ROMI-3.1 Least-Cost Lumber Grade Mix Solver Using Open Source Statistical Software

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Abstract

The least-cost lumber grade mix solution has been a topic of interest to both industry and academia for many years due to its potential to help wood processing operations reduce costs. A least-cost lumber grade mix solver is a rough mill decision support system that describes the lumber grade or grade mix needed to minimize raw material or total production cost (raw materials plus processing cost). Because raw material costs in typical rough mills comprise 40 to 70 percent of total rough mill manufacturing expenses, the least-cost lumber grade mix problem, as it is referred to, is important.

An existing second-order polynomial least-cost lumber grade mix model integrated into the US Department of Agriculture (USDA) Forest Service's rough mill simulator, ROMI-3.0, which uses SAS 8.2 for statistical calculations, was used for the research described in this article. For this existing model, the USDA Forest Service purchased a SAS server license to allow free use of the software to least-cost lumber grade mix users via the Internet. Several issues around this rather involved setup necessitated the search for an alternative, local solution for the statistical computations. The open source statistical package R 2.7.2 was tested to see if it is an equivalent replacement for SAS 8.2. Comparisons of the SAS-based and a newly developed R-based least-cost lumber grade mix solver indicate no statistically significant difference between the two decision support systems. Therefore, the new R-based least-cost lumber grade mix solver was incorporated into ROMI-3.0. Thus, rough mill operators now have a new version of ROMI-3.0 with the integrated least-cost lumber grade mix solver at their disposal that does not require their computers to communicate with an outside server.

For typical solid hardwood products manufacturers in the United States, up to 70 percent of rough mill costs are incurred from the purchase of the hardwood lumber raw material (Carino and Foronda 1990, Wengert and Lamb 1994, Mitchell et al. 2005). Therefore, the industry focuses heavily on minimizing lumber raw material costs when producing solid hardwood dimension parts to reduce rough mill expenses to be able to competitively price their final product. Dimension parts, slightly oversized rectangular pieces of solid wood intended to become parts of final wood products, refer to all solid wood parts that are used in the furniture, cabinet, and all other dimension part industries. In industry parlance, dimension parts are also called blanks, cutting stock, component parts, or furniture parts (Buehlmann 1998) and are cut in rough mills. Rough mills are composed of a series of processes that produce semifinished components starting with lumber planning followed by rip and cross-cut sawing and ending with buffering the semifinished dimension parts. Cutting bills, a list of needed pieces, describe the dimension parts to be produced in rough mills. Cutting bills contain information about dimension part sizes, quantities, qualities, acceptability of randomly sized parts, and information about glued-up or finger-jointed parts. The efficiency of the cut-up of lumber into dimension parts in rough mills is typically measured as the ratio of aggregate dimension part surface area output to aggregate lumber area surface input called yield (Gatchell 1985, Buehlmann 1998). Yield is the single most important metric because all solid hardwood products manufacturers strive to reduce lumber raw material cost.

Apart from industry efforts to increase yield, few options (such as, e.g., process improvements, quality control,

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material size reductions, and material substitution) exist for solid hardwood products manufacturers to reduce solid hardwood lumber dimension part costs. Manufacturers can also strive to minimize their total lumber costs by purchasing the lowest cost lumber grade or grade mix to satisfy a given cutting bill, a practice referred to as the least-cost lumber grade mix search in the industry (Zuo 2003; Zuo et al. 2004; Buehlmann et al. 2004, 2008; Buck 2009). Hardwood lumber, a natural, heterogeneous material of varying geometrical size containing randomly dispersed character marks (e.g., defects) that cover a part of the total lumber board area (Buehlmann and Thomas 2000), is graded according to the National Hardwood Lumber Association's (NHLA) quality standards (NHLA 2003). Official NHLA hardwood lumber quality classes (e.g., ''grades'' in industry parlance) are First and Seconds (FAS), Selects (SEL), No. 1 Common, No. 2A Common, and No. 3A Common. No. 3B Common lumber is also used, but not for appearance products (e.g., products for which appearance is most important) but mostly for industrial products (e.g., packaging; Table 1).

Large price differentials among quality classes exist. Processing costs are minimized by purchasing higher-grade lumber (Willard 1970) because higher-grade lumber requires fewer cuts to remove defects and less material has to be processed thanks to the higher yield achieved from the input material. Also, cutting bill requirements influence the grade that should be used to achieve minimum lumber costs. Lumber cost minimization requires a dynamic search for the least-cost lumber grade or grade mix, taking into account cutting bill requirements and lumber grade price differentials at given times (Zuo 2003; Zuo et al. 2004; Buehlmann et al. 2004, 2008; Buck 2009). Because market forces set hardwood lumber prices, they fluctuate according to supply and demand for each grade and relative to each other over time. It is these changing price differentials that open the opportunity to minimize total hardwood dimension part costs in a rough mill by finding the least-cost lumber grade or grade mix for a specific cutting bill given hardwood lumber market prices at a given moment (Buehlmann et al. 2004).

The least-cost lumber grade mix solver developed by Buehlmann et al. (2004, 2008), Zuo (2003), and Zuo et al. (2004) is a departure from previous solutions by Englerth and Schumann (1969), Hanover et al. (1973), Martens and Nevel (1985), Carino and Foronda (1990), Steele et al. (1990), Timson and Martens (1990), Harding (1991), Fortney (1994), Suter and Calloway (1994), Lawson et al. (1996), and Hamilton et al. (2002), which all used linear programming techniques to find the least-cost lumber grade mix. Such models require that both objective and constraint functions are simple linear (Winston 1994), an assumption that Zuo et al. (2004) proved to be violated by the yield–lumber grade mix relationship. Therefore, Zuo et al. (2004) and Buehlmann et al. (2004, 2008) used a second-order polynomial model, which does not require linearity to produce valid results to find the least-cost lumber grade mix solution. Buehlmann et al. (2008) also compared the performance of the new least-cost lumber grade mix solver with OPTIGRAMI (Lawson et al. 1996), a widely used least-cost lumber grade mix solution created, maintained, and provided for free by the US Department of Agriculture (USDA) Forest Service. A performance comparison by Buehlmann et al. (2008) showed that the new solution of Buehlmann et al. provides lower-cost grade mix solutions with maximum savings of up to 10 percent of total lumber purchasing and processing costs.

However, the least-cost lumber grade mix solver solution from Zuo et al. (2004) and Buehlmann et al. (2008) requires statistical algorithms provided by SAS 8.2 (proc RSREG command; SAS Institute Inc. 2002). SAS is an expensive, specialized statistical business analysis software unlikely to

Table 1.—National Hardwood Lumber Association guidelines.

Grade	Board width and length minimum	Minimum part size	Clear area (%)	Allowable cuts to obtain part	
				Part length	Cuts
FAS	15.2 cm × 2.44 m (6 in. × 8 ft)	10.2 cm × 1.50 m or 7.6 cm × 2.13 m (4 in. × 5 ft or 3 in. × 7 ft)	83⅓	1.22–2.13 m (4–7 ft)	1
				2.44–3.36 m (8–11 ft)	2
				3.66–4.57 m (12–15 ft)	3
				≥4.88 m (≥16 ft)	4
SEL	10.2 cm × 1.83 m (4 in. × 6 ft)	10.2 cm × 1.50 m or 7.6 cm × 2.13 m (4 in. × 5 ft or 3 in. × 7 ft)	66⅔	Better side same as FAS, reverse side better than 1C	
1C	7.6 cm × 1.22 m (3 in. × 4 ft)	10.2 cm × 0.61 m or 7.6 cm × 2.13 m (4 in. × 2 ft or 3 in. × 7 ft)	66⅔	0.92–1.22 m (3–4 ft)	1
				1.50–2.13 m (5–7 ft)	2
				2.44–3.05 m (8–10 ft)	3
				3.36–3.97 m (11–13 ft)	4
				≥4.27 m (≥14 ft)	5
2AC	7.6 cm × 1.22 m (3 in. × 4 ft)	7.6 cm × 0.61 m (3 in. × 2 ft)	50	0.61–0.92 m (2–3 ft)	1
				1.22–1.5 m (4–5 ft)	2
				1.83–2.13 m (6–7 ft)	3
				2.44–2.74 m (8–9 ft)	4
				3.05–3.36 m (10–11 ft)	5
				3.66–3.97 m (12–13 ft)	6
				(≥14 ft)	7
3AC	7.6 cm × 1.22 m (3 in. × 4 ft)	7.6 cm × 0.61 m (3 in. × 2 ft)	33⅓	No limit to no. of cuts	
3BC	7.6 cm × 1.22 m (3 in. × 4 ft)	3.8 cm × 0.61 m (1.5 in. × 2 ft)	25	No limit to no. of cuts	

be found in hardwood lumber processing companies. Therefore, Thomas and Weiss (2006) installed a server running SAS 8.2 at the USDA Forest Service research laboratory in Princeton, West Virginia, so that industry users could remotely have their calculations performed. Rough mill operators investigating the least-cost lumber grade mix solution for their dimension parts needs would run the ROMI-3.0 lumber cut-up simulation on their local computers. They would then transfer the yield data to the USDA Forest Service server running SAS 8.2, which calculates the least-cost lumber grade mix solution and feeds the results back to the remote user. Experience has shown that even with free access to SAS 8.2, rough mill users are reluctant to use the least-cost lumber grade mix solver. Reasons assumed to play a role for industry users' reluctance to use the new least-cost lumber grade mix solver incorporated in ROMI-3.0 include the need to submit proprietary yield and cost data to a government server. Other concerns are the need for an Internet connection, and limitations as to the number of users being able to connect to SAS 8.2 simultaneously at any given time. In its quest to make the US hardwood industries more competitive in global markets, the USDA Forest Service's Wood Education and Resources Center (WERC) funded research to replace SAS 8.2 with a no-cost, locally run statistical package. The WERC thus addressed industry concerns and helped the USDA Forest Service save resources currently spent on purchasing and maintaining the SAS 8.2 statistical package and its associated server. R 2.7.2 (Venables et al. 2008), an open source, free statistical package has response surface modeling capabilities similar to those of SAS 8.2 and was considered as a candidate for this endeavor. Consequently, this research investigated whether R 2.7.2 can provide equivalent statistical calculations to those of SAS 8.2 and whether the least-cost lumber grade mix solver using R 2.7.2 (Buehlmann et al. 2004) can be incorporated into ROMI-3.0 (Weiss and Thomas 2005, Thomas and Weiss 2006).

Materials and Methods

This research involved the least-cost lumber grade mix solver developed by Zuo (2003) and Buehlmann et al. (2004); two statistical software packages, SAS 8.2 (SAS 2002) and R 2.7.2 (Venables et al. 2008); and the USDA Forest Service's rough mill simulation software (Thomas 1999a, 1999b; Weiss and Thomas 2005; Thomas and Weiss 2006).

Least-cost lumber grade mix solver

Buehlmann et al. (2004) and Zuo et al. (2004) conducted the original research leading to the current least-cost lumber grade mix solver solution incorporated into ROMI-3.0 (Weiss and Thomas 2005, Thomas and Weiss 2006).

Using the least-cost grade mix solver requires the rough mill operator to enter rough mill processing information, a cutting bill, as well as raw material and processing costs into ROMI-3.0. ROMI-3.0 then runs simulations for 25 lumber combinations to obtain the initial data to build a cost response surface used for the least-cost determination (Table 2; Zuo 2003). Lumber yields from the 25 simulations are transformed to cost data using cost equations from Zuo (2003). Equation 1 transforms yield to raw material lumber cost per cubic meter (or thousand board feet [MBF]) of parts. A raw material cost response surface is then generated using the yields from the 25 lumber grade combinations discussed above (Table 2) and the cost data.

Table 2.—25 Lumber grade combinations executed by ROMI-3.0 for initial response surface data.

Run no.	FAS	SEL	1C	2AC	3AC
1	0	0	0	20	80
2	0	0	0	60	40
3	0	0	0	100	0
4	0	0	20	0	80
5	0	0	50	50	0
6	0	0	50	50	0
7	0	0	60	0	40
8	0	0	100	0	0
9	0	20	0	0	80
10	0	50	0	50	0
11	0	50	0	50	0
12	0	50	50	0	0
13	0	50	50	0	0
14	0	60	40	0	0
15	0	100	0	0	0
16	50	0	0	50	0
17	50	0	0	50	0
18	50	0	50	0	0
19	50	0	50	0	0
20	50	50	0	0	0
21	50	50	0	0	0
22	60	0	0	0	40
23	60	0	0	0	40
24	100	0	0	0	0
25	100	0	0	0	0

$$\mathrm{Cost}_j = \frac{\sum_{i=1}^{5} G_i M_i}{\mathrm{Yield}_i} \qquad (1)$$

where

G_i = the proportion of each lumber grade;
M_i = the market price per cubic meter (or MBF) of each lumber grade;
i = 1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common, and 5 for 3A Common; and
j = observation of a grade combination run.

Equation 2 transforms yield to total production cost (raw material plus processing costs) per cubic meter (or MBF) of parts and a total production cost response surface is generated.

$$\mathrm{Cost}_i = \frac{\sum_{i=1}^{5} G_i (M_i + P_i)}{\mathrm{Yield}_i} \qquad (2)$$

where

G_i = the proportion of each lumber grade;
M_i = the market price per cubic meter (or MBF) of each lumber grade;
P_i = the processing cost per cubic meter (or MBF) of each lumber grade;
i = 1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common, and 5 for 3A Common; and
j = observation of a grade combination run.

For simplification, Equation 2 is used in the least-cost grade mix solver. Users who only wish to optimize raw material costs enter a zero value as processing cost. The cost response surface model is generated using the response surface regression (RSREG) procedure of SAS 8.2.

Statistical software packages

SAS 8.2 is a widely used, powerful statistical analysis software package created, maintained, and sold by SAS Institute Inc., Cary, North Carolina (SAS 2002). The original version of the least-cost lumber grade mix solver (Zuo et al. 2004; Buehlmann et al. 2004, 2008) uses a second-order polynomial cost response surface based on SAS 8.2's proc RSREG command to generate the solution. The cost response surface created is based on predicted yield information obtained from ROMI-3.0 (Weiss and Thomas 2005, Thomas and Weiss 2006), and lumber and processing cost information supplied by the user.

For this research, in an effort to use the latest version of the SAS software, it was decided to use SAS 9.2 (SAS Institute Inc. 2007) for the tests, although this necessitated the repetition of earlier test runs (Buehlmann et al. 2004, 2008).

R 2.7.2 (Venables et al. 2008), an open source, no-cost statistical package with similar surface modeling capabilities as SAS 9.2 under the response surface methodology (RSM) command, is considered an alternative to SAS 9.2. R 2.7.2 can be run on local computers without incurring charges, avoiding the need to perform statistical calculations on the USDA Forest Service's server running SAS. A copy of R 2.7.2 (Murdoch 2008) and the RSM package (Lenth 2009) was downloaded from the Internet and instructions were studied (Venables et al. 2008). Help in coding the R-based least-cost lumber grade mix solver was obtained from the Laboratory for Interdisciplinary Statistical Analysis at Virginia Polytechnic Institute and State University (LISA 2009), a statistical consulting group associated with the Statistics Department at the university. The R-based least-cost lumber grade mix solver uses the RSM procedure to create the polynomial response surface model. In R 2.7.2, the model is created using the method of least squares. Canonical analysis determines the shape of the cost response surface and ridge analysis determines the absolute minimums or maximums, following essentially the same methods as SAS 9.2 (SAS 2007). The predict (PRED) procedure can be used to predict a grid of least-cost lumber grade mix solutions; in this way, it is not necessary to examine the entire cost response surface. Based on studying the literature and the mathematics involved, it is expected that the R-based least-cost lumber grade mix solver will return the same or similar results to the SAS-based solution.

ROMI settings

Zuo et al. (2004) and Buehlmann et al. (2004, 2008) used ROMI-RIP 2.0 (Thomas 1999a, 1999b) for their research. Weiss and Thomas (2005) and Thomas and Weiss (2006) developed ROMI-3.0 as an improved version of ROMI-RIP 2.0 that also includes cross-cut first capabilities. To avoid confounding of main effects from testing the SAS 9.2–based least-cost lumber grade mix solver to the R 2.7.2–based least-cost lumber grade mix solver, it was decided to use ROMI-3.0 for initial tests. Additional tests were made to compare the original, validated SAS 9.2 least-cost lumber grade mix solver to the new R 2.7.2 least-cost lumber grade mix solver using the SAS 9.2 statistical package and ROMI-RIP 2.0 simulation program and R 2.7.2 statistical package and ROMI-3.0 simulation. Settings of ROMI-3.0 and ROMI-RIP 2.0 for these tests were

- Rip-first lumber cut-up
- All blades movable arbor (24-in. arbor width)
- Salvage parts cut to primary length and width
- Total yield includes primary and salvage yields (e.g., no excess salvage)
- Complex dynamic exponential part prioritization
- No random-width nor random-length parts
- Continuous update of parts
- 0-inch end trim
- ¼-inch side trim, rip kerf, and chop kerf

Lumber data

The Data Bank for Kiln-Dried Red Oak Lumber (Gatchell et al. 1998) was used for this research. Lumber grades used were FAS, SEL, 1 Common, 2A Common, and 3A Common. ROMI randomly generates lumber files according to the 25 lumber grade combinations in Table 2 (Zuo 2003). ROMI-3.0 and ROMI-RIP 2.0 use these lumber files to simulate the lumber cut-up process and returns estimated lumber yields, e.g., the cubic meter (or board feet) of parts obtained over the cubic meter of raw material used (Gatchell 1985, Buehlmann 1998). This yield data is then transformed to cost data using Equation 2. The lumber grade combinations and the cost data are used to build a cost response surface using the least-cost grade mix solver (Zuo 2003).

For the least-cost lumber grade mix solver to find the minimum cost solution, lumber raw material and processing costs must be provided. For this research the following prices taken from the 2009 *Weekly Hardwood Review* (Anonymous 2009) were used: US$470 per m^3 (US$1,110 per MBF) of FAS lumber, US$398 per m^3 (US$940 per MBF) of SEL, US$326 per m^3 (US$770 per MBF) of 1 Common, US$254 per m^3 (US$600 per MBF) of 2A Common, and US$222 per m^3 (US$523 per MBF) of 3A Common lumber. For all tests involving processing costs, US$85 per m^3 (US$200 per MBF) infeed lumber processed was used for all lumber grades (Buehlmann and Zaech 2001).

Cutting bills

Ten industry cutting bills originally used by Wengert and Lamb (1994; cutting bill E), Thomas (1996; cutting bills A, B, C, D, F, G, H, I, and J), and Buehlmann (1998; Buehlmann cutting bill) were used to compare the SAS-based least-cost lumber grade mix solver with the R-based least-cost lumber grade mix solver. Details of the cutting bills used can be found in Table 3 (Zuo et al. 2004) and a more detailed description of the cutting bills is provided in Buck (2009).

Validation of R 2.7.2–based least-cost lumber grade mix solver

The R 2.7.2–based least-cost lumber grade mix solver uses the rough mill simulator ROMI-3.0 (Weiss and Thomas 2005, Thomas and Weiss 2006) and the statistical package R 2.7.2 (Venables et al. 2008). As discussed above, the R-

Table 3.—Rank of difficulty for each cutting bill (Zuo et al. 2004).

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
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 (1996). The ranking for Wengert and Lamb's (1994) cutting bill E and the Buehlmann (1998) cutting bill were ranked using the same criteria used in Thomas (1996).

based least-cost grade mix solver is compared with the SAS 9.2–based (SAS 2007) least-cost lumber grade mix solver. Additional tests were made to compare the original SAS 9.2–based least-cost lumber grade mix solver with the new R 2.7.2–based least-cost lumber grade mix solver using the SAS 9.2 statistical package and ROMI-RIP 2.0 simulation program and the R 2.7.2 statistical package and ROMI-3.0 simulation program. A two-paired t test ($\alpha = 0.05$) was performed to test for differences between yield and the minimum cost solutions (lumber cost or lumber plus processing cost) from both least-cost lumber grade mix solvers (R 2.7.2 and SAS 9.2).

Results

Least-cost lumber grade mix solutions derived by ROMI-3.0 and SAS 9.2 and by ROMI-3.0 and R 2.7.2 were compared to see if both solutions are equivalent. Scenarios involving both lumber costs only and lumber and processing costs combined were tested. Table 4 shows the least-cost lumber grade mix solutions from both the SAS 9.2–based and the R 2.7.2–based versions of the least-cost lumber grade mix solvers for the 11 cutting bills (Zuo et al. 2004) tested. No processing costs were considered in this first set of test runs. Table 5 shows the least-cost lumber grade mix solutions from the SAS 9.2–based and R 2.7.2–based versions including US\$85 per m^3 (US\$200 per MBF) processing costs for all grades for the 11 cutting bills (Zuo et al. 2004) tested.

Least-cost lumber grade mix solutions derived by ROMI-RIP 2.0 and SAS 9.2 and by ROMI-3.0 and R 2.7.2 were compared to see if both solutions are similar. Scenarios involving lumber costs only were tested. Table 6 shows the least-cost lumber grade mix solutions from both the SAS 9.2–based and the R 2.7.2–based versions of the least-cost lumber grade mix solver for the 11 cutting bills (Zuo et al. 2004) tested. No processing costs were considered in this set of test runs.

Discussion

It was expected that the R-based solutions would be equivalent or similar to those of the SAS-based solutions. For direct comparison, the same lumber data, cost data, and initial 25 lumber grade combinations were used to generate the cost response surface and least-cost lumber grade mix.

Tables 4 and 5 show that the least-cost lumber grade mix solutions for the SAS-based and R-based least-cost lumber grade mix solvers were exactly the same. For example, in Table 4, the least-cost lumber grade mix solution for cutting bill A included 100 percent 2AC lumber with a raw material cost of US\$553 per m^3 (US\$1,305 per MBF) for both the SAS 9.2–based and the R 2.7.2–based least-cost lumber grade mix solvers. Similarly, in Table 5, the least-cost lumber grade mix solution for cutting bill A included 100 percent 1C lumber with a total production cost (raw material plus processing) of US\$85 per m^3 (US\$1,667 per MBF) for both the SAS 9.2–based and R 2.7.2–based least-cost lumber grade mix solvers. Since all results from both least-cost lumber grade mix solvers are identical, it is proven that the R 2.7.2–based least-cost lumber grade mix solver is an equivalent alternative for the SAS 9.2–based least-cost lumber grade mix solver. Thus, no statistical testing (at the 95% significance level) was necessary.

Least-cost lumber grade mix solver solutions for raw material only favor using lower quality lumber showing that processing costs are important in determining true least-cost lumber grade mix solutions. In the original setup for the least-cost lumber grade mix model by Zuo (2003) and Buehlmann et al. (2004), only a maximum of 80 percent 3AC lumber is allowed. This is because tests have shown that solutions using more than 80 percent 3AC lumber often result in extremely low yields (Zuo 2003, Buehlmann et al.

Table 4.—Raw material LCGM solutions with the SAS 9.2–based and R 2.7.2–based LCGM solvers.[a]

Cutting bill	SAS 9.2–based LCGM solver								R 2.7.2–based LCGM solver							
	F	S	1	2	3	Y	C_1	C_2	F	S	1	2	3	Y	C_1	C_2
A				100		45.98	553	1,305				100		45.98	553	1,305
B			40	60		53.76	527	1,243			40	60		53.76	527	1,243
C			90	10		51.69	617	1,457			90	10		51.69	617	1,457
D				100		42.17	603	1,423				100		42.17	603	1,423
E	80			20		52.24	821	1,938	80			20		52.24	821	1,938
F	80			20		60.71	704	1,661	80			20		60.71	704	1,661
G	80			20		62.12	688	1,623	80			20		62.12	688	1,623
H	80			20		62.62	682	1,610	80			20		62.62	682	1,610
I			100			56.62	576	1,360			100			56.62	576	1,360
J				100		51.45	494	1,166				100		51.45	494	1,166
Bue.			100			56.83	575	1,356			100			56.83	575	1,356

[a] LCGM = least-cost lumber grade mix; F, S, 1, 2, 3, Y, C_1, and C_2 = FAS, SEL, 1C, 2AC, 3AC, yield (%), cost (US\$ per m^3), and cost (US\$ per MBF), respectively; Bue. = Buehlmann.

Table 5.—Total production LCGM solutions with the SAS 9.2–based and R 2.7.2–based LCGM solvers.[a]

Cutting bill	SAS 9.2–based LCGM solver								R 2.7.2–based LCGM solver							
	F	S	1	2	3	Y	C_1	C_2	F	S	1	2	3	Y	C_1	C_2
A			100			58.19	706	1,667			100			58.19	706	1,667
B			90	10		60.00	673	1,589			90	10		60.00	673	1,589
C			100			53.01	776	1,830			100			53.01	776	1,830
D			100			54.21	758	1,789			100			54.21	758	1,789
E	80			20		52.24	984	2,322	80			20		52.24	984	2,322
F	80			20		60.71	843	1,990	80			20		60.71	843	1,990
G	80			20		62.12	824	1,945	80			20		62.12	824	1,945
H	80			20		66.10	807	1,905	80			20		66.10	807	1,905
I			100			56.62	726	1,713			100			56.62	726	1,713
J			100			64.34	639	1,508			100			64.34	639	1,508
Bue.	20		80			61.76	712	1,681	20		80			61.76	712	1,681

[a] LCGM = least-cost lumber grade mix; F, S, 1, 2, 3, Y, C_1, and C_2 = FAS, SEL, 1C, 2AC, 3AC, yield (%), cost (US$ per m^3), and cost (US$ per MBF), respectively; Bue. = Buehlmann.

Table 6.—Raw material LCGM solutions with original SAS 9.2–based and new R 2.7.2–based LCGM solvers (using ROMI-RIP 2.0 and ROMI-3.0, respectively).[a]

Cutting bill	SAS 9.2–based LCGM solver								R 2.7.2–based LCGM solver							
	F	S	1	2	3	Y	C_1	C_2	F	S	1	2	3	Y	C_1	C_2
A				100		48.36	506	1,241				100		45.98	553	1,305
B				100		55.13	461	1,088			40	60		53.76	527	1,243
C			90		10	55.17	572	1,351			90	10		51.69	617	1,457
D			40	60		47.76	593	1,399				100		42.17	603	1,423
E	80	20				60.62	754	1,779	80			20		52.24	821	1,938
F		60	10		30	51.57	656	1,547	80			20		60.71	704	1,661
G			80		20	52.73	579	1,367	80			20		62.12	688	1,623
H	70			30		61.12	664	1,566	80			20		62.62	682	1,610
I			90		10	57.16	553	1,304			100			56.62	576	1,360
J				100		53.57	475	1,120				100		51.45	494	1,166
Bue.			100			61.42	531	1,254			100			56.83	575	1,356

[a] LCGM = least-cost lumber grade mix; F, S, 1, 2, 3, Y, C_1, and C_2 = FAS, SEL, 1C, 2AC, 3AC, yield (%), cost (US$ per m^3), and cost (US$ per MBF), respectively; Bue. = Buehlmann.

2004). The trend of the model to use high amounts of low quality lumber is expected since lower-grade lumber has lower raw material cost. On the other hand, lower-grade lumber contains a larger number of defects and has fewer clear areas and therefore requires larger amounts of lumber to be processed to satisfy a cutting bill. Therefore, the addition of processing costs penalizes lower quality lumber so that the inclusion or exclusion of processing cost does influence least-cost lumber grade mix results. For example, the least-cost lumber grade mix solution for cutting bill A without processing cost (Table 4) is 100 percent 2AC. The least-cost lumber grade mix solution with processing cost included (Table 5) is 100 percent 1C. Clearly, the addition of processing cost penalizes lower quality lumber since larger amounts of low quality lumber are needed to satisfy a cutting bill (Buehlmann et al. 2008). When including processing costs, input lumber grade quality requested either increased or stayed the same. Some of the more difficult cutting bills (cutting bills G, H, and I) required substantially higher quality lumber for a least-cost lumber grade mix solution when processing costs of US$85 per m^3 ($200 per MBF) were added. Solutions derived with the R 2.7.2–based least-cost lumber grade mix solver were always equivalent to that from the SAS 9.2–based model. Therefore, the new R 2.7.2–based least-cost lumber grade mix solver is an equivalent replacement of the SAS 9.2–based least-cost lumber grade mix solver. The new R-based least-cost lumber grade mix solver Decision Support System (DSS) incorporated into ROMI-3.0 will make it easier for industry participants to obtain and use the model. It provides convenient, unlimited access to the statistical package (R 2.7.2) needed to find the least-cost lumber grade mix solution for a given cutting bill. Given that lumber costs constitute the major cost proportion for rough mills, the R-based least-cost lumber grade mix solver will prove valuable in the industry's efforts to minimize those costs.

The additional tests that compare the original SAS 9.2–based least-cost lumber grade mix solver with the new R 2.7.2–based least-cost lumber grade mix solver show differences in all cost solutions between the two least-cost lumber grade mix solvers and some differences in lumber combinations in Table 6. For example, the least-cost lumber grade mix solution for cutting bill A (Table 6) gives the same lumber combination, but different cost solutions for the two programs. The lumber combination for both least-cost lumber grade mix solvers is 100 percent 2AC; the yield for the SAS-based solver is 48.36 percent and the cost is US$506 per m^3 (US$1,241 per MBF), and for the R-based solver the yield is 45.98 percent and the cost is US$553 per m^3 (US$1,305 per MBF). For other cutting bills, both the lumber grade combination and the cost solution will vary. For example, the lumber combination for cutting bill B is

100 percent 2AC with a yield solution of 55.13 percent and a cost of US$461 per m^3 ($1,088 per MBF) for the SAS-based program, and it is 40 percent 1C and 60 percent 2AC with a yield solution of 53.76 percent and a cost of US$527 per m^3 ($1,243 per MBF) for the R-based program. A two-paired t test ($\alpha = 0.05$) indicates no significant difference in yield ($P = 0.6609$). However, there is a significant difference in cost ($P < 0.0001$) between the original SAS-based least-cost lumber grade mix solver (that uses ROMI-RIP 2.0) and the new R 2.7.2–based least-cost lumber grade mix solver (that uses ROMI-3.0). These cost differences may be due to differences in the lumber combination and the yield generated by each rough mill simulation program. The yield differences may be due to changes in the all blades movable arbor and in the lumber cut-up optimization between ROMI-3.0 and ROMI-RIP 2.0. Previous results (Tables 4 and 5) show no differences in the statistical packages R 2.7.2 and SAS 9.2, which was the main objective of this research. Table 6 indicates a significant cost difference between the rough mill simulation programs ROMI-RIP 2.0 and ROMI-3.0. Future research is needed to determine which rough mill simulation program provides more realistic results.

Summary and Conclusions

The least-cost lumber grade mix solution has been a topic of interest to both industry and academia due to the importance of lumber costs to wood products manufacturers. Solutions to the problem are obtained from least-cost lumber grade mix solver rough mill DSS that describe the lumber grade or grade mix that minimizes raw material or total dimension parts production costs (raw material plus processing cost).

Earlier least-cost lumber grade mix solvers used linear models to predict least-cost lumber grade mix solutions. Research has shown that linear modeling is sufficient only for a limited number of lumber grade combinations. A second-order polynomial least-cost lumber grade mix model was developed to predict least-cost lumber grade mix solutions without relying on the linearity assumption. This new least-cost lumber grade mix solver was incorporated into ROMI-3.0 and uses SAS 8.2 for statistical calculations. Since few, if any, rough mill operators have access to SAS, the USDA Forest Service purchased a SAS server license to allow free access to least-cost lumber grade mix users via the Internet. This research project investigated the possibility of eliminating the need for the government server running SAS by using the open source statistical package R 2.7.2 instead of SAS 8.2.

Comparison of the SAS-based and R-based least-cost lumber grade mix solvers indicates no difference between the two decision support systems. Therefore, the new R-based least-cost lumber grade mix solver was incorporated into ROMI-3.0. Thus, the new version, ROMI-3.1, includes the R-based least-cost lumber grade mix solver, which can be installed and executed from a personal computer with no external computing resources.

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