of lengths, in millimeters, between industrial cutting bill and clustered cutting bill for the 5 cutting bills used.*

	Length 1	Length 2	Length 3	Length 4	Length 5	All lengths (mm)	
Cutting bill	Average absolute deviation per part (mm)					Average	Total all parts
E	89	32	96	133	165	65	70041
D	no parts	13	97	177	177	124	848106
B	114	30	158	164	76	112	224155
A	108	51	88	86	121	80	67564
C	no parts	37	105	94	167	103	140056
	Average deviation per part (mm)					Average	Total all parts
E	89	−18	−53	19	−165	−13	−13526
D	no parts	13	−89	−177	−177	−117	−802386
B	114	4	−158	−37	76	−46	−92075
A	−108	51	−88	−86	121	−19	−15748
C	no parts	37	5	−60	5	1	1803

length groups. Total absolute deviation and total real deviation for all parts are the sums of all part deviations multiplied by their respective quantities for either absolute or non-absolute measure.

The part-length deviations shown in Table 4 do not fully explain the yield differences between the original industry cutting bills and the clustered cutting bills according to the Buehlmann framework. The number of individual part sizes in different part groups as well as the part quantity requirements influence yield as well. For example, as shown in Table 3, cutting bill A (yield difference owing to clustering −3.57%) has the larger difference from clustering than does cutting bill D (difference from clustering 2.82%). Yet, the deviation between part lengths in the original cutting bill and the clustered cutting bill is higher for cutting bill D (−117 mm) than for cutting bill A (−19 mm, Table 4).

Based on insights gained from Table 4, the magnitude of yield differences due to clustering does not consistently correlate with the deviation of part length. In other words, the absolute average deviation and the average deviation of part lengths from their respective part-group midpoints are not necessarily highest for the cutting bill with the largest yield difference due to clustering. Also, the yield difference cannot be closely correlated to a skewed distribution of original part lengths around the part-group midpoint given by the BCB. The cutting bill whose parts are most extremely skewed to one side of the part-group midpoints, cutting bill D (the bill with the highest total deviation), does not result in the largest yield difference as a result of clustering.

The second factor that contributes to differences in yield between the original industry cutting bills and the clustered versions of these same cutting bills relates to the number of different part sizes being cut. Thomas and Brown (2003) and Buehlmann (1998) have elaborated on the influence of the number of part sizes being cut simultaneously on lumber yield. The clustering of part sizes into part groups may lead to fewer part sizes being cut at the same time, thus altering the yield obtained. Observations on cutting bills E (lowest yield deviation) and C (largest yield deviation) support this claim. Both cutting bills originally require 36 different part sizes to be cut, yet cutting bill E requires 16 different part sizes to be cut after clustering, whereas cutting bill C required only 7 different part sizes. Because of the decreased number of different part sizes to be cut, cutting bill C achieves 64.00% yield when clustered, whereas it achieved 68.48% yield in its original form, a 4.50% reduction (Table 3). Cutting bill E's yield was reduced by a lesser amount, 2.23% (from 72.39% yield for the industrial cutting bill to 70.16% for the clustered bill). Similar observations can be made between cutting bills D and B. Cutting bill D has 8 different parts, which is reduced to 7 when the parts are clustered. Cutting bill B has 12 parts to begin with, but these are reduced to 7 when the parts are clustered. The yield difference of cutting bill B is 0.34% higher than the difference for cutting bill D. One also should keep in mind that in actual rough-mill operations, the number of part sizes being cut at any given time is normally smaller than 10 due to system and human capability restrictions.

The third source of yield difference between the 2 cutting bills is associated with the part quantity framework of the standard BCB and closely relates to the second reason discussed above. The standard BCB was designed with parts cut from all of the 20 part groups. However, after clustering the parts for the 5 industrial cutting bills, 4 of the 5 required parts from less than half of the 20 part groups (Table 4). Cutting bill E (lowest yield difference) and cutting bill C (largest yield difference) again are the most revealing in support of this observation. Both industrial cutting bills require 36 different part sizes. However, when adapted to the framework, cutting bill E's part sizes are spread over 16 part groups in the BCB, whereas cutting bill C's part sizes are spread over only 7 part groups. Table 5 shows the distribution of the 36 different part sizes over the respective part groups for both cutting bills. The letters in the cells indicate the relative quantities of parts in each part/group for

TABLE 5. *Distribution of part sizes and approximate part-group quantities for cutting bills E and C.*

Cutting bill E*						Cutting bill C*					
L\W	L1	L2	L3	L4	L5	L\W	L1	L2	L3	L4	L5
W1	L	M	L			W1			M		
W2	L	M	L	L		W2		L	H	L	H
W3	L	L	M	M	L	W3			H	L	
W4	L	M	L	L	M	W4					

* An "L" entry in a cell means that part group contains only 1–33% as many parts as compared with Buehlmann, an "M" means the group contains only 33–67% as many parts, and an "H" means the group contains more than 67% of the part quantity specified in the BCB.

the 2 industrial cutting bills compared with the cutting bill quantities per group contained in the BCB (Buehlmann et al 2008; Table 5). Empty cells indicate that no parts were required that fell within the cell's size ranges. Table 5 shows that cutting bill E parts dispersed over 16 different part groups, and 6 of the 16 groups require more than 33% of the originally required quantity (Araman et al 1982; Buehlmann 1998). Conversely, cutting bill C's 36 different part sizes fell into only 7 different part groups when clustered and only 4 of these groups require 33% or more of the original quantity.

The variability of the cell entries in Table 5 shows the major differences between the original cutting bills E and C and the BCB. Cutting bill part groups in Table 5 with an "L" indicate that the original cutting bill contains less than 33% part quantity requirements compared with the standardized BCB. An "M" indicates that between 33 and 67% and "H" more than 67% of the quantity requirements of the standardized BCB were required by the original cutting bill. While cutting bill E resembles the quantity requirements of the BCB to a certain degree, cutting bill C, in which many cells are empty and others contain an "L" indicates major differences in part quantity requirement between cutting bill C and the BCB.

While the sources and magnitudes of the yield differences observed cannot be quantified and tested because of the design of the current study, it appears that the largest source of yield variance due to clustering results from the decrease in number of parts to be cut between the original and the clustered cutting bill. Minimizing the yield differences would entail introducing more part groups, which would reduce the difference in the number of different part sizes to be cut in between the original and the clustered cutting bills. Also, it would make the difference in part sizes to be cut between the original and the clustered cutting bill smaller, thus decreasing the average absolute and non-absolute yield differences. However, more part groups would make the analytical work more difficult for the BCB that was created in the first place. The rules followed when creating the standard BCB were set up to achieve a meaningful trade-off between simplification and precision of yield estimation.

Part groups can be used to standardize cutting bills such that their complexity for analytical purposes decreases. However, part groups introduce a yield difference between the original and the standardized, clustered cutting bill (Buehlmann 1998). The major source of the yield difference is believed to be due to the decrease in the number of parts to be cut simultaneously. Nonetheless, the concept of part groups to standardize cutting bills is important, since it allows a decrease in the complexity of cutting bills and thus makes yield analyses easier to manipulate and understand.

SUMMARY AND CONCLUSIONS

The BCB is an attempt to create a standardized, simplified cutting bill to facilitate analysis of the influence of cutting bill requirements on lumber yield. It also offers a means of creating a yield estimator that does not rely on yield nomograms or simulation. The BCB, although based on statistical methods, has not previously been validated.

Tests were conducted to assure that part size changes within individual part groups do not influence yield significantly ($\alpha = 0.01$). None of the 20 part groups contained in the BCB violated the significance threshold ($\alpha = 0.01$). The part group with the maximum yield influence affected yield by 1.99%, while the group having the minimum was 0.02%. The overall average yield effect that resulted from changing the part size used to represent each part group (for all 20 part groups) was 0.86%. To decrease the yield influence of individual part groups further, more part groups would be required. However, doing so would make the standardized and simplified cutting bill more complex. Since this would complicate using the cutting bill for analytical purposes, the existing part-group matrix was accepted as the best solution to the part-group formation problem.

The yield differences measured in tests on cutting bills from industrial operations were larger that those measured in the first series of tests conducted on the BCB 20 part groups. These differences represent the fit of the industrial bills to the Buehlmann framework. An overall average absolute yield deviation between the original cutting bill and the clustered BCB of 3.25% was measured for the 5 cutting bills tested. The minimum yield difference observed between an original industrial vs clustered bill was 1.82%; the maximum was 4.48%. Several factors lead to these yield differences, among them the reduction in the number of different part sizes to be cut, the uneven distribution of cutting bill part sizes around the part-group midpoints for the industrial cutting bills, and changes in the distribution of part quantity requirements for the industrial cutting bills.

Although clustering of parts into the standardized and simplified BCB framework introduces changes in absolute yield, this study has shown that the BCB meets the statistical requirements established for its creation. Thus, the BCB should prove helpful in future studies to further the understanding of the complex relationship between cutting bill requirements and lumber yield. The cutting bill may also prove helpful for the creation of a new yield estimator that does not rely on yield nomograms or simulation.

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