Lumber Cost Minimization through Optimum Grade-Mix Selection

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ABSTRACT
Rough mills process kiln-dried lumber into components for the furniture and wood products industries, Lumber is a significant portion of total rough mill costs and lumber quality can have a serious impact on mill productivity, Lower quality lumber is less expensive yet is harder to process. Higher quality lumber is more expensive yet easier to process, The problem of balancing lumber cost with production capacity to yield the minimal total cost is referred to as the least-cost lumber grade mix problem, Several models to this problem have been proposed over the past decades, most of them relying on linear programming to find the optimum solution, However, research conducted for this project showed that the linearity assumption underlying these solutions is violated in more than 90 percent of the cases. Therefore, a new solution is needed,

A statistical optimization method based on a mixture design was employed. Using the USDA Forest Service's computer simulator ROMI-RIP, the model creates a lumber and cost response surface for all input solutions, By locating the lowest cost point on the surface, the corresponding lumber grade or grade mix is obtained. This optimal solution can consist of any number of different grades and allows the user to pre-specify the lumber grades and grade proportions available in a given situation, if necessary.
Keywords: Rough mill; Least-cost; Lumber grade combination; Mixture design.

1. INTRODUCTION

A rough mill is defined as an operation that converts hardwood lumber into dimension parts that subsequently will be machined and finished into usable parts for furniture, cabinets, or other secondary wood products. A cutting bill is a customer order that specifies the required part sizes, qualities, and quantities. The goal of a rough mill is to satisfy the cutting bill requirements at the overall least cost

Lumber cost can contribute more than 50 percent of total rough mill operating cost [1] [2], which makes rough mills particularly sensitive to changes in lumber quality and price. The proportion of raw material cost can be higher as a result of incorrect lumber allocation [1]. Like other industries, the wood products industry faces the problem of allocating input resources in such a way that maximum revenue from the input is obtained [3]. A rough mill strives for minimum cost by efficiently processing lumber of the appropriate quality class (called a "grade" in the industry) for a given cutting bill. This is referred to as the least-cost lumber grade-mix problem Such cost minimization creates competitive advantages by reducing raw material and processing costs without incurring additional expenses.

Hardwood lumber is classified into six grades named FAS, FAS ONE FACE (FIF), SELECTS(SEL), No.1 Common, No. 2A Common, and No. 3A Common. Grade allocation is mainly based on the amount of usable area available within a board [4]. Higher grade lumber such as FAS, FIF, and SEL has more clear surface area and fewer defects. In contrast, lower grades such as No. 2A Common and No. 3A Common boards are narrower and shorter with more defects. Higher quality lumber is expensive, but is easier to process and allows a greater number of larger parts to be obtained. It also results in higher material yields. Lower grade lumber is cheaper but does not yield as many large parts and results in lower material yield. A general rule is *to* cut long and wide parts from high-grade lumber and short and narrow parts from low-grade lumber. Determination of the optimal lumber grade mix that fulfills specific cutting bill requirements at minimum cost is difficult because the relationship between lumber quality and yield is complex and lumber prices for different grades (qualities) fluctuate over time.

The scientific search for the optimal lumber grade combination started in the 1960's [5]. Since then, various models have been created and some have been developed into software. Among the methodologies employed. linear programming is the most widely applied approach in solving the least-cost lumber grade-mix problem One reason for this preference is the ability of linear programming technology to produce fast solutions [6]. Linear programming is a technique to maximize or minimize (i.e., optimize) the objective variable by providing optimal combinations for constraint variables from a series of simple linear functions [7]. After WWII, the wood products industry was an early adopter of linear optimization technology. The first reported application of linear programming in the wood products industry was at a North Carolina plywood plant in 1957 [6]. Since then, linear programming has been widely employed to determine optimum processing strategies for wood products plants. Early applications were formulated to solve planning and distribution problems for the plywood industry [6][8][9]. Later, linear programming technology was extended to solve planning and inventory problems of sawmills [10], as well as machine loading and production problems for furniture companies [3][11]. It was Hanover et a1. [12] who first employed linear programming to solve the least-cost grade mix problem for hardwood dimension manufacturers.

Based on Hanover et al.'s [12] idea, several models were built. The best known, OPTIGRAMI evolved from initial work done by Martens and Nevel [13], followed by work of Timson and Martens [14] and Lawson, Thomas and Walker [15J. Other models were built by Carino and Foronda [1], Fortney [16], Suter and Calloway [17] and Harding and Steele [18].

The application of linear programming was believed to be helpful for the wood products industry to survive serious competitive pressures as it could help companies to become more cost competitive [11J. When striving to lower cost, linear programming was employed to solve the least-cost-grade mix problem. The crucial requirement for applying linear programming is that both objective functions and constraint functions be simple linear [6]. It was only in the early 1990's that Ruddel et a1. [19] indicated the nonlinear relationship between lumber price and yield. Ruddel et a1's observation did not refer to the relationship of lumber grade-mix and yield but to the relationship between lumber grades and prices. It nonetheless indicated that there might be a non-linear relationship between grade-mix and yield.

In fact, to the knowledge of the authors, the assumption of a linear relationship between yield and grade-mix has never been scientifically verified. Thus, the first objective of this study was to investigate the assumed linear relationship between yield and lumber grade mix. Should non-linearity be proven, a statistical optimization methodology was to be used to solve the least-cost lumber grade-mix problem to avoid the violation of the linearity assumption.

2. MATERIAL AND METHODS

The study used the lumber cut-up simulator and lumber data from the USDA Forest Service and cutting bills from academia and industry to investigate the relationship between yield and lumber grade mix and to search for the optimal grade-mix solution.

2.1 Lumber cut-up simulator

The feasibility of conducting studies on an actual production line is constrained by a limited amount of time, equipment, and research budgets. J3y using simulation, it is possible to obtain information that is not feasible to directly observe [20]. Also, the use of simulation to model cut-up operations permits easy and rapid comparative evaluation of the process, the lumber mix, or the product (cutting bill) while other factors can be held constant. ROMI-RIP (RR2), the USDA Forest Service's gang-rip-first simulation tool developed by Thomas [21][22], has been proven to accurately model an actual rough mill [23][24].

RR2 processes one board at a time. As a board is fed into the gang-ripsaw, the program determines the best feed (fence position) to produce the optimal rip strips and determines the optimal cutting patterns at the chop saw. The program stops processing boards when all part requirements are satisfied or all the boards in the dataset are processed. In this study, the RR2 simulator [22] was employed to collect simulated yield information from the cut-up of lumber in a rip-first rough mill. The settings employed are listed below:

- All- blades - movable arbor type
- Salvage cut to primary length and width
- Total yield used consists of primary and salvage yield (e.g., no excess salvage yield)
- Complex dynamic exponential part prioritization
- No random-width nor random-length parts
- Continuous update of part counts
- ¼ inch end and side trim

2.2 Cutting bill

A large part of customer orders included in cutting bills (approximately 95%) require part lengths between 5 inches and 85 inches and widths from 1 inch to 4.75 inches [25]. It is, however, difficult to include all part width and length combinations into one cutting bill for simulation purposes. To be able to make an inference for the population, the cutting bill created by Buehlmann [25] was used in this study with an adjustment of part quantities. This cutting bill (Table 1) represents the "average" cutting bill used by the wood products industry and researchers with respect to part sizes and quantities as defined by Buehlmann [25].

Table 1. Number of parts of each size required by the "Buehlmann" cutting bill.

Part width	Part length (in.)				
(in.)	10	17.5	27.5	47.5	72.5
1.50	136	297	433	243	10.3
2.50	152	298	480	262	98
3.50	46	102	146	88	57
4.25	49	99	458	85	40

To assure that the Buehlmann [25] cutting bill is not an anomaly, 10 additional cutting bills used by industry and published by various researchers [2][26] were included in these tests. The basic characteristics of these ten cutting bills are listed in Table 2.

Table 2. Basic characteristics of 11 cutting bills used in the study.

Cutting bill	Rank[a]	# of parts	# of widths	# of lengths
A	1	5	3	4
B	2	10	4	9
C	3	25	7	16
[)	4	5	3	5
E	5	4	4	4
F	6	12	4	6
Buehlmann	7	20	4	5
G	8	20	7	12
H	9	8	2	8
I	10	16	4	11
J	11	9	5	4

[a] The cutting bills were ranked from easiest to hardest as defined in Thomas's study [26].

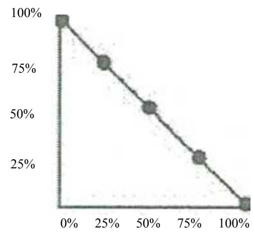
2.3 Lumber data

Red oak is the most abundant eastern United States hardwood species [27J and is the dominant species used by secondary hardwood manufacturers. accounting for 39 percent of all hardwood usage in the Nation [28]. Therefore, this is the lumber species used in this study. The lumber data used in this research is from the 1998 Kiln-Dried Red Oak Data Bank 129]. The five grades used in this study were FAS, SEL, 1 Common, 2A Common, and 3A Common lumber. For each grade combination, three sub-sample sets were composed by randomly choosing the boards from the data bank to allow performing three replicates of each test.

2.4 Experimental design

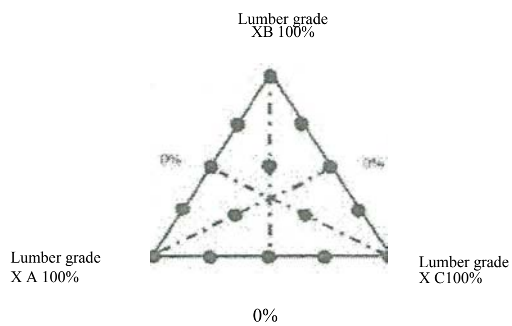
A mixture design is a special response surface methodology that is applied for optimizing several factors for a dependent variable [30]. The weight of each factor must lie between 0 and 1 and the sum of all factors must equal to 1. Unlike other experimental designs, the experimental space of mixture designs has n-l dimensions, where n is the number of factors. For the design of this study, each of the five lumber grades was considered a factor and each grade's weight could be between 0 and 1 with the constraint that the sum of all grades be equal to 1.

To investigate the relationship between yield and grade mix, only two- and three-grade combinations were tested because higher-grade combinations (e.g., four- and five-grade combinations) are unlikely to be used in industrial settings. Additionally, because FAS and SEL are normally combined together in lumber marketing [31], no FAS - SEL combination was tested in this study. Instead, a SEL&BETTER grade, which consisted of 34.8 percent FAS, 27.2 percent FIF and 38.6 percent SEL, was tested [32]. The design points for two-grade and three-grade combinations are shown in Figures 1 and 2 respectively. Preliminary tests showed that long and/or wide parts, such as dimension parts 72.5 inches long and 4 inches wide couldn't be obtained in sufficient numbers from 3A Common lumber alone, therefore, an upper bound constraint was applied for the 3ACommon lumber.



XA - The better grades in the grade mix
XB - The lower grade in the grade mix

.Figure 1. Mixture design points for testing two grade combinations.



XA - The better grades in the grade mix.
XB - T he lower grade in the grade mix.
XC - The lowest grade in the grade mix,

Figure 2. Mixture design points for testing three grade combinations.

2.5 Statistical analysis

The general second order polynomial model for a response surface is:

$$u_y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum \sum_{i<j} \beta_{ij} x_i x_j \quad (1)$$

where u_y -- yield of a given cutting bill

x_i -- the proportions of each lumber grade

β_0 -- the intercept

β_i -- the coefficients of linear terms

β_{ii} -- the coefficients of quadratic terms

β_{ij} -- the coefficients of the interaction terms

n -- number of factors

Due to the constraint $\sum_{i=1}^{n} x_i = 1$ that is applied in the mixture design, equation 1 is reduced to

$$u_y = \sum_{i=1}^{n} \beta_i^* x_i + \sum \sum_{i<j} \beta_{ij}^* x_i x_j \quad (2)$$

by transforming $\beta_i = \beta_0 + \beta_i + \beta_{ii}$, and $\beta_{ij} = \beta_{ij} - \beta_{ii} - \beta_{jj}$ [33]. A backward model selection method that excludes insignificant terms from the full model step by step using a level of significance of 0.05 was applied to build the model [34]. If the simple linearity condition holds between yield and grade combinations, the higher order coefficients β_{ij} * should not be significant based on a 0.05 level of significance. The hypothesis for this test thus is:

H_0: $\beta_{ij} = 0$: vs H a : $\beta_{ij} \neq 0$

Should the hypothesis above be rejected, a statistical model would have to be used to find the least-cost lumber grade mix since linearity between yield and grade mix would not hold. This response surface would have to include all five lumber grades with a constraint on 3A Common lumber. The model has to minimize total cost while fulfilling given cutting hill requirements. Therefore, lumber price, lumber yield by grade. and processing costs had to be included into the function as shown in equation 3:

$$\text{cost} = \frac{\Sigma G_i + P_i}{Yield} \quad (3)$$

where G is the percentage of each lumber grade; P is the price of each lumber grade; yield is the yield for a cutting bill; i is from 1 to 5, where 1 is PAS, 2 is SEL, 3 is 1Com, 4 is 2A Com, and 5 is 3A Com.

3. RESULTS AND DISCUSSION

The results from testing the null hypothesis on the two [umber grade mix combinations for the Buehlmann cutting bill [25] are shown in Figure 3. Six out of 12 grade combinations tested were found to have a non-linear relationship. These cases are shown with dashed lines in Figure 3.

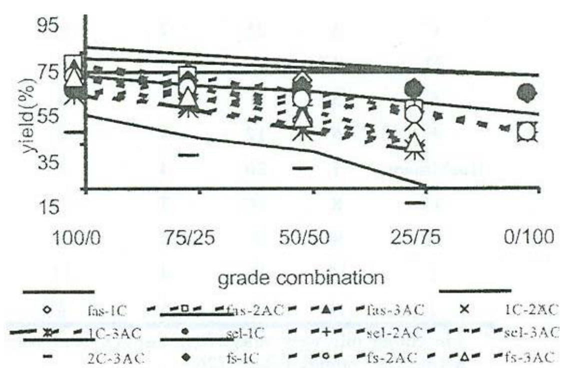


Figure 3. Yield and statistical results from testing the simple linearity assumption of two-grade lumber combinations.

Interestingly, non-linear behavior of the grade mix - yield relationship was found in all grade-mixes that involve one higher quality (e.g. FAS, SEL, or SEL&BETR) and one lower quality (e.g., 2A Common or 3A Common) grade. For the combinations consisting of more alike grades (FAS 1 Common, SEL&BETR - I Common, SEL - 1 Common, 1 Common - 2A Common, 1 Common 3A Common and 2A Common - 3A Common), a linear relationship between lumber grade mix and yield was found. This result may be explained by the increasing differences in lumber quality among grades. When two non-alike grades such as FAS 3A Common lumber are combined together, the yield change from altering the grade mix distribution is larger than when the grade mix is altered involving alike lumber grades. Thus, the larger impact on yield of changing grade-mix compositions of dislike grades, is more likely to lead to non-linear results.

Similar observations can be made when testing three-lumber-grade combinations and the Buehlmann cutting bill. All three-lumber-grade-combinations tested had at least one significant higher order term, which means all of the 10 three-grade combinations tested behaved non-linearly. In 5 out of 10 cases, the model required two interaction terms to be included. Dissimilar grades, as was observed for the two-grade model, lead to more nonlinear behavior of the yield grade mix relationship. The interaction term for the lowest and highest grade of any given grade-mix combination was found to be significant in a]) cases except in the case of the SEL&BETR - I Common 2A Common grade mix. These three grades are "neighbors" in the quality-scale of lumber grades.

To assure validity of the observations made using the Bnehlmann cutting bill, 10 industrial cutting bills (Table 2) used by Thomas (26) and Wengert and Lamb (2) were subjects of the same three grades tests. Table 4 shows the results for these 10 industrial cutting bills in regards to linear behavior of the lumber grade-mix - yield relationship. Black areas denote a cutting bill yield - grade mix relationship that requires at least one higher order polynomial term to construct the response surface. It can be seen that no cutting bill satisfies the simple linearity assumption for all grade combinations.

Table 4. Cutting bill- three grade lumber combinations with and without linear relationships.

Cutting bill / Grade mix	A	B	C	D	E	F	b*	G	H	I	J
FAS-1Com-2ACom					■	■	■			■	■
SEL&BETR-1Com-2ACom					■	■	■			■	■
SEL-1Com-2ACom			■			■	■	■	■	■	■
SEL-2ACom-3ACom					■	■	■	■	■	■	■
SEL-1Com-3ACom		■	■			■	■	■	■	■	■
FAS-1Com-3ACom		■			■	■	■	■	■	■	■
1Com-2ACom-3ACom		■	■		■	■	■	■	■	■	■
SEL&BETR-1Com-3ACom		■	■		■	■	■	■	■	■	■
SEL&BETR-2ACom-3ACom	■	■	■		■	■	■	■	■	■	■
FAS-2ACom-3ACom		■	■	■	■	■	■	■	■	■	■

Note: Black areas denote cutting bills where a higher order polynomial model is needed at the 0.05 level of significance.
b* is Buehlmann's cutting bill

Table 4 shows that linearity between yield and lumber grade combinations is dependent on the characteristics of the cutting bill and the lumber grade combinations involved. Generally speaking, cutting bills that are viewed as more difficult to be processed and satisfied [26J require more complex models (e.g. more higher order terms) to describe their yield - grade mix response surface. For example, cutting bills I and J, which are the most difficult cutting bills used in the study, ranked 9^{th} and 11^{th} (e.g., third most complex and most complex) in terms of complexity of the model required to describe the yield - grade mix relationship.

These results show that the simple linearity assumption for the grade-mix - yield relationship used in several linear programming models [12] [13] [14] [l5] [16] [18] does not reflect the true relationship between yield and grade mix. The complexity of the yield - grade mix response makes it impossible to predict the shape of the yield response from a particular cutting bill and a particular lumber grade combination. The high frequency of non-linear behavior found in this study combined with the inability to predict which cutting bill - grade mix: combinations result in linear or non-linear responses, required a new least-cost-grade mix model to be created and tested.

The model created uses a five-factor mixture design with an 80 percent constraint on 3A Common lumber to determine the necessary simulation runs to establish a higher order response surface. Since cost is to be minimized, this surface is built using cost data based on lumber yield as well as on lumber and processing costs, as shown in equation 3. Once this response surface is created, the lowest surface point, e.g., the minimum cost point is searched for by specialized software [35].

Preliminary tests of the model show a high sensitivity to changing lumber and processing costs. For example, when processing costs increase, lower grade lumber is used less frequently and is substituted by higher quality lumber. Yield from lower grade lumber is lower and therefore more lumber needs to be processed to obtain the required parts. When processing costs are high, total costs are also higher when processing lower grade lumber, thus making a solution that employs more expensive higher grade lumber more cost efficient since less of it needs to be processed.

Further research needs to be conducted to verify and validate the model [36]. Also, additional effort needs to be spent on making the model relevant for industry use. That means creating a user-friendly Gill (Graphical User Interface) and assuring accessibility from the workplace [37]. Since the underlying statistical software package is expensive, a web-enabled solution will have to be developed. Other features, such as enabling the program to limit the lumber grades available as well as to put quantity limits on individual lumber grades, need to be incorporated into the software as well.

4. SUMMARY

In a time of increasing competitive pressure, decreasing production cost<; in the rough mill is a necessity for the secondary wood products industries. Minimizing lumber and lumber processing costs has the largest impact on rough mill costs, since they can account for more than 50 percent of all costs incurred.

Efforts to solve the least cost lumber grade mix problem have been made in the past decades. Most models were designed using a linear programming approach. However, the assumption of linear behavior between lumber grade-mix and yield was never scientifically proven. Results ii-om this study revealed that a linear relationship between lumber grade-mix and yield does exist only in some of the scenarios tested. These findings question the validity of models using linear programming.

To avoid the violation of the linearity assumption, a statistical optimization methodology was applied in a new model based on findings of this study. Preliminary findings indicate that the model predicts the lowest cost lumber grade-mix reliably and consistently. However, more work is needed to verify and validate the mode! and to make it user-friendly for industry-wide use.

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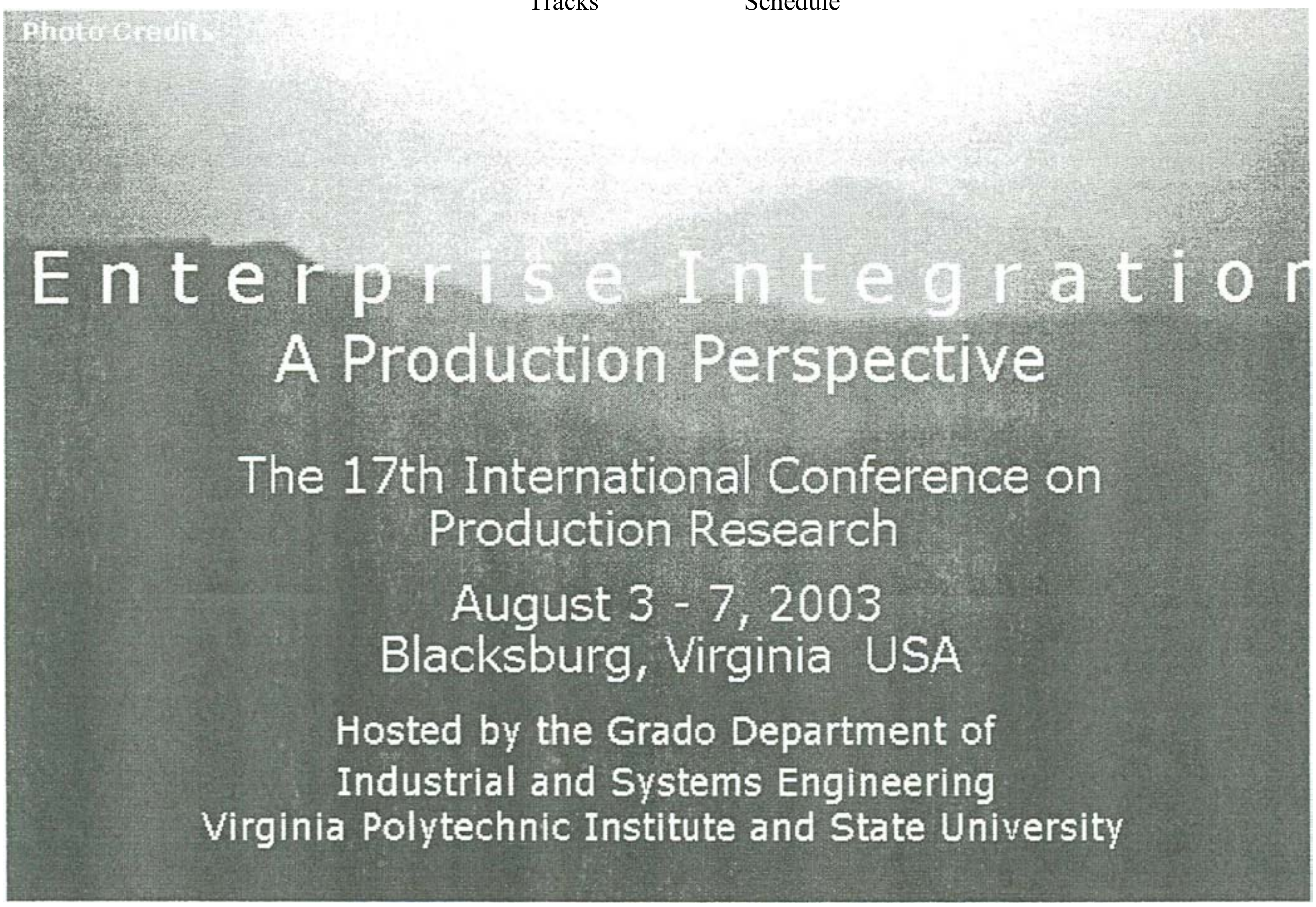

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