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Cost minimization through optimized raw material quality composition ☆

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ABSTRACT

Lumber, a heterogeneous, anisotropic material produced from sawing logs, contains a varying number of randomly dispersed, unusable areas (defects) distributed over each boards' surface area. Each board's quality is determined by the frequency and distribution of these defects and the board's dimension. Typically, the industry classifies lumber into five quality classes, ranking board quality in respect to use for the production of wooden components and its resulting material yield. Price differentials between individual lumber quality classes vary over time driven by market forces. Manufacturers using hardwood lumber can minimize their production costs by proper selection of the minimum cost lumber quality combination, an optimization problem referred to as the least-cost lumber grade-mix problem in industry parlance. However, finding the minimum cost lumber quality combination requires that lumber cut-up simulations are conducted and statistical calculations are performed. While the lumber cut-up simulation can be done on a local computing workstation, the statistical calculations require a remote station running commercial statistical software. A second order polynomial model is presented for finding the least-cost lumber grade-mix that manufacturers of wood products can use to minimize their raw material costs. Tests of the newly developed model, which has been incorporated into a user-friendly decision support system, revealed that only a limited amount of lower quality raw material (e.g. lumber with a high frequency of defects in boards and/or small board sizes) can be accepted, as otherwise the lumber quality mix cannot supply all the parts required. However, the new model suggested solutions that resulted in lower raw material costs than solutions from older models.

1. Introduction

Manufacturers of solid wood products cut kiln-dried hardwood boards (lumber) into dimension parts of specified sizes, qualities, and quantities according to customer orders, called cutting bills [1]. Dimension parts are slightly oversized rectangular pieces cut from lumber that are further processed through a series of manufacturing steps into final components for products sold by the wood products industry [1]. These parts are cut in rough mills from lumber of varying geometrical sizes (length/width) through a series of guillotine cuts such that randomly dispersed and shaped defective areas (such as knots, splits, or discolorations) are cut out, leaving dimension parts without defects for further processing [2]. Lumber is traded in five quality classes (called “grades” in industry parlance) with First and Seconds (FAS) being the best quality consisting of large boards with few defects, followed, in decreasing order of quality, by Selects (SEL), 1 Common (1C), 2A Common (2AC) and 3A Common (3AC), the lowest quality lumber that can be purchased for appearance products [3]. Fig. 1 displays two boards, the top one graded FAS, e.g. the best quality, and the bottom one graded 3AC, e.g. the lowest quality. The usable areas contained in these boards differ greatly. While the FAS board, according to the quality standards setting body of the industry [3], contains a minimum of 83.3% usable, clear area, the 3AC board must contain at least 33.3% usable, clear area. The amount of usable, clear area for given quality classes is determined in the grading rules for all quality classes, e.g. FAS 83.3%, SEL 66.7% (one side must contain 83.3%), 1C 66.7% (both sides), 2AC 50%, 3AC 33.3%, respectively [4].

Lumber costs are the single largest cost position incurred by secondary wood products manufacturers [5]. Depending on the product manufactured, an estimated 40–70% of total production costs of raw dimension parts in rough mills of the secondary wood industry stem from the procurement of lumber [6–9]. Understandably, the industry undertakes considerable efforts to minimize lumber procurement costs first and foremost by increasing yield from a given set of input lumber. Lumber yield in rough mills is defined as the “ratio of aggregate part surface output to aggregate lumber surface area input ([10] p. 13)” and is

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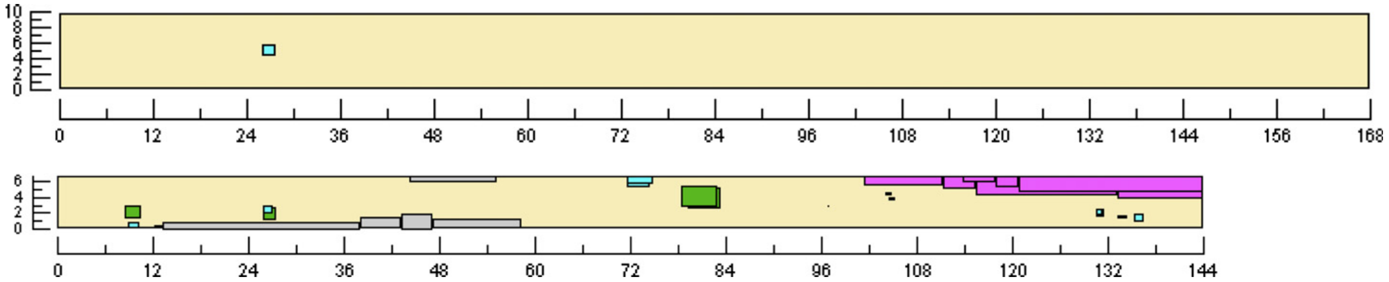


Fig. 1. Digital representation of two kiln-dried lumber boards from the highest (FAS) and the lowest quality class (3A C). The shaded rectangles signify defects, e.g. unusable areas within the board's surface.

the single most important benchmark used in the industry. Most research has focused on efforts to improve lumber yield through finding optimum cut-up patterns for each board, which is a typical cutting stock problem encountered in numerous industries [11,12]. Examples include the paper, glass, metal, and the wood products industries [13–17]. Gilmore and Gomory [18–21] in the 1960s published a series of solutions to the cutting stock problem involving linear and dynamic programming. Over the following years, numerous researchers have added to the methodology and expanded the scope of problems that can be addressed, such as expanding the dimensions in which solutions are sought [22–32].

However, the quest for increased yield from lumber is only one way manufacturers try to minimize their raw material costs. Solid wood products manufacturers also try to minimize costs through optimizing their lumber purchases, in particular through management of the price differential that exists between different lumber quality classes. In general, the better the lumber quality purchased, the higher the per unit price set by the markets. Different industry segments prefer to purchase different lumber qualities dependent on the dimension part sizes they produce. Typically, manufacturers who require a large amount of long and/or wide dimension parts to be cut from their lumber will purchase higher quality lumber. Manufacturers, who need only moderate amounts of long and/or wide parts, will tend to buy lower quality lumber. Since lumber prices fluctuate in absolute terms but also relative to each lumber quality class, an opportunity exists to minimize total lumber costs by finding the minimum cost lumber quality or mix of qualities to obtain the dimension parts needed.

The industry refers to this problem as the least-cost lumber grade-mix problem and much research has been conducted since the 1960s [9,33–42]. In essence, the problem is to minimize the cost of purchasing all the lumber needed to obtain all the required dimension parts for a given production run. Yield obtained from different lumber quality classes is dependent on the part size requirements specified in the cutting bill [10]. Thus, depending on the part size requirements for a given production run, different lumber quality classes or combinations of lumber quality classes result in different levels of yield and thus result in higher or lower total lumber procurement costs. One lumber quality may be better suited to obtain a specific size-range of parts but be expensive to purchase per unit versus another quality that may be good enough to obtain the needed parts and be relatively inexpensive. For example, when a cutting bill asks for long and/or wide parts to be cut, but also requires smaller parts, it is often advantageous to purchase a mix of high quality lumber (i.e. expensive lumber) and lower quality lumber (i.e. less expensive lumber) to minimize total lumber procurement costs.

In the past, the least-cost lumber grade-mix optimization problem was typically solved using linear programming models, which require that both objective and constraint functions are simple linear [43]. However, Zuo et al. [44] found that the relationship between yield and lumber quality or lumber quality mix is not always linear, in fact, an estimated 90% of scenarios tested by these authors were found not to have a linear relationship between lumber yield and lumber quality or quality mix. Thus, the authors suggested that the existing least-cost lumber grade-mix problem solvers using linear programming may not return true minimum cost solutions and the industry may be ill-advised to use those models. The objective of this research was to create a user-friendly least-cost lumber grade-mix Decision Support System (DSS) for industry practitioners that does not rely on linear optimization to find the minimum cost solution.

2. Materials and methods

Solving the least-cost lumber grade-mix problem is dependent on the expected lumber yield results for a given set of dimension part requirements (e.g. cutting bill). For this purpose, Thomas' [45] rip-first rough mill yield simulator (ROMI-ROP 2.0) was used together with digital representations [46] of red oak lumber [47].

2.1. Lumber cut-up simulator

The USDA Forest Service's ROMI-RIP 2.0 (RR2) simulation software [45] was employed in this research to simulate the actual cut-up of hardwood lumber in a rough mill of the secondary wood products industry [1,48]. The study employed commonly used industry operation parameters to reflect actual industry operations. Settings used included movable saw-blade positions; obtain extra dimension parts through additional processing after the first iteration, if possible; employ complex dynamic part prioritization [49]; and do not allow random length and random width parts to be cut.

2.2. Cutting bill

This study used Buehlmann's cutting bill [10,50,51], a theoretical representation of the "average" industrial cutting bill with respect to size and quantity requirements. The part quantity requirements were proportionally adjusted to fit the lumber samples used for this study. Additionally, seven industrial cutting bills were also examined in this study [8,54]. Table 1 summarizes the dimension part requirements of all eight cutting bills and ranks the cutting bills in order of their difficulty to obtain all parts from a given set of lumber [52].

2.3. Lumber data

Red oak, a hardwood species growing widely in Eastern U.S. Forests and used in all segments of the U.S. wood products industry, was the wood of choice for this study [53]. While lumber from

Table 1
Length and width summary and difficulty rank for the 11 cutting bills used in this study.

Cutting bill	Rank[a]	No. of parts	No. of widths	No. of lengths
A	1	5	3	4
B	2	10	4	9
C	3	25	7	16
D	4	5	3	5
E	5	4	4	4
F	6	12	4	6
Buehlmann	7	20	4	5
H	8	8	2	8

[a] The cutting bills were ranked from easiest to hardest as defined in Thomas's study [49], the ranking for the Wengert and Lamb [8] and Buehlmann [10] cutting bills was based on the same criteria as employed in Thomas' study.

different species have similar raw material characteristics and are processed the same way in the rough mills of the industry, red oak, due to its economic importance to the industry, has been closely researched and libraries of digitized lumber exist [46,47].

The study employed the following lumber qualities, ranked from best to worst quality: FAS, SEL, 1C, 2AC, and 3AC [4]. Since each lumber grade was used as a factor in the model, a five-factor model was created. Increments of 10% were used for creating the lumber grade combinations. Three replicates of each lumber cut-up simulation were conducted to smooth out random variations. For this purpose, three lumber grade or grade combination samples were randomly selected from the 1998 Kiln Dried Red Oak Data Bank [47] using RR2's data randomization utility [45] for each lumber grade combination.

2.4. Statistical model

Each lumber quality was made up with between 0% and 100% of the lumber contained in each lumber set tested. Lumber quality combinations always summed to 100%. Since five different lumber qualities were involved, a five-factor mixture design [54] was applied. The five factors are the proportion of each lumber quality utilized in a given lumber set. Three AC lumber was constrained with an upper bound of 80%, since 3AC, the lowest quality lumber used in this study is not capable of yielding the larger/wider parts demanded by typical industry cutting bills. Fig. 2 shows the treatment combinations of the design. Table 2 shows the details of the lumber grade mixture design executed to derive the model's response surface for the eight cutting bills (Table 2, columns 1–6).

The simulated yields (Table 2, columns 7–14) from the 25 grade combination sample runs on RR2 [45] were used to build the response surface. However, since the lumber quality combination with the least-cost was searched for, Eq. (1) had to be employed for the transformation of yields to cost. Eq. (1) correlates yield, the quality distribution, the market price for each lumber quality, and processing costs with total costs.

2.5. Cost calculations

Like the steel [13], glass [14], paper [15,29], or other industries [16,17,24], the hardwood industry faces trade-offs when trying to minimize its raw material purchasing costs. In the hardwood industry, to determine the lumber quality combination that satisfies each cutting bill at the lowest raw material (e.g. lumber) and processing cost, cost information for each lumber quality was acquired to build a cost-response surface.

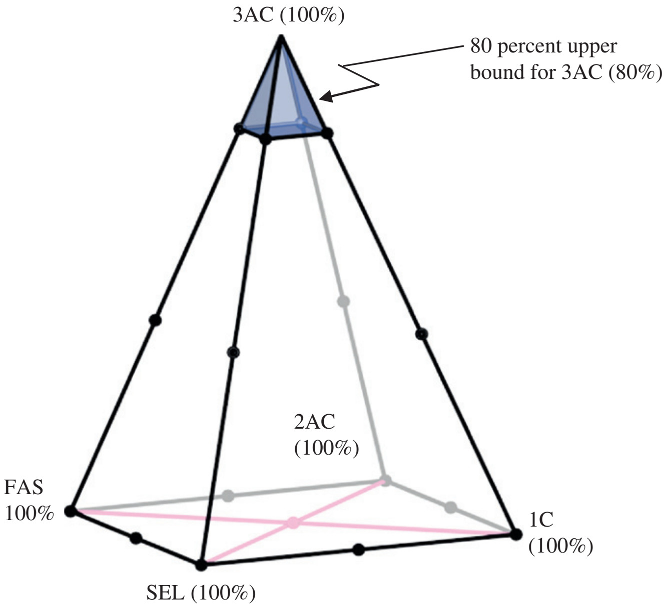


Fig. 2. Design space and treatment combinations for a 5-factor mixture design with an 80% upper bound for 3A Common lumber.

The secondary wood industry trades hardwood lumber in board feet, a volume of one foot by one foot by one inch. Typically, trades occur in thousand board feet increments (mbf), or approximately 2.36 m^3. Price information for 4/4 in thick, kiln dried red oak lumber published in the Weekly Hardwood Review [55], a trade publication, was used to calculate total lumber costs per thousand board feet (mbf) for satisfying a given cutting bill. Lumber prices used were, in particular: FAS – $1570 per mbf, SEL – $1350 per mbf, 1C – $1000 per mbf, 2AC – $748 per mbf, and 3AC – $500 per mbf.

While lower quality lumber is considerably less expensive ($500 per mbf for 3AC versus $1570 per mbf for FAS), lower quality lumber requires more input material and processing efforts to extract the same amount of usable parts compared to higher quality lumber. Thus, lower quality lumber is less expensive to purchase, but creates higher costs when processing. As a rough approximation of true processing costs involved in processing lumber in rough mills of the secondary wood products industry, Buehlmann and Zaech [56] calculated processing costs to be $200 per thousand board feet of lumber processed in the mill. Since lower quality lumber requires more input lumber to obtain an equal amount of usable parts compared to higher quality lumber, lower quality lumber is penalized and the sum of raw material (lumber) cost plus processing cost approximately reflects the true costs incurred. Production costs thus become the sum of market price of lumber (Mi) plus $200 processing costs (Pi), e.g., FAS – $1770 per mbf, SEL – $1550 per mbf, 1C – $1200 per mbf, 2AC – $948 per mbf, and 3AC – $700 per mbf. Eq. (1) calculates total costs (lumber plus processing) for using a given solution. Total cost is then used in the second order polynomial model (Eq. (2)) to generate the cost-response surface based on which the minimum cost point can be located:

$$\text{Cost}_j = \frac{\sum_i^5 G_i(M_i + P_i)}{\text{Yield}_j} \tag{1}$$

where G_i is the proportion of each lumber quality, M_i the market price per mbf of each lumber quality, P_i the processing cost per mbf of each lumber quality, i is equal to 1 for FAS, 2 for SEL, 3 for

Table 2
Design matrix for 5-factor mixture design with 80% upper bound for 3A Common lumber and average yield response from 3 replicates for 8 cutting bills tested.

Runs	FAS (%)	SEL (%)	1Com (%)	2ACom (%)	3ACom (%)	Average yield (%)							
						A	B	C	D	E	F	Buehlmann	H
1	0	0	0	20	80	29.31	37.39	44.17	37.16	15.59	8.92	27.03	19.65
2	0	0	0	60	40	36.71	47.70	49.38	43.02	24.88	18.29	37.06	35.52
3	0	0	0	100	0	42.99	54.98	54.76	48.36	30.95	26.67	47.93	46.29
4	0	0	20	0	80	32.59	44.65	46.37	39.72	21.41	16.45	36.02	31.18
5	0	0	50	50	0	50.09	60.74	60.76	54.14	43.90	43.62	57.68	54.57
6	0	0	50	50	0	49.54	60.36	60.38	53.96	44.37	41.57	57.21	54.68
7	0	0	60	0	40	45.30	56.49	56.68	50.10	38.62	40.79	52.46	50.24
8	0	0	100	0	0	56.43	65.61	65.50	60.08	53.60	54.03	63.83	60.79
9	0	20	0	0	80	33.80	46.40	45.80	40.50	24.37	23.76	39.02	34.97
10	0	50	0	50	0	49.23	62.47	60.17	55.46	48.32	52.93	59.78	56.53
11	0	50	0	50	0	48.30	63.12	60.76	55.88	49.03	52.66	59.09	57.35
12	0	50	50	0	0	55.39	67.37	66.28	60.75	59.95	59.78	65.83	63.34
13	0	50	50	0	0	55.38	67.32	66.03	60.93	58.25	59.30	65.11	62.57
14	0	60	0	0	40	44.00	58.96	54.83	51.17	44.79	48.21	53.98	52.49
15	0	100	0	0	0	54.59	69.56	64.01	61.78	63.34	61.13	66.16	64.95
16	50	0	0	50	0	56.50	66.74	67.00	61.24	60.03	58.78	65.28	60.93
17	50	0	0	50	0	56.24	66.75	66.69	61.14	60.51	59.70	64.70	61.08
18	50	0	50	0	0	63.39	71.01	71.42	66.81	66.33	67.60	70.92	66.49
19	50	0	50	0	0	63.79	70.99	71.36	67.02	66.41	67.30	70.66	67.04
20	50	50	0	0	0	62.86	72.93	72.26	67.81	68.02	68.72	72.45	68.57
21	50	50	0	0	0	62.13	71.97	71.33	67.33	66.78	68.19	71.83	67.67
22	60	0	0	0	40	53.63	64.35	63.92	59.06	58.50	55.49	61.31	58.75
23	60	0	0	0	40	53.16	64.36	63.98	58.73	57.92	55.65	61.55	58.60
24	100	0	0	0	0	70.11	76.08	76.05	73.21	72.64	75.50	76.68	71.80
25	100	0	0	0	0	69.85	76.21	76.61	73.55	72.43	75.61	76.96	71.92

Table 3
Regression parameters for total production cost surfaces of the eight cutting bills investigated.

Cutting bill factor	A	B	C	D	E	F	Buehlmann	H
Intercept	2609.52	1933.41	1703.49	2031.93	4917.70	7639.73	2607.00	3558.46
FAS	−0.80	3.91	6.16	3.80	−24.77	−52.97	−302.50	−10.95
SEL	2.41	3.05	7.18	4.79	−24.20	−48.91	−238.70	−11.09
1Com	−4.85	−0.97	1.28	−0.34	−26.5	−53.65	−718.00	−15.49
2ACom	−4.13	−2.27	−0.02	−0.73	−19.27	−43.44	−662.00	−16.09
FAS × SEL	−0.01	0.00	0.00	−0.00	−0.00	−0.05	−139.20	−0.01
FAS × 1Com	0.00	0.00	0.00	0.00	−0.05	−0.04	6.47	−0.00
FAS × 2ACom	0.02	0.00	0.01	0.01	−0.18	−0.21	−132.20	0.01
FAS × 3ACom	−0.02	−0.03	−0.02	0.01	−0.47	−0.85	−999.30	−0.26
SEL × 1Com	−0.00	0.00	−0.00	0.00	−0.02	−0.08	−111.70	−0.019
SEL × 2ACom	0.02	0.00	0.03	0.00	−0.07	−0.26	−218.60	+0.00
SEL × 3ACom	−0.02	−0.04	−0.00	0.02	−0.39	−1.21	−1272.70	−0.33
1Com × 2ACom	−0.00	0.00	−0.00	0.00	0.08	−0.11	−186.90	−0.01
1Com × 3ACom	−0.04	−0.05	−0.00	−0.01	−0.34	−0.89	−1236.90	−0.32
2ACom × 3ACom	−0.00	0.02	−0.00	−0.00	−0.04	0.21	821.10	0.05

1C, 4 for 2AC, and 5 for 3AC, and *j* is the observation of a quality combination run.

2.6. Model generation

Finding the global optimal minimum cost solution for cutting bills with respect to raw material (lumber) plus processing costs is the objective of the model. A second order polynomial model (Eq. (2)) was used to fit the lumber quality plus processing cost-response surface. SAS Institute's Inc. statistical software package, SAS 8.2 [57], was used to generate the model and analyze the data:

$$u_y = \beta_0^* + \sum_{i=1}^{5} \beta_i^* x_i + \sum \sum_{i<j} \beta_{ij}^* x_i x_j \tag{2}$$

where u_y is the cost of satisfying a given cutting bill, x_i and x_j are the proportions of each lumber grade, β_0^* is the intercept, β_i^* is the coefficient of linear terms; β_{ij}^* is the coefficient of the interaction terms, *i* and *j* are equal to 1 for FAS, 2 for SEL, 3 for 1C, 4 for 2AC, and 5 for 3AC.

Based on the lumber grade plus processing cost-response surface created by SAS 8.2 [57], an iterative search over the complete solution space is conducted to locate the lowest cost point, corresponding with the least-cost lumber grade-mix solution. The SAS code used is shown in Appendix A, and more details about the procedure, initial values, and the number of iterations can be found in Zuo [58].

3. Results and discussions

Results for the eight cutting bills used in this study [8,49,50] are shown and a discussion about the results is given. Thereafter, the Decision Support System (DSS) to minimize raw material (lumber) procurement costs is presented.

3.1. *Least-cost lumber grade-mix solutions*

The full model for the lumber grade – total production costs (e.g., lumber costs plus processing costs) – is shown in Eq. (3) [11]:

$$\begin{aligned}\text{Cost} = {} & 2607 - 302.50 \times \text{FAS} - 238.70 \times \text{SEL} \\ & -718.00 \times \text{1Com} - 662.00 \times \text{2Acom} - 139.20 \times \text{FAS} \times \text{SEL} \\ & +6.47 \times \text{FAS} \times \text{1Com} - 132.20 \times \text{FAS} \times \text{2ACom} \\ & -999.30 \times \text{FAS} \times \text{3ACom} - 111.70 \times \text{SEL} \times \text{1Com} \\ & -218.60 \times \text{SEL} \times \text{2ACom} - (3)1272.70 \times \text{SEL} \times \text{3ACom} \\ & -186.90 \times \text{1Com} \times \text{2ACom} - 1236.90 \times \text{1Com} \times \text{3Acom} \\ & +821.10 \times \text{2ACom} \times \text{3ACom} \qquad (3)\end{aligned}$$

Using this fitted response surface, the program conducts an interactive search for the minimum cost point. Table 3 displays the parameters for each factor (quality of lumber) and each factor interaction for the eight cutting bills employed in this study. The polynomial regression model parameters are different for each cutting bill, accounting for the variability in part requirements by each cutting bill. Using these polynomial regression surface model parameters, iterative searches were conducted to find the least-cost lumber grade-mix (e.g. lowest cost) solution using SAS [57].

Table 4
Optimal lumber grade-mix to minimize total production cost based on the five-factor statistical model with interactions (with processing costs included).

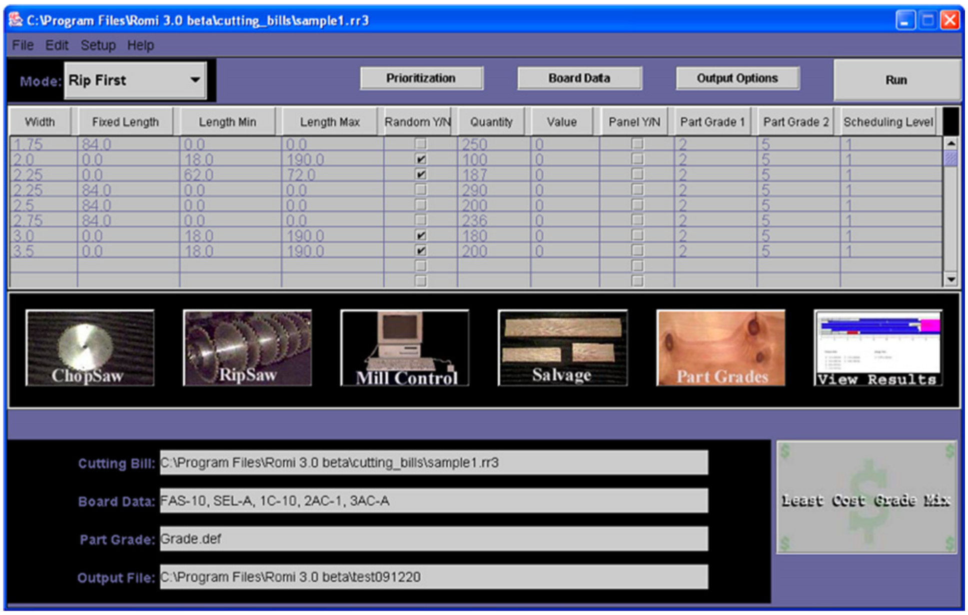
Cutting bill	Difficulty rank	With $200/mbf processing cost				
		FAS (%)	SEL (%)	1Com (%)	2ACom (%)	3ACom (%)
A	1				100	
D[a]	4				100	
C	3				20	80
B	2				100	
H	8			70		30
E[a]	5	50		30		20
Buehlmann[a]	7			80		20
F[a]	6		60	10		30

[a] Cutting bills for which the optimal least-cost lumber grade mix shifted when processing costs were included in the model.

Table 4 shows the least-cost lumber grade-mix solution for the eight cutting bills tested in this study. Results for the Buehlmann cutting bill [50], the most thoroughly tested and analyzed cutting bill of the study, indicate that the lowest cost solution consists of using 80% 1C and 20% 3AC lumber. The sizeable amount of better quality, 1C lumber required for the minimum cost solution, is due to the large number of long and wide parts that are required by the Buehlmann cutting bill. As pointed out before, such long and wide parts are difficult to obtain in the small clear areas of low-quality (e.g., 2AC and 3AC) lumber. To investigate the sensitivity of the model to changing lumber prices, a scenario involving the Buehlmann cutting bill [50] was tested with all lumber prices reduced by $200 per mbf. In this case, when the lower grade lumber gets disproportionally cheaper (a $200 per mbf price reduction for each lumber quality reduces the total price for FAS by 11%, SEL by 13%, 1C by 17%, 2AC by 21%, and 3AC by 29%), more lower quality lumber is requested for the least-cost lumber grade-mix solution. The least-cost solution found by the model in this case is 70% 1C and 30% 3AC lumber, e.g., more lower quality lumber is requested by the model.

Cutting bills can be ranked according to the ease of cutting all the parts required. For example, a cutting bill that requires no parts longer than 50 in and wider than 3 in is an easy-to-cut cutting bill. A cutting bill asking for a large number of parts longer than 70 in and wider than 4.5 in, conversely, would be a difficult-to-cut cutting bill [44]. Using a ranking created by Zuo et al. [44] in an earlier study, cutting bills in Table 4 have been listed in increasing order of difficulty. Thus, cutting bill A is the easiest-to-cut cutting bill, while cutting bill F is the most difficult-to-cut cutting bill (Table 4, column 2). When cutting bills are harder-to-cut, e.g. when their difficulty rank gets higher, the minimum cost lumber quality mix (e.g. the least-cost lumber grade-mix solution) requires more higher quality lumber to be used in the process to obtain the larger parts needed. However, since lower quality lumber is less expensive per unit of part obtained, the model always tries to use as much lower quality lumber as possible.

In an attempt to verify the merit of the new methodology, Buehlmann et al. [52] compared solutions from the new, statistical, polynomial model described in this article with minimum cost solutions derived with a traditional, linear



Width	Fixed Length	Length Min	Length Max	Random Y/N	Quantity	Value	Panel Y/N	Part Grade 1	Part Grade 2	Scheduling Level
1.75	84.0	0.0	0.0	☐	250	0	☐	2	5	1
2.0	0.0	18.0	190.0	☑	100	0	☐	2	5	1
2.25	0.0	62.0	72.0	☑	187	0	☐	2	5	1
2.25	84.0	0.0	0.0	☐	290	0	☐	2	5	1
2.5	84.0	0.0	0.0	☐	200	0	☐	2	5	1
2.75	84.0	0.0	0.0	☐	236	0	☐	2	5	1
3.0	0.0	18.0	190.0	☑	180	0	☐	2	5	1
3.5	0.0	18.0	190.0	☑	200	0	☐	2	5	1
				☐			☐			
				☐			☐			

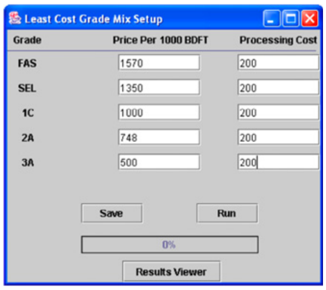
Cutting Bill: C:\Program Files\Romi 3.0 beta\cutting_bills\sample1.rr3
Board Data: FAS-10, SEL-A, 1C-10, 2AC-1, 3AC-A
Part Grade: Grade.def
Output File: C:\Program Files\Romi 3.0 beta\test091220

Fig. 3. ROMI 3.0 data entry GUI to control the rough mill operations settings.

programming-based least-cost lumber grade-mix model, OPTIGRAMI [41]. The new model presented in this article found, on average of ten cutting bills tested, 3.6% cheaper solutions than did the traditional model. The maximum cost savings from the new model was 9.4%. However, OPTIGRAMI found two lower cost solutions, one cheaper by 5.3% and one by 0.8%. Buehlmann et al. [52] suspect the reason for this inferior performance of the new model to be associated with the large increments used in generating the cost-response surface (10% lumber quality increments used in the preliminary simulation tests to generate the cost response surface).

3.2. Decision Support System (DSS)

Advanced algorithms such as the least-cost lumber grade-mix solution discussed in this publication allow practitioners to solve complex problems without knowledge of the underlying algorithms. However, the solution has to be presented as a user-friendly, easy to understand, and easily accessible Decision Support System (DSS) [59,60]. The USDA Forest Service has created and maintains a number of DSS intended to help the wood products industry to better compete in the global marketplace. For example, the Ultimate Grading and Remanufacturing System (UGRS) [61] helps sawmills improve their lumber quality sorting, SOLVE assists sawmill managers in improving efficiency and solving problems commonly found in hardwood sawmills [62], or Cost of Sawing Timber (COST) calculates the cost of operations per minute and per unit output for hardwood sawmills [63]. ROMI, "*The ROugh MIll simulator … is a computer software package for personal computers that simulates current industrial practices for … lumber processing* (p. 2 [64])." ROMI 3.0, the most current rough mill simulator, offers a wide range of operational settings, allowing industrial practitioners to simulate almost any rough mill. Fig. 3 shows the main Graphical Users' Interface (GUI) of ROMI. The GUI (Fig. 3) allows practitioners to enter the operational data necessary to simulate the cut-up of lumber according to their operation's set-up. Thereafter, a second GUI (Fig. 4) allows users to enter data pertinent to their lumber-purchasing situation. Once all data have been entered, the underlying rough mill simulation program, ROMI, runs the lumber cut-up simulation necessary to obtain the lumber yield-data used to calculate and create the response surface in SAS 8.2 [57]. The least-cost lumber grade-mix solver algorithm (Appendix A) then finds the minimum cost raw material (lumber) solution and returns these values to the user (Fig. 5).



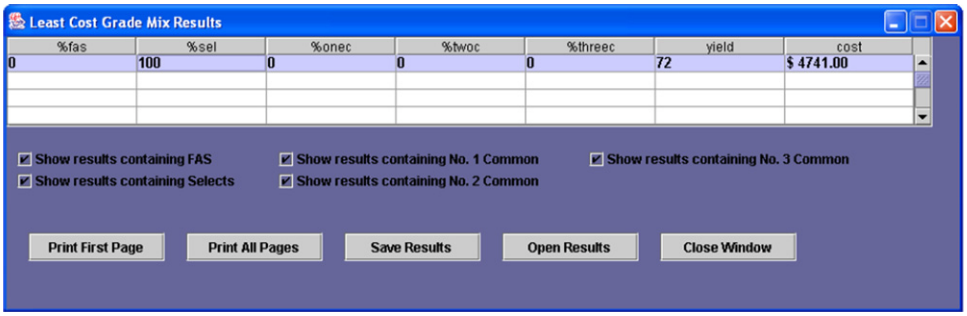
Grade	Price Per 1000 BDFT	Processing Cost
FAS	1570	200
SEL	1350	200
1C	1000	200
2A	748	200
3A	500	200

Fig. 4. Data entry GUI for the least-cost lumber grade-mix solver algorithm.

However, what appears as a fairly straightforward process to the user, in fact, involves some rather advanced programming. While the lumber cut-up simulation program, ROMI 3.0 [64], is a local application and runs on individual user's computers, it also contains the interface to the least-cost lumber grade-mix algorithm. However, since the least-cost lumber grade-mix algorithm needs access to a copy of SAS' statistical package and industry practitioners are highly unlikely to have SAS' software [57] installed on their premise, Weiss and Thomas [64] set-up an Internet connection between the ROMI package run on individual user's computers and a server running the SAS' statistical package in the USDA Forest Service's laboratory. Thus, the user runs ROMI 3.0 on his local computer to obtain the necessary lumber cut-up information (Fig. 3) and enters lumber purchasing and processing cost information (Fig. 4), then ROMI feeds this information to SAS 8.2 [57] running on a remote USDA Forest Service server. The server creates the response surface that is used to find the minimum cost lumber quality solution (e.g. the least-cost lumber grade-mix) and returns the minimum cost solution to the user's GUI (Fig. 5). The user thus obtains the least-cost lumber grade-mix solution from running algorithms on his computer and on a remote government server. Although the user is aware of this fact since he had to make sure that his machine is connected to the Internet, nothing in the execution of the code indicates that part of the calculation is done on a remote machine. Thus, for the user, the program is simple to use and delivers the least-cost lumber grade-mix solution without the need to install advanced, expensive statistical software on local computers.

3.3. Implications

The methodology used for the least-cost lumber grade-mix solver discussed in this article can potentially be applied to other problems in industries that entails the selection of different materials at different costs to achieve a defined outcome. While hardwood lumber quality and its respective cost was the input variable in this example, the steel or glass industries can similarly choose different input materials and processing variables to achieve an outcome with specified characteristics. The paper or engineered wood products industries have choices when selecting their input material and processing parameters to achieve specified outcomes. For problems like this, the model developed in this



%fas	%sel	%onec	%twoc	%threec	yield	cost
0	100	0	0	0	72	$ 4741.00

☑ Show results containing FAS
☑ Show results containing Selects
☑ Show results containing No. 1 Common
☑ Show results containing No. 2 Common
☑ Show results containing No. 3 Common

Fig. 5. Solution GUI for displaying the least-cost lumber grade-mix solution.

research should be considered, especially when optimizing problems that do not necessarily have a linear relationship.

4. Summary

A statistical model to find the minimum cost lumber quality mix (called the least-cost lumber grade-mix problem in industry parlance) was developed. The model uses a mixture designed to establish a test protocol to obtain simulated yields from the USDA Forest Service's ROMI 3.0 rough mill lumber cut-up simulator. Results from these simulations are then used to build a polynomial cost-response surface that allows for an exhaustive search for the lowest cost lumber quality mix.

The minimum-cost lumber quality-mix solutions found by the newly developed statistical model described in this article tend to use as much low-quality lumber (2AC and 3AC) as possible. Higher quality lumber is only called for when part requirements call for many large, i.e. long and/or wide, parts to be obtained from a given set of lumber. The minimum lumber cost search model developed is sensitive to lumber and processing cost changes. Tests have shown that the model results in lower cost lumber quality-mix decisions for wood products manufacturers compared to existing models. The new model has been incorporated into ROMI 3.0, the free USDA Forest Service rough mill lumber cut-up simulation program. ROMI allows users with only fundamental computer knowledge to simulate their operation and to minimize their lumber-purchasing costs. The industry is thus expected to embrace the new least-cost lumber quality-mix model as it helps their quest to lower production costs.

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Appendix A

```
/************************************************************
* SAS code for searching the optimal grade combination *
* based on yield and lumber cost, as well as processing *
* cost. *
* By Xiaoqiu Zuo *
************************************************************/
data LeastCostSearch;
input fas sel one two three yield;
cards;
/* Put the experimental design and results here*/
0          0          0          0.2        0.8        14.92
0          0          0          0.2        0.8        14.7
0          0          0          0.2        0.8        17.47
0          0          0          0.6        0.4        38.13
0          0          0          0.6        0.4        34.95
0          0          0          0.6        0.4        28.09
……
;
run;
%macro leastcost (fasc=, selc=, onecomc=, twocomc=, threecomc=, process=);
  data LeastCostSearch;
  set LeastCostSearch;
  fasc=&fasc;
  selc=&selc;
  onecomc=&onecomc;
  twocomc=&twocomc;
  threecomc=&threecomc;
  process=&process;
  fasnew=fasc+process;
  selnew=selc+process;
  onecomnew=onecomc+process;
  twocomnew=twocomc+process;
  threecomnew=threecomc+process;
  cost=(fas*fasnew+sel*selnew+one*onecomnew+two*twocomnew+three*threecomnew)/(10000*(yield/100));
data grid;
  set five end=eof;
  output;
  if eof then do;
      yield=.;
      cost=.;
      do fas=0 to 1 by 0.1;
        do sel=0 to 1 by 0.1;
```

```
              do one=0 to 1 by 0.1;
              do two=0 to 1 by 0.1;
              do three=0 to 0.8 by 0.1;
       output;
      end;
     end;
    end;
        end;
  end;
  end;
run;
proc rsreg data=grid out=costout(drop=_type_) noprint;
 model yield cost=fas sel one two three / lackfit predict;
run;
data final;
  set costout;
  if yield < 100 and fas+sel+one+two+three=1;
run;
proc sort data=final;
 by cost;
run;
proc print data=final(obs=40);
 format yield cost 8.2;
 title ’Optimal lumber grade mix with minimum cost’;
run;
%mend leastcost;
ods listing close;
ods rtf bodytitle;
%leastcost(fasc=1570,
   selc=1350,
   onecomc=1000,
   twocomc=748,
   threecomc=500,
   process=200)
ods rtf close;
ods listing;
```

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