Integrating the Least-Cost Grade-Mix Solver into ROMI

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ABSTRACT

Up to 70 percent of rough mill manufacturing expenses stem from raw material (lumber) cost. Rough mill costs can be reduced by optimizing the lumber grade or grades that are purchased. This solution is known as the least-cost lumber grade-mix solution. The least-cost lumber grade-mix solutions has been a topic of great interest to both the secondary hardwood industry and to academia since even small changes in raw material cost can contribute to substantial reduction in rough mill expenses.

A statistical model was developed for finding the least-cost lumber grade-mix which uses the rough mill simulator, ROMI-RIP 2.0, and the statistical package, SAS 8.2. The SAS 8.2-based least-cost lumber grade-mix model was validated by comparing SAS 8.2-based least-cost grade-mix solutions to OPTIGRAMI 2.0, a least-cost lumber grade-mix solver that relies on linear modeling. The SAS 8.2-based least-cost lumber grade-mix solver found lower cost solutions in 9 of 10 cutting bills that were tested. The SAS 8.2-based least-cost lumber grade-mix solver was packaged with ROMI 3.0, an updated version of ROMI-RIP, and provided to industry free of charge by the USDA Forest Service. The USDA Forest Service also purchased a SAS server license to allow least-cost lumber grade-mix solver users free access to SAS 8.2. However, industry users were reluctant to use the USDA Forest Service SAS server since it requires the user to enter individual cost and yield data to a government computer. This solution also required the user to have internet access and limited access to one user at any time. Thus, the goal of this research was to incorporate the least-cost lumber grade-mix solver into ROMI using the free, open source statistical package R 2.7.2. An R 2.7.2-based least-cost lumber grade-mix solver was developed and validated by comparing the R 2.7.2-based least-cost lumber grade-mix solutions to the updated SAS 9.2-based least-cost lumber grade-mix solutions. No differences

were found in the least-cost lumber grade-mix solutions from either solver. Thus, a new least-cost lumber grade-mix solver using the R 2.7.2 open source statistical package was created. R 2.7.2 is installed on each personal computer on which the USDA Forest Service's ROMI rough mill simulation software is installed and, thus, no external computing resources are needed when solving the least-cost lumber grade-mix problem.

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CHAPTER 1 Introduction

Up to 70 percent of rough mill costs stem from raw material lumber cost (Kline et al. 1998; Wengert and Lamb 1994; Carino and Forona 1990). Higher quality lumber has higher raw material cost while lower quality lumber has lower raw material cost. However, low quality lumber has more defects and, thus, requires a larger amount of lumber to satisfy a given cutting bill. In addition, lower quality lumber typically has an overall increased processing cost as compared with higher quality lumber (Williard 1970). To minimize overall production cost (raw material and processing cost), rough mill operators needs to optimize the lumber quality combination, known as the least-cost lumber grade-mix solution in industry parlance, for each cutting bill. The least-cost lumber grade-mix solution is affected by the cutting bill, the raw material/individual grade cost, and the processing costs incurred. Finding the least-cost lumber grade-mix solution is a challenging optimization problem that industry participants cannot solve without assistance.

Over the past decades, several, least-cost lumber grade-mix solvers, among them RIP-X (Harding and Steele 1997), OPTIGRAMI Version 2.0 (Lawson et al. 1996), OPTIGRAMI Version 1.0 for PC's (Timson and Martens 1990), and OPTIGRAMI (Martens and Nevel 1985), have been developed to assist rough mill operators in finding the least-cost lumber grade-mix solution. These least-cost grade-mix solvers rely on linear modeling to predict least-cost solutions. However, in 2004, Zuo et al. tested the assumption of linearity between lumber grades and yield and found that a linear relationship existed only in a limited number of cases. To address the shortcomings of existing models, Zuo (2003) and Buehlmann et al. (2004) developed a statistical model which was validated by Buehlmann et al. (2008). This new statistical model for solving the least-cost lumber grade-mix problem was incorporated into ROMI 3.0 (Thomas and Weiss 2006, Weiss and Thomas 2005) and relies on SAS 8.2 (SAS 2002) for statistical modeling.

SAS, a commercial statistical analysis software package created by SAS Institute, Inc. (SAS 2009) is expensive to license, an expense that few companies in the secondary wood products industry would be willing to incur. Therefore, the USDA Forest Service purchased a SAS server license allowing uses of the least-cost lumber grade-mix solver (Buehlmann et al 2004, Zuo 2003) incorporated into ROMI 3.0 (Thomas and Weiss 2006, Weiss and Thomas 2005) free access to SAS 8.2 via an internet connection. In spite of offering free access to SAS 8.2, industry users were reluctant to send individual yield and cost data to a government server. Using the server also required rough mill operators to have an internet connection and the SAS license limited access to one user at any time. In search of a more attractive, less cumbersome and less expensive solution, the open source, free statistical package R 2.7.2 (Venables et al. 2008) has been discussed as a possible alternative to SAS 8.2 (SAS 2002). R 2.7.2 is expected to have the same response surface modeling capabilities as does SAS 8.2. Using R 2.7.2 would benefit least-cost lumber grade-mix solver users by simplifying their computing needs and help the USDA Forest Service control operational costs as no server would have to be made available anymore. If R 2.7.2 is indeed capable of conducting the necessary statistical calculations equivalent to SAS 8.2, the new least-cost lumber grade-mix solver would be executable on a personal computer with no user license required, and no internet connection to a government server that limits the number of users to one at any time.

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CHAPTER 2 Hypotheses

Companies operating rough mills typically rely on human operators to decide what lumber-grade to purchase to minimize their production costs, a decision-making process known as finding the least-cost lumber grade-mix. Finding the least-cost-grade-mix, has attracted much attention over the past decades, with the first least-cost-grade-mix solvers being based on linear optimization models (Martens and Nevel 1985; Timson and Martens 1990; Lawson et al. 1996; Harding and Steele 1997). However, more recent research by Zuo et al. (2004) has shown that linear models are not sufficient for modeling least-cost-grade-mix solutions. As a consequence, Zuo et al. (unpublished) also developed a statistical response surface model that does not assume linearity between lumber grades or grade mixes and lumber yield (Zuo et al. 2004) to find least-cost grade-mix solutions for rough mill operators. This model was incorporated into ROMI-3.0 by Thomas and Weiss (2006) and made available to industry. The current least-cost grade-mix solver incorporated in ROMI-3.0 uses SAS 8.2 (SAS 2002) to perform the necessary statistical calculations. As with a typical software, SAS user's license carries annual costs exceeding $5,000, the USDA Forest Service offered free access to the SAS statistical package to users of ROMI-3.0 over the Internet. However, industry users are reluctant to send cost and yield data to a government server. Additionally, using the copy of SAS 8.2 installed on the USDA Forest Service server requires an internet connection, something which is not always readily available in the operation management rooms of the wood products industry. Also, due to restrictions in the contract between the USDA Forest Service, access to the SAS statistical package is limited to one user at any one time. Given all these complications, industry has been slow to take advantage of the cost reduction capabilities of ROMI-3.0.

To facilitate the industry's use of the cost-saving potential of ROMI-3.0's least-cost grade-mix search, a decision was made to search for a lower-cost, easier to implement solution for the necessary statistical calculations in the least-cost grade-mix solver program. Thus, the purpose of this research is to find an alternative statistical package that reduces cost for industry and the USDA Forest Service; that requires no data to be sent to a government server; that requires no internet connection from the computer on which ROMI-3.0 is run; and that allows any number of users to obtain solutions at the same time.

The R 2.7.2 statistical package (Venables et al. 2008) has been discussed as an alternative to SAS 8.2 (SAS 2002). R 2.7.2 has response surface modeling capabilities using the rsm procedure which uses the same algorithms as SAS 8.2's rsreg procedure. Thus, this research is investigating if, R can provide equivalent or improved statistical calculations to those of SAS 8.2. The hypothesis researched in this study then is that Buehlmann et al.'s (2008) least-cost grade-mix solver can be incorporated into the USDA Forest Service's rough mill simulator (ROMI-3.0; Weiss and Thomas 2005) using R 2.7.2 (Venables et al. 2008) as an equivalent alternative to SAS 8.2 (SAS 2002).

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CHAPTER 3 Literature Review

The wood product industry value chain is comprised of primary and secondary wood products. Primary products are cut directly from logs and include paper, sawmill, plywood, and composite materials such as particleboard or oriented strand board, among others. Secondary products are produced from primary products. Secondary products include flooring, cabinets, furniture and other products as shown below in Figure 3-1(Buehlmann 2009).

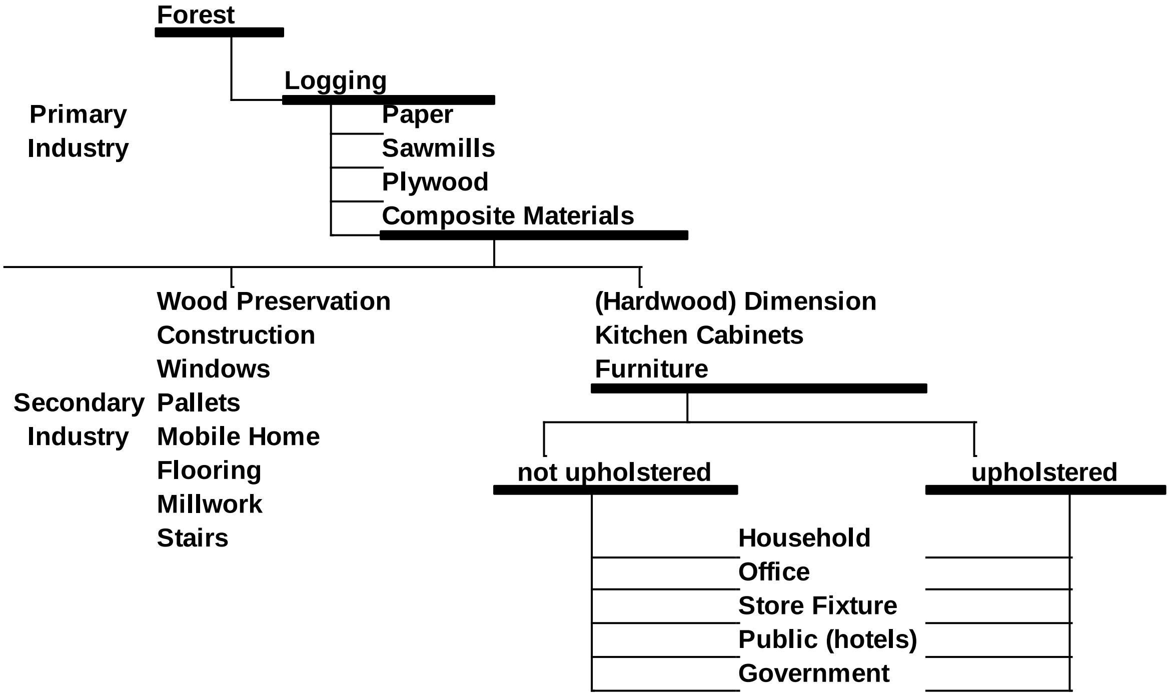

Figure 3-1:Wood Products Industry Classification

Two categories of the North American Industry Classification System (NAICS) pertain to the wood products industries in the U.S. NAICS code 321 provides statistics for the wood products manufacturing industries. Industries listed under NAICS 321 produce wood products such as "*lumber, plywood, veneers, wood containers, wood flooring, wood trusses, manufactured homes (i.e., mobile home), and prefabricated wood buildings* (Census 2007a)." The United States' wood products manufacturing industry employs over 500,000 workers with net sales over $101 billion annually (Census 2007b). NAICS code 337 provides statistics for the United States' furniture and related products manufacturing industry. The furniture and related products manufacturing industry produces secondary wood products such as "*furniture and related articles, such as mattresses, window blinds, cabinets, and fixtures* (Census 2007c)." The furniture and related products manufacturing industry employs over 500,000 workers with net sales over $83 billion annually (Census 2002d).

Wood, a natural, heterogeneous material has been used by humans since before recorded time. The solid wood products industry uses the most sustainable and environmentally friendly raw material available. Substitute products include steel, aluminum, plastic, and concrete (Bowyer et al. 2007a, Bowyer et al. 2007b). According to Bowyer et al. (2007b), solid wood products require less processing and, therefore, less energy consumption to be used for construction and household purposes. Unlike producing steel, aluminum, plastic, and concrete where large amounts of energy are consumed, solid wood products materials energy consumption comes mainly from accelerated drying of the material in dry kilns. Often, however, dry kilns are fueled by woody biomass such as bark, a bi-product from the tree. Using woody biomass to operate the dry kilns significantly reduces both energy cost and non-sustainable energy consumption. Bowyer et al. (2007b) describe environmental advantages of using wood products stating that "*At a time when society increasingly recognizes the need for cost-effective technologies that capture energy from the sun, one of our most common building materials – lumber – is produced using solar energy. Moreover, wood in minimally processed form (lumber) can be produced using comparatively little additional energy inputs, with over one-half of the energy used typically met through combustion of woody biomass, such as bark and sawdust, arising from harvesting or from wood processing. The fact that considerable energy is derived from biomass translates to reduced fossil fuel use and significant reductions in release of CO2 and other emissions related to fossil fuel combustion. There is no other common construction material that comes anywhere* *near lumber in terms of energy efficiency in production. This efficiency, in turn, means that emissions to air and water are also typically vastly lower when producing lumber than when producing functionally equivalent substitute products* (Bowyer et al. 2007b, p3)."

Processing wood is not only more cost and energy efficient when compared to competing materials, but wood is a completely sustainable resource. In the U.S., forest coverage area has remained relatively the same for the past 100 years (Bowyer et al. 2006) suggesting that wood is being consumed at a renewable rate. Society has recently become more environmentally conscious and has placed significant importance on maintaining wood resource sustainability. Future precautions will have to be taken to maximize wood resource sustainability. It is expected that, by 2030, logs will be harvested from tree plantations to minimize forest coverage loss by providing alternative logging sites. (Brown and Ball 2000; Sedjo 2001). In 1990, 3.5 percent of global forests were plantation forests (Brown and Ball 2000). In 2000, industrial plantations were estimated to provide 34 percent of global industry demands with an increase to 44 percent expected by 2020 (Sedjo 2001). Sedjo (2001) predicts plantation forests will supply up to 75 percent of industrial wood demand by 2050. In 2000, many plantation forests produced tropical species. Sedjo (2001) expects a demand for temperate forest plantations to provide alternative logging sites for temperate softwood and hardwood forests. An increase in temperate plantation forests potentially can increase sustainability of temperate forests as well.

3.1 Hardwood Industry

3.1.1 Introduction

Primary and secondary wood products are classified into two lumber categories, e.g. softwood and hardwood lumber. Softwood lumber is mostly used in construction but is also found in furniture, doors, windows, mouldings, and pulp and paper (Wikipedia 2009a). Hardwoods are also used for construction, furniture, and doors in addition to cabinets, flooring, and utensils (Wikipedia 2009b).

The process of manufacturing hardwood products involves tree harvesting and processing in sawmills to cut logs into lumber followed by rough mill processing to cut lumber into parts (Harvesting Process 2007; Smith et al. 2000). Parts are then machined, smoothed or sanded; pre-assembled; finished; and assembled (Buehlmann 2009). The following paragraphs summarize each of the hardwood processing stages from the forest to the saleable product briefly.

3.1.2 Hardwood Tree Harvesting

Harvesting typically includes the collaborative efforts of a forester, the landowner, and loggers (Smith et al. 2000). "*Foresters measure trees for volume, quality, and growth rate. They write forest management plans* (Smith et al. 2000)." Harvesting plans must consider soil, wildlife, streams, and other environmental factors. The forester then works with the landowner to select harvesting method and plan logging roads (Smith et al. 2000). Once all the preparatory work has been done, loggers fell and extract trees to a processing site. At the processing site, logs are cut into sections, a process called bucking in the industry, then sorted for distribution to sawmills, pulpmill, and chip yards. The logs are then loaded onto trucks and sent to their destinations (Hardwood Processing 2007; Smith et al. 2000).

3.2 Sawmill Processing

3.2.1 Sawmill Lumber Cut- Up

Logs sold to sawmills are stored in a log yard until needed for processing (Williston 1988). Before being sawn, logs are debarked and bucked to a suitable size for the headrig. The headrig in industry parlance is used for the primary breakdown of the log into slabs and lumber. A slab is the outer most part of a log, e.g. the first and last cut from the log. Secondary breakdown occurs in the resaw area where lumber is cut into smaller boards. The edger re-rips lumber for a final width by removing wane and defects on the edge, thereby, reducing the lumber's width followed by trimming, e.g. cross-cutting boards to square ends and to remove defects. Final boards are sorted, stacked, and stickered by thickness, length, width, and grade. The lumber is systematically air-dried or kiln-dried to minimize shrinking, warping, and checking associated with improper drying. Drying lumber also reduces the weight of the lumber and reduces the cost of shipping. According to the National Hardwood Lumber Association (NHLA 2003) drying standards, air-dried lumber typically has a moisture content of 15-30 percent. Kiln-dried lumber is dried to a standard moisture content level of 6-10 percent. Wood products are also kiln-dried to relieve stresses and kill insects and organisms that cause stain and decay (NHLA 2003).After being kiln-dried, lumber is graded and sold according to NHLA standards (2003).

3.2.2 NHLA Lumber Grades

Hardwood lumber grade refers to the quality of the wood based on board size, clear board area percentage (e.g. the area of the board that does not contain defects), a minimum part size that can be cut, and restrictions on the number of cuts to obtain clear areas within each board. Clear area is defined by NHLA as the portion of the board with no defects on one (graded as one-face clear) or both sides (graded as two-faces clear). Typically, in the U.S., lumber is graded according to the National Hardwood Lumber Association standards (2003). Official NHLA grades and the most commonly used lumber grades are First and Seconds (FAS), Selects (SEL), No. 1 Common (1C), No. 2 Common (2AC), and No. 3A Common (3AC). No. 3B Common lumber is also used, but not for appearance products (e.g. products where appearance is most important) but mostly for industrial products (e.g. packaging). FAS has the highest board quality standards requiring the largest boards and the fewest defects, thus making it the best quality class overall. To meet FAS standards, the board must have a minimum size of 6in x 8ft with 83 ⅓ percent clear board area. Additionally, the clear area available for the largest clear part size must have a minimum dimension of 4in x 5ft or 3in x 7ft. This clear area has to be created in one to four cuttings. Details of cuts allowed and other pertinent grade rules are listed in Table 3-1. Selects, the second best board quality class designation, has slightly lower standards, requiring the board to be at least 4in x 6ft with 66 ⅔ percent clear area and a minimum part size of 4in x 5ft or 3in x 7ft. The cutting allowance for the better side of the board is the same as FAS and must be better than No. 1 Common for the reverse side. No. 1 Common lumber must be 3in x 4ft with 66 ⅔ percent clear area and minimum part size of 4in x 2ft or 3in x 3ft. One to five cuttings can be made to obtain the clear areas for a No. 1 Common board. No. 2 Common lumber must be 3in x 4ft with 50 percent clear area and minimum part size of 3in x 2ft. Clear areas have to be obtained in one to seven cuttings. No. 3A Common boards must be 3in x 4ft with 33 ⅓ percent clear area, minimum part size of 3in x 2ft, and No. 3B Common boards must be 3in x 4ft with 25 percent clear area and minimum part size of 1 ½in x 2ft. Unlimited numbers of cuttings are allowed for 3A and 3B Common lumber. Unlike 3A Common boards, a 3B Common board may not be structurally sound, e.g. the board may break apart when lifted. Guidelines for FAS, SEL, 1 Common, 2 Common, 3A Common, and 3B Common boards are shown in Table 3-1.

Table 3-1: National Hardwood Lumber Association Guidelines

Grade	Board Length	Board Width	Minimum	Clear Area	Allowable Cuts to Obtain Part	
	Minimum	Minimum	Part Size	(percent)	Part Length	Cuts
FAS	8’	6”	4”x5’ or 3”x7’	83 ⅓	4’- 7’	1
					8’- 11’	2
					12’- 15’	3
					16’ and over	4
SEL	6’	4”	4”x5’ or 3”x7’	66 ⅔	Better side same as FAS reverse side better than 1C	
1C	4’	3”	4”x2’ or 3”x7’	66 ⅔	3’- 4’	1
					5’- 7’	2
					8’-10’	3
					11’-13’	4
					14’ and over	5
2C	4’	3”	3”x2’	50	2’- 3’	1
					4’- 5’	2
					6’- 7’	3
					8’- 9’	4
					10’- 11’	5
					12’- 13’	6
					14’ and over	7
3AC	4’	3”	3”x2’	33 ⅓	No limit to number of cuts	
3BC	4’	3”	1 ½”x2’	25	No limit to number of cuts	

NHLA (2003) lumber grade standards *“... Have been adopted to establish the comparable value of the board and to provide the user with a standard on which he may base his purchase for a particular end use* (NHLA 1998, p4)*.”* Boards are most often graded at the sawmill by a professional lumber grader. Kiln-dried and graded lumber is then purchased by rough mills and other lumber buyers such as export agents and construction companies.

3.3 Rough Mill Processing

3.3.1 Rough Mill Lumber Cut- Up

Rough mills cut primary lumber into secondary parts based on cutting bill part requirements.

“*A cutting bill is a customer order that specifies the required part sizes, quality, and quantities. A cutting is considered a primary cutting if it consists of only cross-cutting and rip-cutting. A salvage cutting* *includes additional cutting beyond primary cutting. Namely, primary parts are cut directly from primary cuttings and salvage parts are cut from remaining unused board areas with additional ripping and crosscutting steps* (Zuo 2003, p.4*).”*

In a typical lumber cut-up process, rough lumber is first “smoothed” by a planner, a machine with circularly rotating cutting knives held at consistent thickness. Lumber is then cut to width with a rip-saw or cut to length with a crosscut-saw. A rip-saw or crosscut-saw first processing is chosen to maximize lumber yield. Yield is defined as the final part boardfoot[1] area divided by the original total infeed lumber board footage expressed as a percentage (Buehlmann 1998). Increasing yield in a rough mill is important for increasing productivity and reducing raw material (lumber) and production costs. Rough mills use either a rip-first or a cross-cut first lumber cut-up process, which are explained in more detail below.

Rip- first processing cuts lumber first into long, narrow strips before cutting the long strips to length. A rip- first rough mill layout is shown in Zuo’s figure (2003, p.5). Lumber is processed first through the gang-rip saw. From this process, long, narrow strips are obtained which are then examined for unacceptable defects such as holes and knots. Defects are marked with fluorescent crayons by rough mill employees known as markers. Improving marker accuracy increases lumber yields by reducing excess waste (Buehlmann and Thomas 2007). After being marked, the marks are read by an automated saw scan and parts are cut to length by an automated chop saw.

The available literature mentions several advantages for rip-first processing, among them that rip- first cutting is better at removing wane and pith (Wiedenbeck et al. 1995; Wiedenbeck 2001). Also, higher yields are expected in rip-first processing when using lower grades to obtain longer parts (Gatchell 1987). Mullin (1990) states that rip-first processing requires fewer and simpler operational decisions to be made. Also, it is easier for operators to locate defects (Mullin 1990). On the other hand, Gatchell (1990a) recommends cross- cutting crooked boards, e.g. boards that are bent or curved, prior to ripping to increase yield in rip-first lumber cut-up systems. Cross-cutting crooked boards reduces the amount of crook or bend in the board. Because the amount of crook in a given board is reduced, more board footage can be utilized from the resulting board when ripping and thus, higher lumber yields are obtained.

Cross-cut first processing reverses the cutting sequence used in rip-first processing and cuts lumber to part length before ripping part width. A cross-cut first rough mill layout is shown in Zuo's figure (2003, p.6). When using a cross-cutting first layout, lumber is evaluated by the marker before any cuts are made. Cross-cuts are then made across the entire board such that defects are removed while high yield is achieved. Cross-cut first rough mills process lumber on the chop saw first, then feed shorter board segments through a straight-line rip-saw. Usually, there are several straight-line rip-saws with individual operators after the cross-cutting operation. Rip-saws typically used after cross-cutting have a single blade only. The operator cuts the boards to width using the straight-line rip-saw, repeating the cutting as many times as cuts are needed to convert a given board-segment into final components. Studies show that cross-cut first mills produces higher yield for wide, short parts from lower board grades and for panel parts (Wiedenbeck 2001). Also, cross-cut first rough mills can better process wood with spike knots, knot clusters, and larger surface knots (Wiedenbeck 2001).

Today, rip-first processing has become the most widely used layout in rough mills (Wiedenbeck and Scheerer 1996; Mullin 1990; BC Wood Specialties Group 1996). Rough mill layouts are designed to increase production efficiencies and reduce overall production cost. For a typical solid hardwood products manufacturer, 50 percent or more of all rough mill expenses stem from raw material costs (Carino and Foronda 1990; Wengert and Lamb 1994; Mitchell et al. 2005). Therefore, minimizing

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[1] A boardfoot (bdft) is the industry measure for lumber used or purchased. A bdft describes a volume of 1 foot by 1 foot by 1 inch (1'x1'x1"), e.g. 0.0833 ft^3 or 0.0024 m^3 (NHLA 2003).

both production and raw material costs can greatly reduce rough mill expenses. Rough mill simulation programs, e.g. software simulating the actual cut-up of lumber in rough mills, enable practitioners and researchers to estimate rough mill yield, raw material, and production costs, and help to minimize actual costs incurred.

3.3.2 Rough Mill Simulation Programs

Rough mill simulation programs simulate the lumber cut- up process and predict lumber cut- up yields. The first rough mill simulation program, YIELD, was developed in the early 1960's by Wodzinski and Hahm (1966). Because most rough mills did not own computers, Englerth and Schumann (1969) made yield information available to industry by creating hard maple yield prediction tables (called yield nomograms) based on the results from YIELD. Black walnut and alder prediction tables were also generated (Schumann 1972 and 1971). Also, Gilmore et al. (1984) created yield prediction tables for yellow-poplar.

In the late 1980's, with the increasing use of computers in industry, simulation programs became more reliable and effective for predicting lumber cut-up yields in the industry. When compared to prediction tables, simulation programs contain more up-to-date data and better estimate lumber cut- up yields (Hoff 2000). Rough mill simulators, such as CORY (Brunner et al. 1989), AGARIS (Thomas et al. 1994), ROMI-RIP (Thomas 1995a, 1995b), RIP- X (Harding and Steele 1997), ROMI-CROSS (Thomas 1998), ROMI- RIP 2.0 (Thomas 1999a, 1999b), Opti2Axes (Caron 2003), and ROMI 3.0 (Weiss and Thomas 2005), calculate expected lumber cut- up yields based on cutting bill, rough mill settings, and lumber grade mix. Simulation programs are recognized for their potential to decrease raw material and production costs (Englerth and Schumann 1969; Hanover et al. 1973; Martens and Nevel 1985; Steele et al. 1990; Timson and Martens 1990; Lawson et al. 1996).

Simulated estimates of expected yield from the simulation programs are used as input for least-cost-grade-mix optimization models.

3.3.3 Least-Cost Lumber Grade-Mix Optimization Models

The least-cost lumber grade-mix optimization solution specifies a lumber grade mix to minimize raw material and production cost. Lower grade lumbers cost less than higher grades. On the other hand, production costs are minimized by purchasing higher grade lumber (Willard 1970) since higher grade lumber requires less cuts to remove defects. Therefore, the least-cost grade-mix determines the best lumber grade combination to optimize raw material and production costs.

The first linear least-cost-grade-mix solutions were determined using lumber yield prediction tables for hard maple (Englerth and Schumann 1969), black walnut (Schumann 1971), alder (Schumann 1972), and yellow-poplar (Gilmore et al. 1984). Simulation programs are used to estimate lumber yield and cost predictions. These least-cost-grade-mix optimization programs assume a linear relationship between lumber grade combination and lumber yield.

3.3.4 Linear Models

3.3.4.1 Linear Programming Techniques

In the past, linear optimization models were typically used to calculate least-cost lumber grade-mix solutions. Linear programming techniques have been used widely in the forest products industries and have been applied to least-cost lumber grade-mix minimization software programs such as OPTIGRAMI (Martens and Nevel 1985), OPTIGRAMI Version 1.0 for PC's (Timson and Martens 1990), OPTIGRAMI Version 2.0 (Lawson et al. 1996), and RIP-X (Harding and Steele 1997). For example, the linear programming (LP) least cost grade mix model of RIP-X determines *"the cost-minimizing volume of each grade required to manufacture the cutting order.* (Harding and Steele

1997).” In particular, the least cost linear programming model (Equation 3-1) developed by Harding and Steele (1997) for RIP-X is:

Objective function:

$$Minimize\ Z = \sum_{i=1}^{6} C_i X_i + 0 \sum_{i=1}^{6} \sum_{j=1}^{n} V_{ij}$$

Equation 3-1

Subject to the following constraints:

Volume constraints by grade
$X_i \leq M_j$ *for i= 1, 2,..., 6*

Parts' volume constraints
$\sum_{i=1}^{6} V_{ij} = P_j$ *for j= 1, 2,..., n i=1, 2,..., 6*

Parts' volume distribution by lumber grade
$Y_{ik} X_i - \sum_{j=1}^{i} V_{i((k+1)-j)} \geq 0$ *for j= i= 1, 2,..., 6; k= 1, 2,..., n*

Non-negativity
$X_i, V_{ij}, P_j, Y_{ik}, C_i \geq 0;\ n > 0$

where:
Z= cost for manufacturing the cutting order ($)
i= index for lumber grade being considered
j= index for required parts volume
k= index for lumber grade yield
n= number of parts in cutting order
M_i*= maximum available lumber volume of grade i (BF)*
X_i*= volume of lumber grade i required to fill cutting order (BF)*
V_{ij}*= volume of part j to be cut from lumber grade i (BF)*
P_j*= total volume of part j to be cut (BF)*
Y_{ik}*= yield of grade i when Σ Vij parts are cut from the grade (percent)*
C_i*= cost of manufacturing 1000 BF of lumber grade i ($/1000)*

The least-cost linear programming model was verified by comparing RIP-X’s least-cost lumber grade-mix solutions to solutions generated with the Rough Mill CostCutter (Steele et al. 1990). Since part lengths in CostCutter are restricted, the part lengths in RIP-X were restricted as well. Comparison of the two models found no significant difference between the prices of the restricted RIP-X and CostCutter solutions ($\alpha = 0.05$). Yield estimates of RIP- X were verified by comparing RIP- X simulation values to yields of an actual mill (Harding and Steele 1997). However, a linear relationship between lumber grade and lumber yield was never tested nor verified by the researchers.

3.3.4.2 Significance of Linear Models

Zuo et al. (2004) and Zuo (2003) studied the assumption of a linear relationship between lumber grade combinations and lumber yield using the U.S. Forest Service's rough mill simulation program ROMI-RIP 2.0 (Thomas 1999a, 1999b). The study showed that linearity between grade combinations and yield was true only in a limited number of cases using various two- and three-grade lumber mixes. Considering two-lumber grade combinations, Zuo et al. (2004) showed that linear results occur in 6 of the 12 lumber grade mixes. This information can be found in Zuo et al.'s (2004, p.553) table. Non-significant p-values for the lack of fit test ($p \geq 0.05$) indicate a linear pattern for the lumber grade combination, significant p-values ($p < 0.05$) indicate a non-linear pattern for the lumber grade combination.

However, only 1 of 10 three- grade lumber combinations was found to have a linear relationship between grade-mix and yield over their entire response yield surfaces. XA, XB, and XC represent the three lumber grades in the lumber grade combination. XA*XB is the interaction of lumber grades XA and XB. A significant interaction ($p < 0.05$) for XA*XB, XA*XC, or XB*XC indicates the interaction is non- linear. Results from Zuo et al.'s (2004, p.554) table show that only the SEL&BETR- 1Com- 2ACom lumber grade-mix combination exhibits linear behavior.

Results were verified comparing lumber yields and lumber grade mixes using 10 additional cutting bills (Zuo et al. 2004). Statistical analysis showed that only 33 of the 100 additional three-grade lumber combinations could be represented using linear models. Overall, less than one third of the combinations proved to have linear properties. Based on these findings, Zuo et al. (2004) concluded that existing least-cost lumber grade-mix models are sub-optimal because linear models do not account for the interaction between terms. To resolve the linearity issues, the authors developed a statistical model to find the least-cost lumber grade-mix without having to rely on linear properties of the grade-mix yield relationship.

3.3.5 Statistical Model

Zuo (2003) and Buehlmann et al. (2004) developed statistical methods to calculate the least-cost-grade-mix. Buehlmann et al.'s (2004) solution was used to create the least-cost-grade-mix solver in ROMI-3.0 (Zuo 2003; Weiss and Thomas 2005). "*This method is a significant departure from previous methods (Wodzinski et al. 1966; Lawson et al. 1996; Schumann 1971) that assumed a linear relationship between cutting bill yields and lumber grades. As shown by Zuo et al. [2004], the existence of a linear relationship cannot always be guaranteed. ROMI-3 develops a series of yields that are based on the user's equipment settings, optimization settings, cutting bill demands, part grades, lumber costs, and processing costs. In this way, the least-cost solution is tailored exactly to the user's processing situation* (Weiss and Thomas 2005, p54)." Using this input data, the least-cost-grade-mix solution is generated using a yield and cost response surface model.

3.3.5.1 Development of Yield and Cost Response Surface

Before yield and cost response surface models are generated, ROMI 3.0's least-cost lumber grade-mix solver prompts the simulation program to calculate lumber yield values for 25 lumber grade combinations shown in Table 3-2 (Zuo 2003).

Table 3-2: Least-cost grade-mix 25 lumber grade combinations

Runs	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

A yield response surface is then constructed based on lumber yield estimates obtained from simulating the actual cut-up of lumber in a rough mill from these 25 grade combination sample runs (Zuo 2003). Equation 3-2 is the second order polynomial model used to create the yield response surface for each cutting bill using yields from the 25 grade combination sample runs.

$$\mu_y = \sum_{i=1}^{5} \beta_i^* x_i + \sum_{i<} \sum_{j} \beta_{ij}^* x_i x_j$$

Equation 3-2

where: $\beta_i^* = \beta_0 + \beta_i + \beta_{ii}$, and $\beta_{ij}^* = \beta_{ij} - \beta_{ii} - \beta_{jj}$

μ_y - the yield of a given cutting bill
x_i, x_j - the proportions of each lumber grade
β_0- the intercept
β_i- the coefficient of linear terms
β_{ii}- the coefficients of quadratic terms
β_{ij} - the coefficients of the interaction terms
i, j - 1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common and 5 for 3A Common

However, to find the minimum cost solution, the cost surface is needed and not the yield surface. Therefore, it is necessary to transform lumber yields to cost data. Equation 3-3 transforms the original 25 lumber yield data to cost data from which a raw material cost surface is generated based on lumber grade combinations and transformed cost data (Zuo 2003).

$$COST_j = \frac{\sum_i^5 G_i M_i}{YIELD_j}$$

Equation 3-3

where:	G_i	the proportion of each lumber grade
	M_i	the market price per thousand board feet of each lumber grade
	i	1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common, and 5 for 3A Common
	j	observation of a grade combination run

The cost transformation equation may also need to include processing cost. Lower quality lumber grades have lower raw material cost; however, these grades may have higher processing costs since more cuts are required to move defects. Furthermore, larger amounts of the lower grade lumber are often necessary since lower quality lumber grades have less clear area to meet a cutting bill. Equation 3-4 transforms the 25 original lumber yields to production cost data. Thus, using results from Equation 3-4, a cost response surface is generated that incorporates both raw material and production costs (Zuo 2003).

$$COST_j = \frac{\sum_i^5 G_i * (M_i + P_i)}{YIELD_j}$$

Equation 3-4

where:	G_i	the proportion of each lumber grade
	M_i	the market price per thousand board feet of each lumber grade
	P_i	the processing cost per thousand board feet of each lumber grade
	i	1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common, and 5 for 3A Common
	j	observation of a grade combination run

For simplification, Equation 3-4 is used in the least-cost-grade-mix code. Users that wish to optimize raw material cost only enter a zero value into processing cost. A cost response surface model is generated with Equation 3-5.

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

Equation 3-5

where: μ_y - the cost of satisfying a given cutting bill
x_i, x_j - the proportions of each lumber grade
β_0^*- the intercept
β_i^*- the coefficient of linear terms
β_{ij}^*- the coefficients of the interaction terms
i, j - 1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common and 5 for 3A Common

The cost response surface predicts cost values of various lumber combinations and outputs the optimum lumber grade combination, the predicted yield value, and raw material cost (Equation 3-3) or total production cost (Equation 3-4) solution for the desired rough mill set-up.

3.3.6 Validation of Least-Cost Grade-Mix Solver

Optimized raw material costs from Equation 3-3 were evaluated by comparing the new statistical model solutions with solutions from the OPTIGRAMI 2.0 least-cost-lumber-grade-mix program (Lawson et al. 1996). "*For 9 of the 10 cutting bills tested, the statistical model found lower-cost solutions compared with those provided by OPTIGRAMI 2.0* (Buehlmann et al. 2008, p1)." Similarly, evaluations of the raw material and production cost solutions from Equation 3-4 showed that the statistical model found lower cost solutions than OPTIGRAMI 2.0 in 8 of the 10 cutting bills tested. Therefore, it was concluded that the statistical model predicts lower cost least-cost-grade-mix solutions in most cases.

3.4 Statistical Analysis Software

3.4.1 Statistical Analysis Software (SAS) 8.2

The least-cost grade-mix solver developed by Zuo et al. (2004) and used in ROMI 3.0 uses SAS Version 8.2 (2002) to perform the necessary statistical calculations. The least-cost-grade-mix solver imports the 25 lumber grade combinations' yield and cost data. This data is then sent to the United States Department of Agriculture (USDA) Forest Service server for statistical calculations in SAS. A copy of SAS 8.2 running on the USDA Forest Service's server uses the yield and cost data from the originating computer to construct yield and cost response surfaces. *"The server analyses the data and returns your least-cost-grade-mix solution"* (Weiss and Thomas 2005, p.54) to the originating computer. The solution consists of the optimum lumber grade combination and the predicted yield and cost values.

Because the least-cost lumber grade-mix calculations are performed using SAS 8.2 (2002), the least-cost lumber grade-mix solver user needs access to the SAS statistical package. As a single user license for a corporation costs a minimum of $5000 per year (Thomas 2009a) Weiss and Thomas (2005) decided to purchase a SAS license for a USDA Forest Service server. The SAS license allows ROMI 3.0 users to access SAS by connecting to the USDA FS server (Weiss and Thomas 2005) without individual industry users having to purchase a SAS license or to pay a fee. ROMI 3.0 users also receive automatic updates to the least cost module by connecting to the Forest Service server (Thomas 2009a).

In spite of these benefits, potential ROMI 3.0 users may be reluctant to connect to the Forest Service server. Many companies are uneasy about sharing cost and yield data with a government computer and software system. User's that do connect to the server, face several limitations. First, user's must have internet connection. Poor internet service may also limit access. Second, the Forest Service server can only handle one connection at a time. Finally, little error checking occurs within the system as a whole, i.e. the users either get results or receive a general error message. Error message does not indicate error origin (Thomas 2009a).

3.4.2 R Statistical Software

R is an open source statistical software package (Venables et al. 2008). Assuming R has the same capabilities of SAS, the incorporation of R into the least-cost-grade-mix solver would eliminate most of the problems that users experience with SAS discussed by Thomas (2009a), such as the expense of software licensing, the need for internet connection, the reluctance of user's to submit cost and yield data to the USDA's Forest Service server, and the limited access provided by the server.

R is an open source package, thus the software is free. Therefore, R can be distributed with the ROMI 3.0 (Thomas and Weiss 2006, Weiss and Thomas 2005) software installation package, and users are not required to purchase any statistical software. The incorporation of R also removes the need to connect to a USDA Forest Service server by industry users. ROMI users would no longer need to submit yield and cost data to a government computer for statistical calculations and no Internet connection is necessary to perform the statistical calculations. Finally, access to R is not restricted. Unlike SAS, which limits connection to one user, users may access R on their personal computer at any time.

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CHAPTER 4 Materials and Methods

The Materials and Methodology chapter gives a technical overview of ROMI 3.0, the least-cost lumber grade-mix solver, and the current use of SAS. The chapter also discusses the expectations of R's capabilities to meet the needs of researchers and industry.

4.1 Technical Overview of ROMI 3.0

ROMI 3.0 is a rough mill simulation program developed by the USDA Forest Service (Thomas and Weiss 2006; Weiss and Thomas 2005). Simulating the cut-up of lumber into components in a rough mill, ROMI uses digitized board data from the *"1998 Data Bank for Kiln-Dried Red Oak Lumber"* (Gatchell et al. 1998). The data bank includes over 3,000 digitized Red Oak boards distributed over all lumber grades, FAS, F1F, Selects, No. 1 Common, No. 2A Common, and No. 3A Common (NHLA 2003). Actual board dimensions and defects are represented using a Cartesian coordinate system (Anderson et al. 1993). A custom datafile utility allows users to create input board files consisting of any lumber grade combination. *"ROMI-3 processes the board data according to... processing specifications. Output, including part counts and yields, graphical plots of processed boards, and processing requirements are available from each run* (Weiss and Thomas 2005, p.1)*."*

ROMI 3.0 is capable of rip-first and cross-cut first operations. Parts are cut according to user-specified part grades, i.e. clear two face (C2F), clear one face (C1F), or sound two face (S2F). A user may cut solid parts, panels, or glue-up parts, as well as random-length parts. Equipment settings and mill settings are user-specific. ROMI 3.0 also includes an arbor generation tool and a least- cost lumber grade- mix solver (Weiss and Thomas 2005). *"The arbor generation tool determines the optimum fixed-blade saw-spacing sequence for a specific cutting bill and lumber-size distribution. The least-cost-grade-mix calculator determines the most cost-efficient grade mix for a specific cutting bill with respect to both lumber and processing costs* (Weiss and Thomas 2005, p.1)*."*

4.2 Technical Overview of the Least-Cost Lumber Grade-Mix Solver

ROMI 3.0's least-cost-grade-mix solver uses a statistical model (Zuo 2003) to predict lumber cost and lumber yield, as previously discussed in 3.3.5.1. Users enter equipment settings, optimization settings, cutting bill demands, and part grades into ROMI 3.0 (Thomas and Weiss 2006, Weiss and Thomas 2005). Lumber and processing costs are entered into the least-cost lumber grade-mix solver. Then, ROMI-3.0 estimates yield values based on 25 possible lumber grade combinations, Table 3-2. Next, the least-cost-grade-mix solver retrieves the lumber grade and volume data required for a given cutting bill and lumber grade combination and calculates lumber material and processing costs for each lumber grade combination. This data is then sent to the USDA Forest Service SAS server where SAS creates both second order polynomial yield and cost response surface models to predict yield and cost values (Zuo 2003). The least-cost-grade-mix solution is found based on the model and returned and displayed to the user. Users may request a least-cost solution that omits a specific lumber grade, i.e. the user may request solutions that do not include 3A Common lumber. Users may also indicate which lumber grades they wish to include. "*In this way, the least-cost solution is tailored exactly to the user's processing situation* (Weiss and Thomas 2005, p.54)*."* However, as described in the literature review, potential users are reluctant to provide lumber cost and yield data to the government server. Users can also be limited by insufficient or non-existent internet access. The following section gives a technical overview of the SAS code used in the least-cost-grade-mix solver.

4.3 Technical Overview of SAS Code

SAS 8.2 (2002) is a statistical analysis software package used in research and business for statistical calculations. The SAS code, developed by Zuo (2003) for the least-cost lumber grade-mix solver (Appendix A), imports yield and cost data from ROMI-3.0 (Thomas and Weiss 2006; Weiss and Thomas 2005) and creates a statistical model to represent the data. Second order polynomial yield and cost response surface models are created using yield data from ROMI-3.0 and user-specified lumber and processing cost data to predict least-cost lumber grade-mix solutions. SAS then exports predicted least-cost and lumber yield values to ROMI-3.0's least-cost lumber grade-mix solver.

Users enter rough mill settings, cutting bills, raw material cost, and processing costs into ROMI-3.0's least-cost lumber grade-mix solver program (Weiss and Thomas 2005). The program calculates lumber yield and cost values of 25 lumber grade combinations. Yield and cost values are imported into SAS 8.2 (SAS 2002) using an input command. The SAS code imports the lumber grade combination and the lumber yield estimate found by ROMI 3.0, and also imports the raw material cost and processing cost entered by the user; and the estimated cost of each lumber combination per thousand board feet. An IML (interactive matrix language) procedure checks for interaction effects between lumber terms. Zuo (2003) ranked terms to indicate need for the statistical model over the linear model. Significance of any interaction terms indicates the statistical model should be used for calculations. Linear modeling is appropriate only when the rank test indicates no significance for all interaction terms associated with each lumber grade combination. The IML procedure was only used to determine if a linear model was sufficient. Statistical modeling was performed on all eleven scenarios. A lack-of-fit test is used later to ensure that the statistical model is sufficient. Next a DO LOOP creates a matrix of new lumber combinations, which vary on increments of ten percent, that will be used to predict and find least-cost lumber grade-mix solutions. An RSREG (response surface regression) procedure creates the statistical model (Equation 3-2), builds yield and cost response surfaces to predict optimum lumber yield and cost values, which are entered into the table created by the DO LOOP. Results are exported to ROMI-3.0 using a basic export procedure. ROMI-3.0 then displays the least-cost lumber grade-mix solution to the user.

4.4 Expectation of R

R is a statistical software package (Venables et al. 2008). It is expected that ROMI can be updated using R as an alternative statistical package to SAS 8.2 (SAS 2002). The algorithms used in R are the same as the algorithms used in SAS. Comparisons of least-cost lumber grade-mix results from eleven cutting bills will be used to test for differences between the two least-cost lumber grade-mix solvers. ANOVA testing ($p<0.05$) of cost results will determine the significance of any differences that are found. Results are expected to be similar between the two least-cost lumber grade-mix solvers. Rounding difference may lead to small variations in least-cost lumber grade-mix results.

The necessary R packages and proper coding will be researched with the help of the Laboratory for Interdisciplinary Statistical Analysis (LISA), an organization at Virginia Tech that provides statistical services to the Virginia Tech community (Department of Statistics 2009). Consultants are available for one-on-one assistance regarding response surface models and R. Once R coding is determined, the R code will be incorporated into the least-cost lumber grade-mix solver. Assuming R can be incorporated into ROMI's least-cost lumber grade-mix solver, users will be able to run the updated version of ROMI from a personal computer. A new user's manual will be provided with each copy of the updated version of ROMI.

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CHAPTER 5 R-Based Decision Support System Finds Least-Cost Lumber Grade-Mix Solution

5.1 Abstract

Hardwood lumber is for many secondary wood products manufacturers the largest cost incurred. Hardwood is purchased in five quality classes (known as lumber grades in industry), ranging from best quality, i.e. lumber boards that are large and have little or no defects, to the lowest quality material, i.e. lumber boards with numerous defects. Industry undertakes considerable efforts to increase the amount of usable material obtained from a given set of hardwood lumber but faces limits due to the presence of defects. However, the industry can reduce hardwood lumber procurement costs by buying the least-cost lumber grade-mix that yields all the necessary components the lowest total purchasing and processing cost. The least-cost lumber grade-mix problem has attracted considerable attention researchers and numerous solutions exist.

One such solution is the least-cost lumber grade-mix solver DSS developed by Buehlmann et al. and Zuo that relies on the proprietary SAS 8.2 statistical analysis software package for finding the solution and requires a user license to perform statistical calculations. An open source, free version of the least-cost lumber grade-mix solver was necessary. For this purpose, R 2.7.2, an open source, freely available statistical analysis software package was incorporated into the least-cost lumber grade-mix solver DSS, replacing the proprietary SAS 8.2 software. It was hypothesized that by using R, the entire least-cost lumber grade-mix problem could be solved on the user's local computer without any third party involvement. Comparisons were made between the new R-based least-cost grade-mix solver DSS and the proprietary SAS-based least-cost lumber grade-mix solver DSS with eleven part size requirement scenarios. For these tests the newest version of SAS, SAS 9.2, was used since this version

has no modifications on the routines involved compared to SAS 8.2. Both solutions produced identical results. Thus, the new R-based DSS is an identical replacement of the SAS-based DSS. However, the new version is available to users for free and can execute all necessary calculations from a local computer

5.2 Introduction

The secondary wood products industry manufactures products like furniture, kitchen cabinetry, flooring, and others, all of which have to fulfill manifold aesthetic, functional, maintenance, and safety requirements. These products are used in one way or another in almost all human activities and are produced in a wide variety of designs, configurations, fashions, price segments, and levels of usefulness. The secondary wood products industry, NAICS code 321 (Census 2007a), is an important economic entity in the U.S. The NAICS 321 industry sector employs over 500,000 workers and has an annual turnover of $101 billion (Census 2007b). Solid hardwoods, mainly from forests in the Eastern part of the U.S., are frequently used for secondary wood products, especially for higher-end, higher price offerings because of the relatively high price of hardwood lumber as compared to alternative materials like softwood lumber, veneered engineered wood composite, metal, or plastic materials.

In a typical secondary wood products operation, lumber expenses are the single most important cost the business incurs. Forty to 70 percent of total product costs manufacturing solid hardwood products stem from the purchase of the necessary hardwood lumber (Kline et al. 1998; Wengert and Lamb 1994; Carino and Forona. 1990), underscoring the critical importance of minimizing lumber costs. Lumber is cut into components[2] in what the secondary wood industry refers to as the "rough mill," a series of processes that takes kiln-dried lumber boards, optimizes each one of them in respect to the best way the board can be cut into components, cuts the components from the board accordingly,

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[2] Components, in this case, refer to all solid wood parts that are used in the furniture, cabinet, and dimension part industries. Components are also called blanks, cutting stock, dimension parts, or furniture parts in the industry.

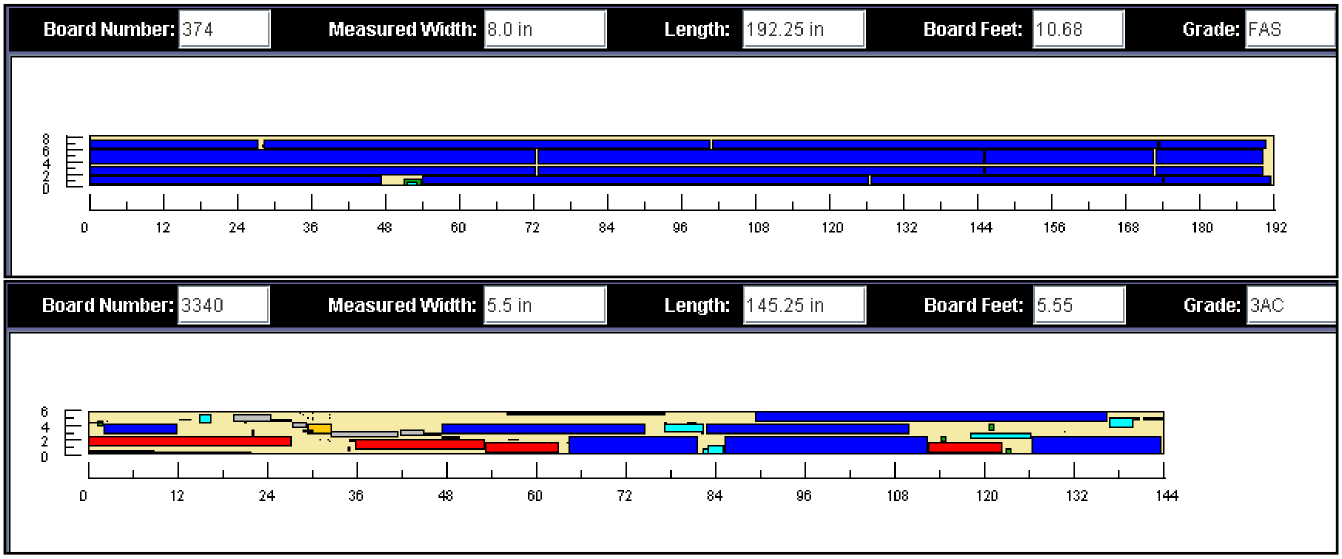
and sorts the resulting components based on size and quality (Buehlmann and Thomas 2001). Lumber yield, the ratio of aggregate component surface area output to aggregate lumber surface input, is the most commonly used measure of efficiency in the rough mill (Buehlmann 1998). Yield directly relates to product costs, as higher yield translates into lower hardwood lumber purchasing requirements. Given the dominant cost position of buying hardwood lumber for industry participants, an intense focus on increasing yield is prevalent. In an average-sized solid hardwood products manufacturing business, a one percent hardwood lumber yield improvement translates into a $150,000 per annum material purchasing cost saving (Kline et al. 1998).

5.2.1 Raw material cost purchasing minimization

The value chain for solid hardwood products such as furniture and cabinetry starts with logs being cut from the forest that are then processed to lumber in sawmills. The lumber is then dried in a kiln and sorted according to species and board qualities, which contain randomly dispersed and shaped defects, e.g. areas on the surface of the board that cannot be included in the components used for the product (Buehlmann and Thomas 2001, Buehlmann et al. 1998).

According to the National Hardwood Lumber Association (NHLA 2003), the standard setting body of the hardwood lumber industry, lumber quality is categorized by lumber board quality, called “grades.” Typical grades are First and Seconds (FAS), Selects (SEL), 1 Common (1C), 2A Common (2AC), and 3A Common (3AC), respectively. FAS is the highest quality lumber and boards must be a minimum of 8 feet long and 6 inches wide with at least 83 ⅓ percent usable area (named “clear area” in industry parlance), e.g. 83 ⅓ percent of the lumber surface must be without defects. SEL lumber is of slightly lower quality and must be a minimum of 6 feet long and 4 inches wide with at least 66 ⅔ percent clear area. 1C lumber is a minimum of 4 feet long and 3 inches wide with a clear area of at least 66 ⅔ percent while 2AC lumber must be a minimum of 4 feet long and 3 inches wide with at least

50 percent clear area. 3AC lumber, the lowest quality lumber grade used, must be a minimum of 4 feet long and 3 inches wide with at least 33 ⅓ percent clear area. Figure 5-1 shows a graphical representation of a digitized FAS (best quality) and 3AC (worst quality) boards and Table 5-1 summarizes the National Hardwood Lumber Association’s quality classification rules (NHLA 2003).



Board Number: 374 Measured Width: 8.0 in Length: 192.25 in Board Feet: 10.68 Grade: FAS

Board Number: 3340 Measured Width: 5.5 in Length: 145.25 in Board Feet: 5.55 Grade: 3AC

Figure 5-1. Digitized FAS and 3AC Boards

Table 5-1. National Lumber Harwood Association Guidelines

Grade	Board Length Minimum	Board Width Minimum	Minimum Part Size	Clear Area (%)	Allowable Cuts to Obtain Part	
					Part Length	Cuts
FAS	8'	6”	4”x5' or 3”x7'	83 1/3	4'- 7'	1
					8'- 11'	2
					12'- 15'	3
					16' and over	4
Selects	6'	4”	4”x5' or 3”x7'	66 2/3	Better side same as FAS reverse side better than 1C	
No. 1 Common	4'	3”	4”x2' or 3”x3'	66 2/3	3'- 4'	1
					5'- 7'	2
					8'- 10'	3
					11'- 13'	4
					14' and over	5
No. 2 Common	4'	3”	3”x2'	50	2'- 3'	1
					4'- 5'	2
					6'- 7'	3
					8'- 9'	4
					10'- 11'	5
					12'- 13'	6
					14' and over	7
No. 3A Common	4'	3”	3”x2'	33 1/3	No limit to number of cuttings	
No. 3B Common	4'	3”	1-1/2”x2'	25	No limit to number of cuttings	

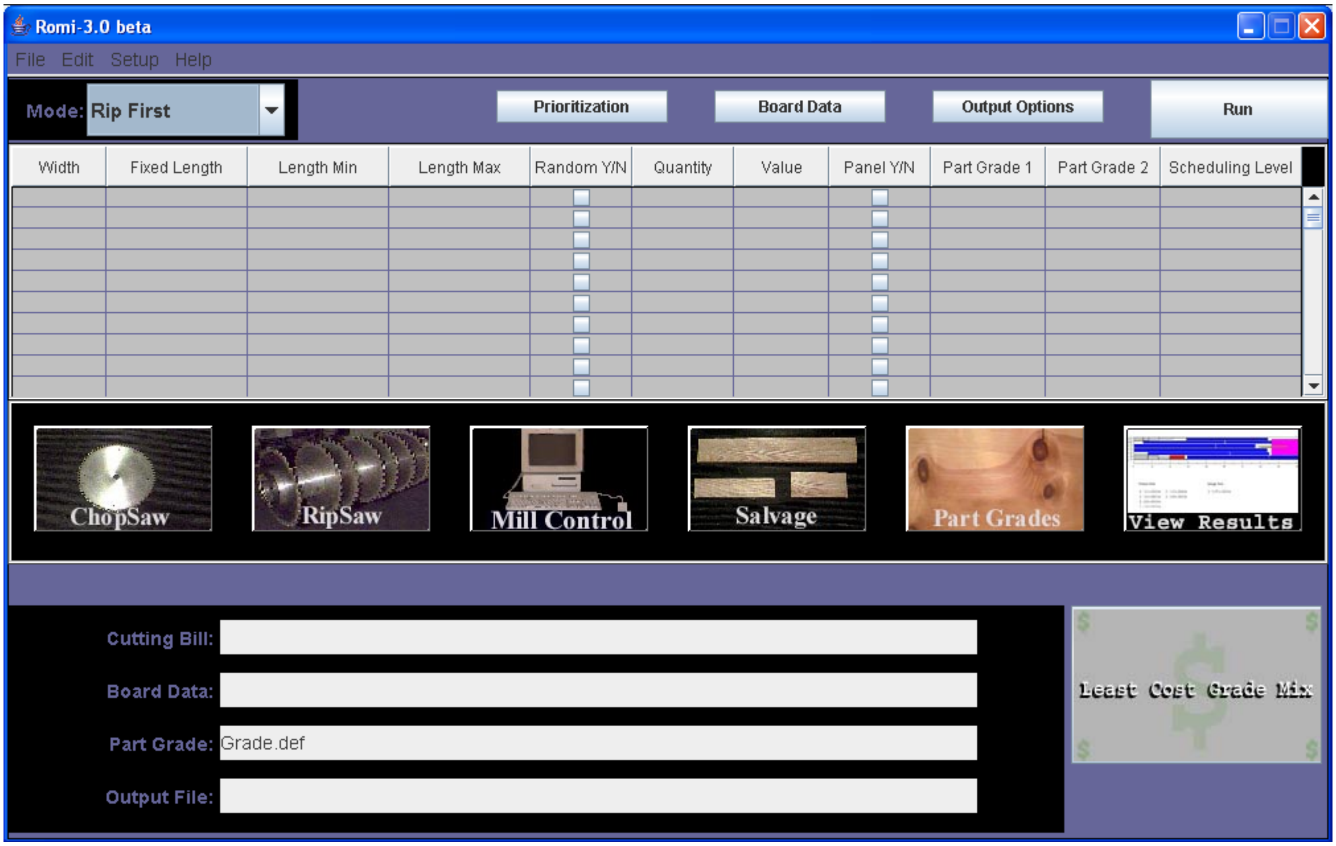
Higher quality lumber is sold at a premium with FAS grade (i.e. the best quality) being about twice as expensive as 1C hardwood lumber (Hardwood Market Report 2009). Thus, while a higher quality grade does result in more usable output, its procurement cost also is higher. Higher quality lumber has less defects and higher raw material costs while lower quality lumber has more defects and lower raw material costs. However, larger amounts of low quality lumber are required to satisfy production requirements for a given production run (Willard 1970). How much lower quality lumber can be used for a given production run depends on the component sizes and quantities that need to be obtained. If large components (e.g. long and/or wide components) need to be obtained in large quantities, more volume of higher quality lumber needs to be utilized, as lower quality lumber does not possess enough large clear areas where such larger components can be cut. Typically, lumber purchasing costs can be minimized by using as much lower quality lumber that yields enough large, clear areas to meet the component requirements of a given production run as lower quality lumber is less costly per unit component than higher quality lumber. Finding the minimum lumber cost grade or grade- mix that meets the component requirements is complicated by the ever-changing price differentials between different lumber grades (e.g. qualities) dictated by hardwood lumber market dynamics. Which lumber quality or combinations of lumber qualities to purchase to fulfill given production requirements is a challenging optimization problem that has attracted considerable attention in the hardwood products community and is commonly referred to as the least-cost lumber grade-mix problem (Weiss and Thomas 2005; Buehlmann et al. 2004; Zuo 2003; Lawson et al. 1996; Harding and Steele 1997; Timson and Martens 1990; Martens and Nevel 1985).

5.2.2 Decision Support Systems (DSS) in the industry

Given hardwood lumber's dominant influence on production costs in secondary wood products producing entities, extensive efforts have been made to more effectively use the available raw material.

Decision support systems (DSS) have assumed a critical role in this quest. A plethora of computer-based DSS help the industry practitioner make better operational and tactical decisions, including but not limited to, supply chain management DSS, lumber drying DSS, lumber cut-up simulation DSS, production-scheduling DSS, least-cost lumber grade-mix DSS, as well as numerous other applications.

A useful DSS has to be user-friendly, functional, and accessible from the workplace. The DSS also should be inexpensive to purchase or develop while not requiring extensive maintenance (Ragsdale 2008; Buehlmann et al. 2000; Sauter 1997). While designing a DSS, user-friendly GUIs, good functionality, easy workplace accessibility, and low maintenance requirements most often can be designed by the creators while the DSS' overall cost often is dictated by the need for underlying standard software, without which the DSS is not functional. For example, if a DSS requires the use of advanced statistical methods for solving the decision problem, significant costs are added to the project as such statistical software is costly. The DSS described in this manuscript is a good case in point. While the underlying DSS itself is a free program created and maintained by the USDA Forest Service (Thomas and Weiss 2006) driven by a user-friendly GUI (Figure 5-2) and executable on any stand-alone computer running Linux, Apple OS X, or Microsoft Windows 95/98/ME/XP (Weiss and Thomas 2005), a user would have to invest a large amount of money into purchasing and installing a copy of SAS 8.2, a statistical business analysis software package, to perform the necessary statistical calculations (SAS 2002). Very few participants of the secondary hardwood industry would be willing or able to spend such a sum for a statistical business analysis software package and even fewer would have the knowledge needed to install, maintain, and operate such a package.

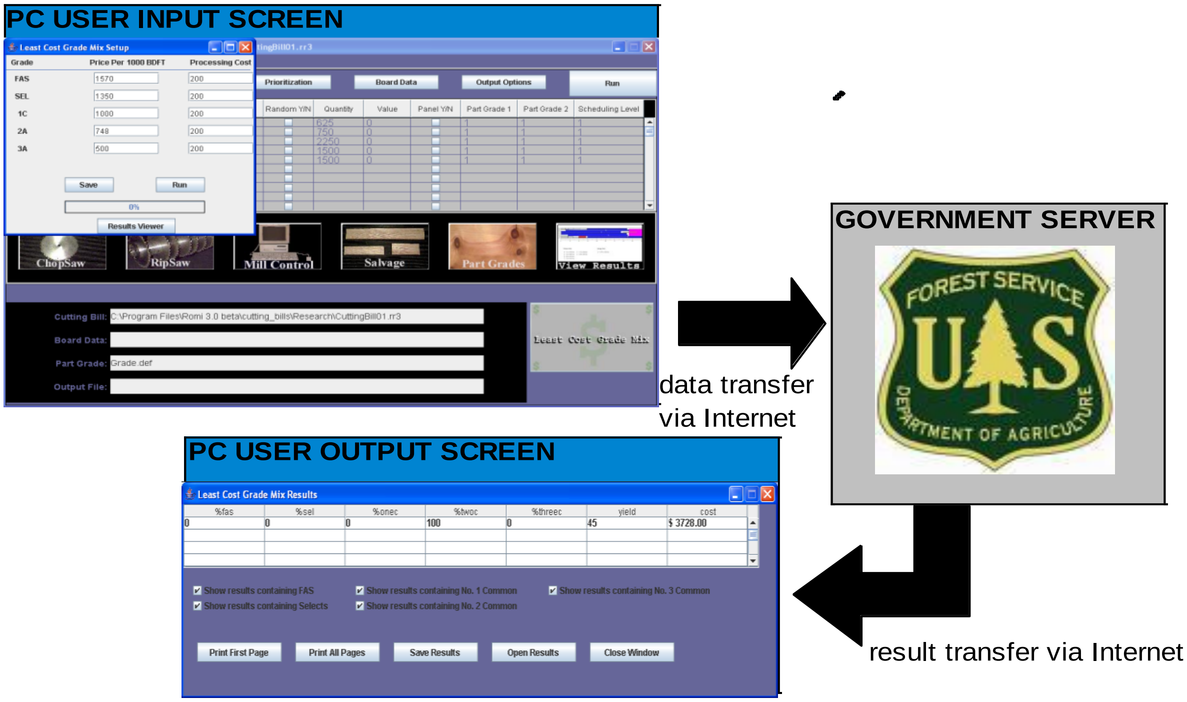


Mode: Rip First

Part Grade: Grade.def

Figure 5-2. Graphical User Interface (GUI) of the SAS 8.2-Based Decision Support System (DSS)

In an earlier version of the DSS (Buehlmann et al. 2004; Zuo 2003), the USDA Forest Service ran SAS 8.2 on a server to avoid the need for individual industry users to have to purchase, install, operate, and maintain the SAS 8.2 software. The server could be assessed with the information needed from individual DSS-user's local computer over an internet connection (Thomas and Weiss 2006; Weiss and Thomas 2005). A schematic representation of this set-up is shown in Figure 5-3.



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

Random Y/N	Quantity	Value	Panel Y/N	Part Grade 1	Part Grade 2	Scheduling Level
☐	625	0	☐	1	1	1
☐	750	0	☐	1	1	1
☐	2250	0	☐	1	1	1
☐	1500	0	☐	1	1	1
☐	1500	0	☐	1	1	1

Cutting Bill: C:\Program Files\Romi 3.0 beta\cutting_bills\Research\CuttingBill01.rr3
Board Data:
Part Grade: Grade.def
Output File:

%fas	%sel	%onec	%twoc	%threec	yield	cost
0	0	0	100	0	45	$ 3728.00

☑ 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

Figure 5-3. SAS 8.2-Based Decision Support System Process

Due to limitations in the software agreement between the USDA Forest Service and SAS Institute Inc., the statistical software package provider, only one user, at any one time, could access the server over an internet connection and have his/her optimization problem solved, while all other potential users got rejected. Also, empirical evidence from industry observations indicates that many industry users are uncomfortable sending their company data to a U.S. government server for fear of being tracked and monitored. Thus, from a software usability viewpoint, either solution of having the industry participant to buy an expensive statistical business analysis software package or running the statistical business analysis software package on a government server and offering its use to industry participants for free, has its setbacks. Consequently, the need for a more user-friendly solution became evident.

5.2.3 The Decision Problem

Producing solid hardwood dimension components in rough mills of the secondary wood products industry from hardwood lumber is a 2-dimensional cutting stock problem that is subject to four constraints: (1) the stock material contains defects, i.e. features that cannot be allowed in the components and whose positions within the boards are unknown beforehand (Figure 5-1), (2) the stock's geometrical sizes are not known beforehand (Figure 5-1), (3) cuts will be made sequentially in perpendicular or parallel direction to all the other cuts and will be guillotine cuts, and (4) piece orientation is important since wood is an anisotropic material (Buehlmann et al. 1999, Anderson et al. 1996). As no mathematical solution to this optimization problem has yet been found, the industry uses heuristic, iterative, optimum search algorithms (Banks 1998, Andradottir 1998) and refers to them as rough-mill simulation programs. Recent examples of such rough-mill lumber-cut up DSS include RIP-X (Harding and Steele 1997), Opti2Axes (Caron 2003), and ROMI 3.0 (Thomas and Weiss 2006), each one simulating the cut-up of digitized lumber (Anderson et al. 1993) into solid hardwood components and each one has its own special features, strengths and weaknesses. Such rough-mill lumber cut-up simulation software is widely used in industry for operational, tactical and strategic decision-analysis and mostly focuses on finding estimated yields from cutting sets of lumber for given component requirements.

In addition to finding yield estimates, these DSS offer additional functionalities. ROMI (Thomas and Weiss 2006), the USDA Forest Service's rough-mill lumber cut-up simulation DSS, offers users the ability to find the least-cost grade or grade-mix for given component requirements. As discussed above, determining the lumber grade or grade-mix (e.g. determining the quality-mix of the raw material to be bought) that a rough mill should purchase to minimize cost is a crucial decision for the operation's profitability. Thomas and Weiss (2006) and Weiss and Thomas (2005) integrated a least-cost-grade-mix solver model developed by Buehlmann et al.(2004) and Zuo (2003) that uses a second order polynomial model to create a cost response surface to predict least-cost grade-mix solutions, into the ROMI 3.0 DSS. Buehlmann et al.'s (2004) least-cost-grade-mix solver model uses the basis functionality of the ROMI 3.0 DSS to obtain yield estimates for a given set of component requirements and for different lumber grade or grade-mix compositions. The user, when using the ROMI 3.0 DSS' least-cost lumber grade-mix solver capabilities, must first enter the component requirements list (called a cutting bill in industry parlance) and general rough mill operation information in ROMI 3.0's GUI (Figure 5-2). When the least-cost grade-mix solver button is activated (bottom right, Figure 5-2), the DSS asks for the raw material (e.g. lumber) costs and rough mill processing costs, per thousand boardfoot[3] (mbf) for each lumber grade (Figure 5-4). Once all input data has been acquired, the least-cost grade-mix solver DSS prompts ROMI 3.0 to run 25 preliminary test runs using the yield estimation rough mill lumber cut-up simulation program.

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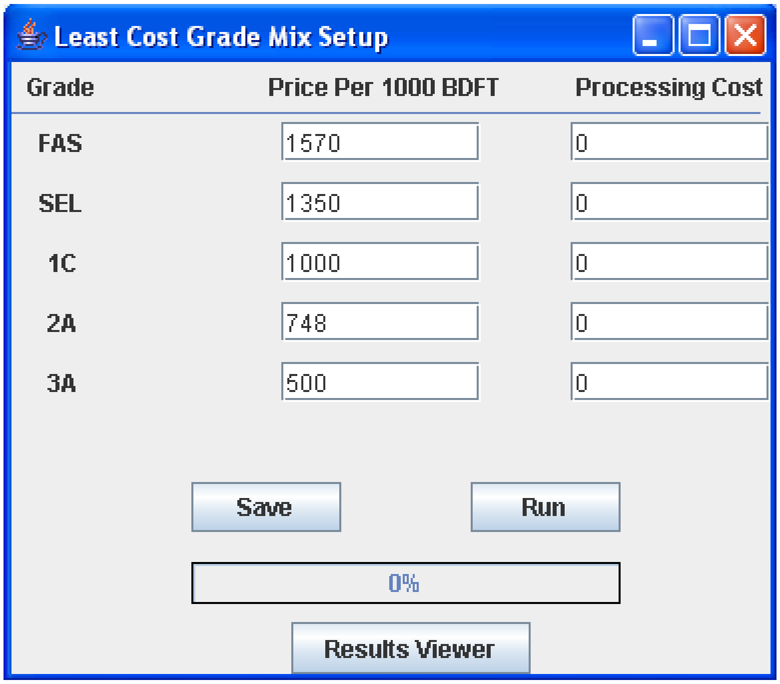
[3] A boardfoot (bdft) is the industry measure for volume of lumber used or purchased. A bdft describes a volume of 1 foot by 1 food by 1 inch (1'x1'x1"), e.g. 0.0833 feet^3 or 0.0024 m^3 (NHLA 2003).



Grade	Price Per 1000 BDFT	Processing Cost
FAS	1570	0
SEL	1350	0
1C	1000	0
2A	748	0
3A	500	0

Figure 5-4. Graphical User Interface (GUI) of Least-Cost Grade-Mix (LCGM) Solver

Table 5-2 displays the lumber grade or grade-mix composition used in these 25 test runs (Zuo 2003).

Table 5-2. Least-Cost Lumber Grade Mix 25 Lumber Grade-Mix Combinations

RUN	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	0	0	40
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

Once these 25 test runs have been conducted and yield information been obtained, the least-cost lumber grade-mix solver program (Buehlmann et al. 2004; Zuo 2003) then transforms the lumber yield data into raw material (lumber) costs by multiplying the volume of lumber required to obtain all the required components for a given grade or grade-mix times the lumber and processing costs (Equation 5-1; Zuo 2003) and then creates a cost response surface using a second order polynomial equation (Equation 5-2; Zuo 2003).

$$COST_j = \frac{\sum_i^5 G_i M_i}{YIELD_j}$$

Equation 5-1

where:	G_i	the proportion of each lumber grade
	M_i	the market price per thousand board feet of each lumber grade
	P_i	the processing cost per thousand board feet of each lumber grade
	i	1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common, and 5 for 3A Common
	j	observation of a grade combination run

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

Equation 5-2

where: μ_y - the cost of satisfying a given cutting bill
x_i, x_j - the proportions of each lumber grade
β_0^*- the intercept
β_i^*- the coefficient of linear terms
β_{ij}^*- the coefficients of the interaction terms
i, j - 1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common and 5 for 3A Common

After performing the lumber yield estimation simulations (ROMI 3.0), the yield to cost conversion (ROMI 3.0), the cost response surface creation (SAS), and the least-cost lumber-grade mix determination (Buehlmann et al. 2004). ROMI 3.0's GUI then displays the minimum cost lumber grade or grade mix in a separate, new least-cost lumber grade-mix results GUI (Figure 5-3). The merit of Buehlmann et al's (2004) and Zuo's (2003) least-cost lumber grade-mix solution was investigated by Buehlmann et al. (2008) who found Zuo's model to find lower cost solutions in 9 of 10 tests conducted compared to the more widely used least-cost grade-mix solver DSS by Lawson et al. (1996) called OPTIGRAMI.

The statistical calculations involved in estimating the cost response surface using a second order polynomial equation require the involvement of an advanced statistical software package, SAS 8.2 (SAS 2002). Thus, the ROMI 3.0 DSS uses SAS 8.2 to perform statistical calculations using the original 25 lumber yield estimates simulated by ROMI 3.0 and lumber and production cost data from the user input GUI (Figure 5-4). Using this data, SAS generates a surface model for cost data using a response surface regression (RSREG, SAS 2002) procedure. RSREG uses the method of least squares to fit a quadratic response surface regression model and uses canonical analysis of the response surface to find maximums, minimums, saddles, and ridges of the response surface model (SAS 1999). As discussed above, the involvement of SAS 8.2 necessitated the set-up of a server at a USDA Forest Service lab so that industry users could perform the statistical calculations. Thus, the ROMI 3.0 DSS, a local application programmed in C and Java, feeds the necessary data needed for the SAS calculations over the internet to the USDA Forest Service. After having received the results from the calculations done by SAS on the USDA Forest Service server, the DSS displays the returned results to the user on the least-cost lumber grade-mix results GUI (Figure 5-3). Budget restrictions at the U.S. Forest Service, user concerns about data privacy, and limitations of the number of users allowed to use the SAS software simultaneously, necessitated the search for a new approach to solve the least-cost lumber grade-mix problem.

5.3 Materials and Methodology

The least-cost lumber grade-mix solver (Buehlmann et al. 2004; Zuo 2003) is a DSS incorporated into a larger, more encompassing DSS called ROMI 3.0 that was created, maintained and made available for free to industry by the USDA Forest Service (Thomas and Weiss 2006; Weiss and Thomas 2005). The main function of ROMI 3.0 is to simulate the cut-up of hardwood lumber in rough mills of the secondary wood products manufacturing industry. The least-cost lumber grade-mix solver, a sub-DSS within the ROMI 3.0 lumber cut-up simulation program helps rough mill operators in the secondary wood products manufacturing industry reduce solid wood component production costs by optimizing the lumber grade selection used for a given production run. The current version of the least-cost lumber grade-mix solver (Buehlmann et al 2004; Zuo 2003) uses SAS 8.2 (SAS 2002) to predict total rough mill material and production cost based on the input of the least-cost lumber grade or grade-mix combination. While SAS 8.2 capabilities and functionalities are suited perfectly well in undertaking the necessary calculations, its cost and complexity are prohibitive for the secondary wood products industry. It was hypothesized, that SAS 8.2 (SAS 2002) could be replaced by R 2.7.2 (Vernables et al. 2008), an open source, free statistical package with similar capabilities as SAS 8.2. Since open source software is free or carries minimal costs or fees, it was hypothesized that by using R, the entire least-cost lumber grade-mix problem could be solved on the user's local computer without any third party involvement.

5.3.1 SAS 8.2

ROMI 3.0 (Thomas and Weiss 2006; Weiss and Thomas 2005), the USDA Forest Service's rough mill simulator containing the least-cost lumber grade-mix solver (Buehlmann et al. 2004; Zuo 2003) uses SAS Institute Inc.'s SAS 8.2 software (SAS 2002) to create a cost response surface and to predict the least-cost lumber grade-mix for rough mill operators. SAS 8.2 ranks the input cost data, creates a quadratic response surface model, and predicts cost values from the cost response surface using the proc iml and proc rsreg commands (SAS 2002). The proc IML command, an interactive matrix language procedure, uses a matrix of eigenvalues to rank terms (SAS 1999). The eigenvalue matrix is based on input data for FAS, SEL, 1C, and 2C lumber. Proc IML determines the rank, or the degrees of freedom, of the input data terms. The degrees of freedom indicate the appropriateness of a quadratic model. Proc RSREG is a response surface regression procedure that fits quadratic response surface models (SAS 1999) using the method of least squares. Proc RSREG creates a cost response surface model based on input data for FAS, SEL, 1C, 2C, and 3AC lumber grades. The LACKFIT command (SAS 1999) was attached to the RSREG procedure to examine the model for lack-of-fit. If the variation in mean values of the model is significantly higher than variation in mean value of observed replications, then the model is considered inadequate (SAS 1999). Thus, the lack-of-fit test ensures that an appropriate model is used. Lack-of-fit data is not automatically displayed; however, data can be retrieved manually from the SAS data. The shape of the quadratic response surface model is determined by the RSREG procedure using canonical analysis (SAS 1999). The quadratic response surface model is written in the form of Equation 5-3 (SAS 1999).

$$y_i = x_i^{'} A x_i + b' x_i + c' z_i + \epsilon_i$$

Equation 5-3

where:
y_i is the ith observation of the response variable
x_i $(x_{i1}, x_{i2},\dots, x_{ik})$ are the k factor variables for the ith observation
z_i $(z_{i1}, z_{i2},\dots, z_{iL})$ are the L covariates, including the intercept terms
A is the kxk symmetrized matrix of quadratic parameter, with diagonal elements equal to the coefficients of the pure quadratic terms in the model and off-diagonal elements equal to half the coefficient of the corresponding cross product
b is the kx1 vector of linear parameters
c is the Lx1 vector of covariate parameters, one of which is the intercept
ε_i is the error associated with the ith observation

To determine the shape of the response surface, the RSREG procedure takes the partial derivative of Equation 5-3with respect to x and solves for the critical values of x. Eigenvalues of matrix A determines if the solution is a maximum, a minimum, a saddle, or a flat surface. The RSREG procedure uses ridge analysis to determine the absolute maximum or absolute minimum location on a ridge (SAS 1999). Specific search values may be indicated using the PREDICT command. The PREDICT command generates predicted values for a grid of points (SAS 1999). The points correspond to the predicted cost for a set of pre-determined lumber grade combinations, which includes lumber grade-mix combinations that vary by increments of 10 percent. In this way, it is not necessary to search the entire surface. Thus, the least-cost lumber grade-mix solution comes from a set of pre-determined lumber values.

5.3.2 R 2.7.2

R 2.7.2 founded by Ihaka and Gentleman at the University of Auckland, NZ, is an open source programming language and software environment for statistical computing and graphics (Vernables et al. 2008; Ihaka 1998). Anecdotal evidence existed that R 2.7.2 has the same statistical capabilities as does SAS 8.2 in respect to this project. In particular, the response surface methodology command, RSM (Sztendur and Diamond 2008; Venables et al. 2008; Lenth 2009), and the predict command, PRED (Venables et al. 2008), of R seem to be equivalent to the proc RSREG commands in SAS. The RSM command uses the method of least squares, canonical analysis, and ridge analysis to generate a quadratic response surface model, determine the shape of the response surface, and find absolute maximum or minimum points (Szendur and Diamond 2008). The SUMMARY command in R is added to perform a lack-of-fit test to determine the adequacy of the model (Lenth 2009). The predict command in R, PRED, makes cost predictions for a grid of points using the response surface (Lenth 2009). R's RSM package has been used in other projects, for example, to optimize a polymer stud grid array design (Vandevelde and Beyne 1999), to optimize alkaline protease production (Puri et al. 2002), or to optimize the experimental condition on the surfactin fermentation process (Sen and Swaminathan 1997). It is expected that the RSM package may also be used to optimize the lumber grade combinations for rough mill components production.

5.3.3 Least-Cost Lumber Grade-Mix Solver

A rough mill manager attempting to minimize her solid hardwood component cost by buying the least-cost lumber grade or grade-mix for a given set of production requirements starts by opening the ROMI 3.0 DSS' general GUI (Figure 5-2). ROMI 3.0's simulation settings can be altered to represent individual rough mill operation settings (Figure 5-2). Detailed explanations of rough mill options can be found in the ROMI-3.0 user’s guide (Weiss and Thomas 2005). Typically, the user enters a cutting bill (e.g. the component requirements) and then sets specific operational rough mill settings. For this research, the following settings for ROMI 3.0 (Weiss and Thomas 2005) were used for all tests: all blades movable arbor (e.g. saw blades will change position when a better solution can be achieved by so doing), obtain parts salvaged through additional processing, use complex dynamic exponential component prioritization (the program chooses the component to be cut according to a calculated probability to obtain this part from the following boards, Thomas 1996), and no random length or random width components are produced (a strategy that some manufacturers use to decrease their lumber cost by gluing random-size parts into components).

When searching for the least-cost lumber grade-mix solution, users also have to enter the cost for the different lumber grades according to internal or market data concerning lumber purchasing costs and the processing costs that the operation incurs from processing a given set of lumber. In fact, raw material prices (lumber) fluctuate considerably over time and have to be adjusted whenever the least-cost lumber grade-mix DSS is used. For this study, raw material cost were obtained from a trade journal publication that publishes weekly pricing data by region for hardwood lumber (Hardwood Review Weekly 2002) and were set at \$1570 per mbf for First and Seconds (FAS) lumber, \$1350 per mbf for Selects (SEL), \$1000 per mbf for 1 Common (1C), \$748 per mbf for 2A Common (2AC), and \$500 per mbf for 3A Common (3AC) lumber. Processing costs were set at \$200 per mbf for all grades (Buehlmann and Zaech 2001).

Table 5-3. Raw material cost for each lumber grade

Cost	FAS	SEL	1C	2AC	3AC
(\$/mbf)	1570	1350	1000	748	500

5.3.4 Equivalence testing of SAS-based and R-based DSS

To assure the equivalence of the ROMI 3.0 DSS (Weiss and Thomas 2005) supported by R 2.7.2 (Venables 2008) instead of SAS 8.2 (SAS 2002), eleven scenarios using different component requirements (e.g. cutting bills) were designed and solved using the least-cost lumber grade-mix solver (Buehlmann et al. 2004; Zuo 2003). To account for the inherent variability of lumber cut-up simulations due to the variability of hardwood lumber, three repetitions of each scenario were conducted. Thus, a total of 66 test scenarios were executed. Also, to assure that the latest versions of each software was used, SAS 9.2 (SAS 2007) was used instead of SAS 8.2 (SAS 2002), however, no indication could be found in the SAS literature that any function in SAS used for this project was changed between these two iterations of the SAS statistical analysis package. Using the results from the 66 tests, the mean cost of the R-based least-cost lumber grade-mix solver DSS were then compared to the mean cost of the SAS-based least-cost lumber grade mix solver DSS using ANOVA testing at 95 percent level of significance.

5.3.5 Least-Cost Lumber Grade-Mix Solutions with Current Lumber Prices

Current least-cost lumber grade-mix solutions were determined for each of the eleven scenarios. Lumber prices from a trade journal (Hardwood Review Weekly 2002) were used to determine the current least-cost lumber grade-mix solutions for the eleven cutting bills.

5.4 Results & Discussion

Appendices A and B show the code executing the least-cost lumber grade-mix solver minimum cost search algorithm (Buehlmann et al. 2004; Zuo 2003) in SAS 9.2 (SAS 2007) and R 2.7.2 (Venables et al. 2008), respectively. All eleven scenarios tested for this study (three repetitions) were executed using ROMI 3.0 and the respective statistical software (SAS 9.2 or R 2.7.2). Table 5-4shows the minimum cost lumber combination solutions identified by the least-cost lumber grade-mix solver using SAS 9.2 (left half of Table 5-4) and R 2.7.2 (right half of Table 5-4), average yield (three repetitions), and total production (raw material plus processing costs) for each of the eleven scenarios investigated. For example, for both solutions, SAS 9.2 and R 2.7.2, cutting bill 1 requires a lumber grade mix of 20 percent 1C and 80 percent 3AC lumber grades, resulting in 38.18 percent yield (individual yield results were: 37.77, 37.85, and 38.92 percent respectively), and total average cost of

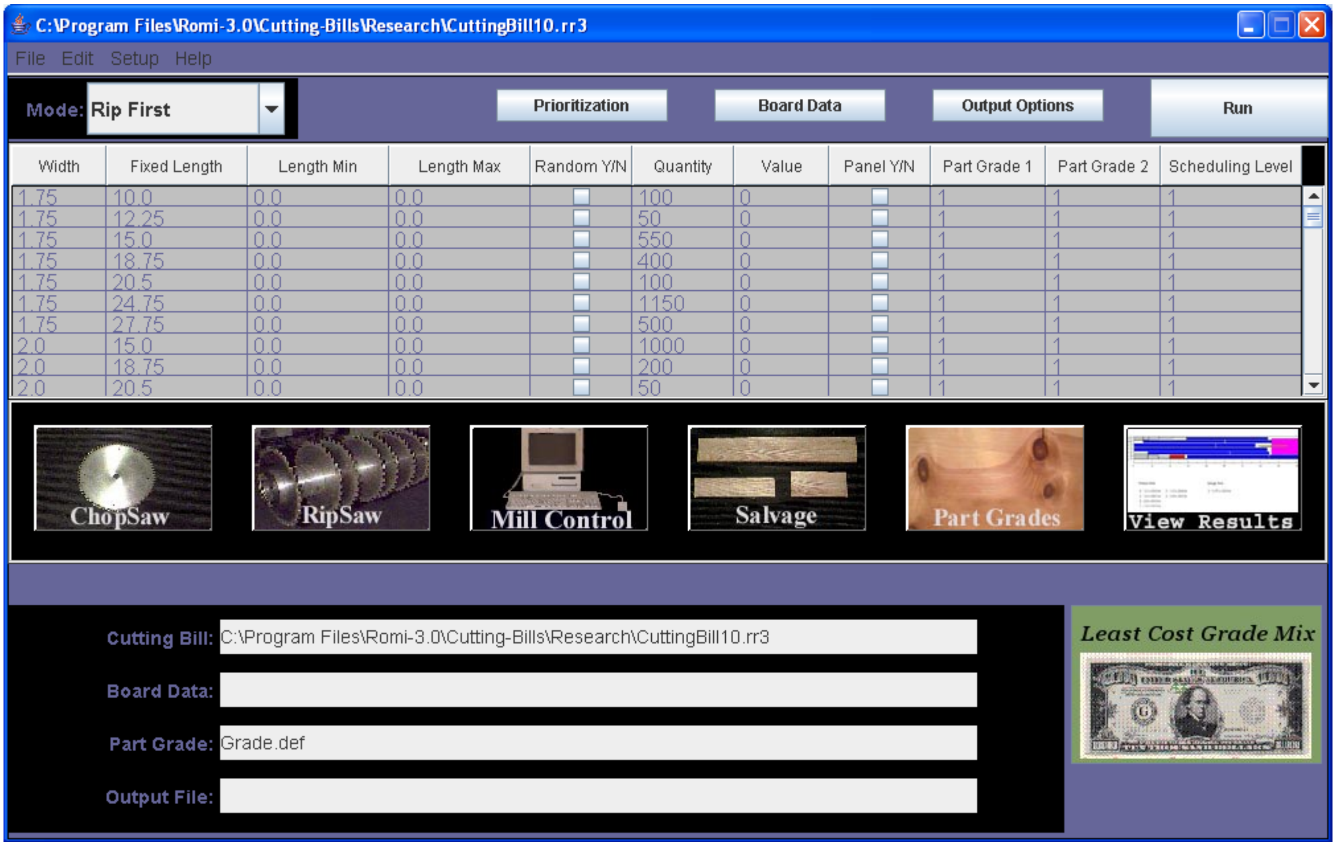
$2096 to fulfill a thousand bdft (mbf) of part requirements. Thus, the SAS 9.2 and the R 2.7.2-based least-cost lumber grade-mix solver DSS solution for cutting bill 1 are identical.

Table 5-4. Yield and total production cost for SAS- and R-based DSS

Cutting	ROMI-3.0 & SAS 9.2					Average	Average	ROMI-3.0 & R 2.7.2					Average	Average
Bill	FAS	SEL	1C	2AC	3AC	Yield	Cost	FAS	SEL	1C	2AC	3AC	Yield	Cost
A			20		80	38.18	2096			20		80	38.18	2096
B			20		80	36.82	2176			20		80	36.82	2176
C	20				80	32.70	2796	20				80	32.70	2796
D			20		80	32.57	2456			20		80	32.57	2456
E	80			20		52.24	3087	80			20		52.24	3087
F	20				80	25.60	3575	20				80	25.60	3575
G	80			20		62.12	2585	80			20		62.12	2585
H	80			20		62.62	2564	80			20		62.62	2564
I			100			56.62	2120			100			56.62	2120
J			20		80	45.07	1775			20		80	45.07	1775
Buehl.	20				80	38.28	2388	20				80	38.28	2388

In fact, Table 5-4 shows that there are no differences between least-cost lumber grade-mix solutions derived using the least-cost lumber grade-mix solver DSS (Zuo 2003) with either SAS 9.2 (SAS 2007) or R 2.7.2 (Venables et al. 2008) for any of the scenarios tested. As results are identical, no statistical tests were needed to conclude that the R 2.7.2 based least-cost lumber grade-mix solver solution is identical to the SAS 9.2-based least-cost lumber grade-mix solution.

Using the results from this research, the USDA Forest Service has created a new version of the rough mill simulator, ROMI 3.1 (Figure 5-5; Thomas et al. 2010).



Mode: Rip First

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	10.0	0.0	0.0	☐	100	0	☐	1	1	1
1.75	12.25	0.0	0.0	☐	50	0	☐	1	1	1
1.75	15.0	0.0	0.0	☐	550	0	☐	1	1	1
1.75	18.75	0.0	0.0	☐	400	0	☐	1	1	1
1.75	20.5	0.0	0.0	☐	100	0	☐	1	1	1
1.75	24.75	0.0	0.0	☐	1150	0	☐	1	1	1
1.75	27.75	0.0	0.0	☐	500	0	☐	1	1	1
2.0	15.0	0.0	0.0	☐	1000	0	☐	1	1	1
2.0	18.75	0.0	0.0	☐	200	0	☐	1	1	1
2.0	20.5	0.0	0.0	☐	50	0	☐	1	1	1

Cutting Bill: C:\Program Files\Romi-3.0\Cutting-Bills\Research\CuttingBill10.rr3
Board Data:
Part Grade: Grade.def
Output File:

Figure 5-5. Graphical User Interface (GUI) of the R 2.7.2-Based Decision Support System (DSS)

The new ROMI 3.1 (Thomas et al. 2010) no longer needs to communicate with an external server running SAS. This has considerably simplified the necessary software code in ROMI 3.1.. The ROMI 3.1 installer now includes a copy of R 2.7.2, which is automatically installed onto the user's computer when ROMI 3.1 is set-up. Executing the least-cost lumber grade-mix solver occurs locally and no data is transferred. Thus, any fears that the government could access user data when using a copy of SAS 8.2 run on a USDA Forest Service server have been eliminated. Also, the USDA Forest Service reduces its operational expenses by no longer being forced to buy, install, maintain, and back-up third party commercial software on their server. Thus, the secondary wood industry now has a fully functional free rough mill simulator (ROMI 3.1) that includes a locally executable least-cost lumber grade-mix solver (Buck 2009).

5.5 Conclusions

Hardwood lumber is for many secondary wood products manufacturers the single largest cost incurred. Hardwood is traded in five quality classes (called "grades" in the industry), ranging from best quality, i.e. lumber boards that are large and have little or no defects, to the lowest quality material, i.e. small boards with numerous deficiencies. Yield, the amount of usable material extracted from hardwood lumber, a natural, heterogeneous, anisotropic material with unusable defects randomly spread over each board's area, typically does not exceed 60 percent. Thus, the industry undertakes considerable efforts to increase the amount of usable material obtained from a given set of hardwood lumber but faces limits due to the presence of the defects. However, the industry can reduce hardwood lumber procurement costs by buying the least-cost lumber grade or grade-mix that yields all the components needed using the lowest-cost lumber quality or quality mix. The least-cost lumber grade-mix problem, as it is called in the industry, has attracted considerable attention by researchers and numerous solutions exist.

Using one of the least-cost lumber grade-mix solutions, the least-cost lumber grade-mix solver DSS developed by Buehlmann et al. (2004) and Zuo (2003) that relies on the proprietary SAS 8.2 (SAS 2002) statistical analysis software package for finding the solution, an open source, free version of the least-cost lumber grade-mix solver was developed. For this purpose, R 2.7.2 (Venables et al. 2008), an open source, freely available statistical analysis software package was incorporated into the least-cost lumber grade-mix solver DSS, replacing the proprietary SAS 8.2 software.

Testing the new R 2.7.2-based solution with eleven raw material requirements scenarios, both solutions, the one using SAS 9.2 (for these tests, the newest version of SAS was used as this version has no modifications on the routines involved compared to SAS 8.2) and the one using R 2.7.2, produced identical results. The new least-cost lumber grade-mix solver thus is an identical replacement for the SAS 8.2-based least-cost lumber grade-mix solver DSS. However, with this new version, users do not need to have access to the proprietary, for-fee SAS software and can execute all the necessary calculations on their local computer. The secondary hardwood products manufacturing industry thus now has access to a free, powerful least-cost lumber grade-mix solver DSS that runs on their local computers.

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Appendix A. Code to run SAS 9.2 for the least-cost lumber grade-mix solver

```
/*****************************************************
* SAS code for LEAST_COST LUMBER GRADE_MIX problem   *
*                         Xiaoqiu Zuo                  *
*              Necessary modifications by John Brown    *
*****************************************************/
/*input experimental results from a text file, I dropped only those variables being used.*/
data grid(keep=fas sel onec twoc threec yield cost);
    infile “c:program files/romi 3.0 beta/lcg-res.txt”;
        input fas sel onec twoc threec yield fasc selc onecomc twocomc threecomc process fasnew
        selnew onecomnew twocomnew threecomnew MBF cost;
run;

/*Check to make sure the correct df are there for a full model with four terms.*/
proc iml;
use grid;
read all var {fas sel onec twoc} into a;
rank_tmp=round(trace(ginv(a)*a));
create rank from rank_tmp[colname='rank'];
    append from rank_tmp;
quit;

data statement;
        set rank;
        if rank ne 5 then statement='There are linearly dependent grades';
                else statement='Grade matrix is full rank';
run;

data _temp;
do fas=0 to 1 by 0.1;
        do sel=0 to 1 by 0.1;
                do onec=0 to 1 by 0.1;
                        do twoc=0 to 1 by 0.1;
                                do threec=0 to 0.8 by 0.1;
                                yield=.;
                                        cost=.;
                                        output;
                                end;
                        end;
                end;
        end;
end;
run;

proc append data=_temp(where=(fas+sel+onec+twoc+threec=1)) base=grid;
run;
```

```
/*search for the optimal results using rsreg (response surface methodology) ods ouputs df (among other
information).  */
proc rsreg data=grid out=costout;
          model yield cost=fas sel onec twoc threec / lackfit predict;
run;

/*export the rank test to a text file*/
proc export data=statement
          outfile="c:/program files/SAS Foundation/9.2/linear_dependent_check.txt" /*give the file name
          and directory*/
          replace;
run;

/*export the results to a text file-Data includes new predictions and original data*/
proc export data=costout
    outfile="c:/program files/SAS Foundation.9.2/sas-output.txt" /*give the file name and directory*/
          replace;
run;
```

Appendix B. Code to run R 2.7.2 for the least-cost lumber grade-mix solver

```
#Sets file containing data.
setwd("C:/Program Files/Romi 3.0 beta/")

#Reads in the data.
dat<-read.table("lcg-res.txt",col.names=c("fas", "sel", "onec", "twoc", "threec", "yield", "fasc", "selc", "onecomc", "twocomc",
"threecomc", "process", "fasnew", "selnew", "onecomnew", "twocomnew", "threecomnew", "MBF", "cost"))

#Loads the rsm library.
library (rsm)

#Fits the response surface models.
dat.rsm.y = rsm (yield ~ FO(fas, sel, onec, twoc, threec)+TWI(fas, sel, onec, twoc, threec) -1, data = dat)
dat.rsm.c = rsm (cost ~ FO(fas, sel, onec, twoc, threec)+TWI(fas, sel, onec, twoc, threec) -1, data = dat)

#Displays ANOVA table and some other goodies.
summary(dat.rsm.y)
summary(dat.rsm.c)

#Saves the coefficients from the ANOVA tables for predictions.
beta.y<-coef(dat.rsm.y)
beta.c<-coef(dat.rsm.c)

#The following creates the output lumber combination matrix.
col1<-NULL
for(i in seq(0,1,by=.1)){
        col1<-c(col1,rep(i,11979))
}
col2<-NULL
for(i in seq(0,1,by=.1)){
        col2<-c(col2,rep(i,11979/11))
}
col2.<-NULL
```

```
for(i in 1:11){
	col2.<-c(col2.,col2)
}
col2<-col2.
col3<-NULL
for(i in seq(0,1,by=.1)){
	col3<-c(col3,rep(i,11979/(11*11)))
}
col3.<-NULL
for(i in 1:(11*11)){
	col3.<-c(col3.,col3)
}
col3<-col3.
col4<-NULL
for(i in seq(0,1,by=.1)){
	col4<-c(col4,rep(i,11979/(11*11*11)))
}
col4.<-NULL
for(i in 1:(11*11*11)){
	col4.<-c(col4.,col4)
}
col4<-col4.
col5<-seq(0,.8,by=.1)
col5.<-NULL
for(i in 1:(11*11*11*11)){
	col5.<-c(col5.,col5)
}
col5<-col5.
p<-cbind(col1,col2,col3,col4,col5)
p<-cbind(p,p%*%rep(1,5))
p.<-NULL
for(i in 1:length(p[,6])){
	if(p[i,6]==1) p.<-rbind(p.,p[i,])
}
```

```
p<-p.
p<-p[,-6]
p<-cbind(p,p[,1]*p[,2],p[,1]*p[,3],p[,1]*p[,4],p[,1]*p[,5],p[,2]*p[,3],p[,2]*p[,4],p[,2]*p[,5],p[,3]*p[,4],p[,3]*p[,5],p[,4]*p[,5])
#End of matrix.

#Predicts yield and cost for all values in the matrix.
y.pred<-p%*%beta.y
c.pred<-p%*%beta.c

#Creates a new data frame out of the matrix and the predicted cost and yield.
p<-cbind(p,y.pred,c.pred)
p<-data.frame(p)
names(p)<-c("fas", "sel", "onec", "twoc", "threec",
"fas:sel","fas:onec","fas:twoc","fas:threec","sel:onec","sel:twoc","sel:threec","onec:twoc","onec:threec","twoc:threec","Predicted Yield","Predicted Cost")

#Creates a new matrix where the observations are ordered by cost and then yield.
p.order<-p[do.call(order,p[,17:16]),]
names(p.order)<-c("fas", "sel", "onec", "twoc", "threec",
"fas:sel","fas:onec","fas:twoc","fas:threec","sel:onec","sel:twoc","sel:threec","onec:twoc","onec:threec","twoc:threec","Predicted Yield","Predicted Cost")

#Plots the ordered yield and cost.
par(mfrow=c(2,1))
plot(p.order[,16],main="Yield",ylab="Predicted",xlab="Row of ordered matrix, p.order",type="l")
plot(p.order[,17],main="Cost",ylab="Predicted",xlab="Row of ordered matrix, p.order",type="l")

#Writes a .txt file containing the ordered yield and cost in the directory and filename specified.
#write.table(p.order,file="C:/Program Files/R/R-2.9.0/R-output.txt")

#create and dump brief Results to output
lcg <- cbind(p.order[,1], p.order[,2], p.order[,3], p.order[,4], p.order[,5], p.order[,16], p.order[,17])
colnames(lcg) <-c("fas","sel","onec","twoc","threec","pYield","pCost")
```

```
#print(lcg);
write.table(lcg, row.names = FALSE, file="lcg-results.txt")
```

CHAPTER 6 Least-Cost Lumber Grade-Mix Solver For Romi 3.0 Using R Statistical Software

6.1 Abstract

The least-cost lumber grade-mix solution has been a topic of interest to both industry and academia for the last decades due to its potential to help operations to reduce their costs. A least-cost lumber grade-mix solver is a rough mill decision support system (DSS) that describes the lumber grade or grade-mix needed to minimize raw material or total production cost (raw materials plus processing cost). Since raw material costs in typical rough mills comprises 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 USDA Forest Service's rough mill simulator, ROMI 3.0, which employs SAS 8.2 for statistical calculations, was used for the research described in this manuscript. 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 internet. However, several issues around this rather involved set-up 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 of SAS 8.2. Comparisons of the SAS-based and a newly developed R-based least-cost lumber grade-mix solver indicate 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, rough mill operators now have a new version of ROMI 3.0 with the integrated least-cost lumber grade-mix solver at their disposal which does not necessitate their computers to communicate with any outside server.

6.2 Introduction

For typical solid hardwood products manufacturers in the United States, up to 70 percent of rough mill costs stem from the purchase of the hardwood lumber raw material (Mitchell et al. 2005; Wengert and Lamb 1994; Carino and Foronda 1990). 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 over-sized 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). Such dimension parts are cut in rough mills, departments at the beginning of the process of hardwood products manufacturing entities such as furniture, kitchen cabinetry, and flooring producers, to name a few. Rough mills consist of a series of processes intended to produce semi-finished components starting with lumber planning followed by rip and cross-cut sawing and ending with buffering the semi-finished 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 (Buehlmann 1998, Gatchell 1985). Yield is the single most important metric in all solid hardwood products manufacturers' strive to reduce lumber raw material cost and extensive efforts have been made to increase the yields obtained from a given set of input material.

Apart from industry efforts to increase yield, few options exist for solid hardwood products manufacturers to reduce solid hardwood lumber dimension part costs. Reducing dimension part sizes (e.g. final assembled part sizes) may violate a products' design, structural integrity, and may not be tolerated by the customers. The same holds for trying to replace solid wood dimension parts with engineered, veneered products or with alternative, less expensive materials. Thus, apart from increasing yield in the rough mill through more efficient use of the hardwood lumber resource, manufacturers can 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 (Buck 2009, Buehlmann et al. 2008 and 2004, Zuo et al. 2004, Zuo 2003). Hardwood lumber, a natural, heterogeneous material of varying geometrical size containing randomly dispersed character marks (e.g. defects) that cover a certain percentage 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, 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 where appearance is most important) but mostly for industrial products (e.g. packaging). FAS has the highest board quality standards requiring the largest boards and the fewest defects, thus making it the best quality class overall. To meet FAS standards, the board must have a minimum size of 6in x 8ft with 83 ⅓ percent clear board area. Additionally, the clear area available for the largest clear part size must have a minimum dimension of at least 4in x 5ft or 3in x 7ft. This clear area has to be created in one to four cuttings. Details of cuts allowed and other pertinent grade rules are listed in Table 6-1 (NHLA 2003). Selects, the second best board quality class designation, has slightly lower standards, requiring the board to be at least 4in x 6ft with 66 ⅔ percent clear area and a minimum part size of 4in x 5ft or 3in x 7ft. The cutting allowance for the better side of the board is the same as FAS and must be better than No. 1 Common for the reverse side. No. 1 Common lumber must be 3in x 4ft with 66 ⅔ percent clear area and minimum part size of 4in x 2ft or 3in x 3ft. One to five cuttings can be made to obtain the clear areas for a No. 1 Common board. No. 2 Common lumber must be 3in x 4ft with 50 percent clear area and minimum part size of 3in x 2ft. Clear areas have to be obtained in one to seven cuttings. No. 3A Common boards must be 3in x 4ft with 33 ⅓ percent clear area, minimum part size of 3in x 2ft, and No. 3B Common boards must be 3in x 4ft with 25 percent clear area and minimum part size of 1 ½in x 2ft. Unlimited numbers of cuttings are allowed for 3A and 3B Common lumber. Unlike 3A Common boards, a 3B Common board may not be structurally sound, e.g. the board may break apart when lifted.

Table 6-1: National Hardwood Lumber Association Guidelines

Grade	Board Length	Board Width	Minimum	Clear Area	Allowable Cuts to Obtain Part	
	Minimum	Minimum	Part Size	(percent)	Part Length	Cuts
FAS	8’	6”	4”x5’ or 3”x7’	83 ⅓	4’- 7’	1
					8’- 11’	2
					12’- 15’	3
					16’ and over	4
SEL	6’	4”	4”x5’ or 3”x7’	66 ⅔	Better side same as FAS reverse side better than 1C	
1C	4’	3”	4”x2’ or 3”x7’	66 ⅔	3’- 4’	1
					5’- 7’	2
					8’-10’	3
					11’-13’	4
					14’ and over	5
2AC	4’	3”	3”x2’	50	2’- 3’	1
					4’- 5’	2
					6’- 7’	3
					8’- 9’	4
					10’- 11’	5
					12’- 13’	6
					14’ and over	7
3AC	4’	3”	3”x2’	33 ⅓	No limit to number of cuts	
3BC	4’	3”	1 ½”x2’	25	No limit to number of cuts	

Large price differentials between quality classes exist. Lower grade lumbers costs less than higher grades. Processing costs are minimized by purchasing higher-grade lumber (Willard 1970) because higher-grade lumber requires less 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. For example, if cutting bill requirements ask for large quantities of large dimension parts, higher grade lumber is typically required as lower grade lumber may not be able to yield sufficient quantities of such parts resulting in unacceptably low yield and high costs. Lumber cost minimization thus requires to dynamically search for the least-cost lumber grade or grade-mix, taking into account cutting bill requirements and lumber grade price differentials at given times (Buck 2009, Buehlmann et al. 2008 and 2004, Zuo et al. 2004, Zuo 2003). As 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. (2008 and 2004), Zuo et al. (2004), and Zuo (2003) is a departure from previous solutions by Hamilton et al. (2002); Lawson et al. (1996); Suter and Calloway (1994); Fortney (1994); Harding (1991); Steele et al. (1990); Timson and Martens (1990); Carino and Foronda (1990); Martens and Nevel (1985); Hanover et al. (1973); and Englerth and Schumann (1969), which all employed linear programming techniques to find the least-cost lumber grade-mix. However, 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, Buehlmann et al.'s (2008 and 2004) and Zuo et al.'s (2004) least-cost lumber grade-mix solution 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 USDA Forest Service. Buehlmann et al.'s (2008) performance comparison showed that the new solution provides lower-cost grade-mix solutions with maximum savings of up to 10 percent of total lumber purchasing and processing costs.

However, Buehlmann et al.'s (2008) and Zuo et al.'s (2004) least-cost lumber grade-mix solver solution requires statistical algorithms provided by SAS 8.2 (proc RSREG command; SAS 2002). SAS is an expensive, specialized statistical business analysis software unlikely to 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, WV so that industry users could remotely have their calculations performed. A rough mill operator investigating the least-cost lumber grade-mix solution for his dimension parts needs would run ROMI 3.0's lumber cut-up simulation on her local computer, then transfer the yield data to the USDA Forest Service server running SAS 8.2, which then calculates the least-cost lumber grade-mix solution and feeds the results back to the remote user. However, 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, the need of 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 U.S. 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, thereby addressing the industry's concerns and saving the USDA Forest Service 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 SAS 8.2's and thus was considered as a candidate for this endeavor. Consequently, this research is investigating if R 2.7.2 can provide equivalent statistical calculations to those of SAS 8.2 and if Buehlmann et al.'s (2004) least-cost lumber grade-mix solver using R 2.7.2 can be incorporated into the USDA Forest Service's rough mill simulator ROMI 3.0 (Thomas and Weiss 2006; Weiss and Thomas 2005).

6.3 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 2008), the USDA Forest Service's ROMI 3.0 rough mill simulation software (Thomas and Weiss 2006, Weiss and Thomas 2005), eleven cutting bills from earlier studies (Buehlmann 1998; Thomas 1996, Wengert and Lamb 1994) digitized red oak lumber board representations from the 1998 Red Oak Lumber Database (Gatchell et al. 1998) and Appalachian Red Oak lumber prices from January 4, 2002 (Hardwood Review Weekly 2002). Also, specifying details pertaining to the performance comparison between the SAS 8.2-based and the R-2.7.2 based least-cost lumber grade-mix solver was necessary.

6.3.1 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 in the USDA Forest Service's ROMI 3.0 rough mill simulator (Thomas and Weiss 2006; Weiss and Thomas 2005).

Using the least-cost grade-mix solver requires that the rough mill operator enters 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 with which the least-cost determination is conducted, (Table 6-2; Zuo 2003).

Table 6-2. 25 Lumber grade combinations executed by ROMI-3.0 for initial response surface data

Runs	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

Lumber yields from the 25 simulations are transformed to cost data using cost equations from Zuo (2003). Equation 6-1 transforms yield to raw material lumber cost per thousand board foot of parts. A raw material cost response surface is then generated using the yields from the 25 lumber grade combinations discussed above (Table 6-2) and the cost data.

$$COST_j = \frac{\sum_{i=1}^{5} G_i M_i}{YIELD_i}$$

Equation 6-1

where:	Gi	the proportion of each lumber grade
	Mi	the market price per thousand board feet of each lumber grade
	i	1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common, and 5 for 3A Common
	j	observation of a grade combination run

Equation 6-2 transforms yield to total production cost (raw material plus processing costs) per thousand board foot of parts and a total production cost response surface is generated.

$$COST_j = \frac{\sum_{i=1}^{5} G_i (M_i + \mathrm{P_i})}{YIELD_i}$$

Equation 6-2

where:	Gi	the proportion of each lumber grade
	Mi	the market price per thousand board feet of each lumber grade
	Pi	the processing cost per thousand board feet of each lumber grade
	i	1 for FAS, 2 for SEL, 3 for 1 Common, 4 for 2A Common, and 5 for 3A Common
	j	observation of a grade combination run

For simplification, Equation 6-2 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 (SAS 2002).

6.3.2 Statistical software packages

SAS 8.2 is a widely used, powerful statistical analysis software package created, maintained, and sold by SAS Institute Inc., Carry, NC (SAS 2002). In the current version of the least-cost lumber grade-mix solver (Buehlmann et al. 2008 and 2004, Zuo et al. 2004), a second order polynomial cost response surface using the SAS 8.2 proc RSREG command based on the predicted yield information obtained from simulating the lumber cut-up in ROMI 3.0 (Thomas and Weiss 2006, Weiss and Thomas

2005), as well as 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 2007) for the tests in this research, although this necessitated the repetition of Buehlmann et al.'s (2008 and 2004) test runs.

R 2.7.2 (Vernables 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, has been considered as an alternative to SAS 9.2. R 2.7.2 can be run on local computers without incurring charges, thus avoiding the need to perform statistical calculations on the USDA Forest Service server running SAS. A copy of R 2.7.2 (Murdoch 2008) and the response surface methodology (RSM) package (Lenth 2009) was downloaded from the internet and instructions were studied (Vernables 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 Virginia Tech. 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.

6.3.3 ROMI Settings

Buehlmann et al.'s (2008 and 2004) and Zuo et al.'s (2004) study employed ROMI-RIP 2.0, the USDA Forest Service's Rough Mill Rip-First lumber cut-up simulator (Thomas 1999) for their research. In 2005, 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 all tests in this research, although this necessitated the repetition of Buehlmann et al.'s (2008 and 2004) performed with SAS 8.2 (SAS 2002). Settings of ROMI 3.0 for these tests were:

- Rip-first lumber cut-up
- All blades movable arbor (24 inch 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
- ¼-inch edge and side trim

6.3.4 Lumber data

Gatchell et al.'s (1998) Data Bank for Kiln-Dried Red Oak Lumber was used for this research. Lumber grades used were FAS, SEL, 1 Common, 2A Common, and 3A Common. ROMI 3.0 randomly generates lumber files according to the 25 lumber grade combinations in Table 6-2 (Zuo 2003). ROMI 3.0 uses these lumber board files to simulate the lumber cut-up process and returns estimated lumber yields, e.g. the boardfootage of parts obtained over the boardfootage of raw material used (Buehlmann 1998, Gatchell 1985). This yield data is then transformed to cost data using Equation 6-2. 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 2002 Hardwood Review Weekly (HRW 2002) were used: $1570 per thousand boardfoot FAS lumber, $1350 per thousand boardfoot SEL, $1000 per thousand boardfoot 1 Common, $748 per thousand boardfoot 2A Common, and $500 per thousand boardfoot 3A Common lumber. For all tests involving processing costs, $200 per thousand boardfoot infeed lumber processed was used for all lumber grades (Buehlmann and Zaech 2001).

6.3.5 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, 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 Zuo et al.'s (2004) table and a more detailed description of the cutting bills are provided in Buck (2009).

6.3.6 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 and the statistical package R 2.7.2 (Venables et al. 2008). As discussed above, the R-based least-cost grade-mix solver is compared with the SAS-based least-cost lumber grade-mix solver which uses the ROMI 3.0 rough mill simulator (Thomas and Weiss 2006 and Weiss and Thomas 2005) and SAS 9.2 (SAS 2008) as to not to confound the main effect (difference in least-cost lumber grade-mix cost calculated by least-cost lumber grade-mix solver using either R 2.7.2 or SAS 9.2). ANOVA testing ($\alpha = 0.05$) was performed to test for differences between 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).

6.4 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 6-3shows the least-cost lumber grade-mix solutions from both, the SAS 9.2 and the R 2.7.2-based version of the least-cost lumber grade-mix solver for the eleven cutting bills (Zuo et al. 2004) tested. No processing costs were considered in this first set of test runs.

Table 6-3**.** Raw material LCGM solutions with the SAS 9.2- and R 2.7.2-based LCGM solvers

	SAS 9.2-based LCGM solver						R 2.7.2-based LCGM Solver					
Cutting Bill	FAS	SEL	1C	2AC	3AC	Cost	FAS	SEL	1C	2AC	3AC	COST
A				20	80	1614				20	80	1614
B			20		80	1632			20		80	1632
C			20		80	2381			20		80	2381
D			20		80	1842			20		80	1842
E	80			20		2702	80			20		2702
F	20				80	2793	20				80	2793
G	20				80	2753	20				80	2753
H	20				80	3230	20				80	3230
I	20				80	2321	20				80	2321
J			10	10	80	1344			10	10	80	1344
Buehlmann			20		80	1844			20		80	1844

Table 6-4 shows the least-cost lumber grade-mix solutions from the SAS 9.2 and R 2.7.2-based version including $200 per thousand bdft processing costs for all grades for the eleven cutting bills (Zuo et al. 2004) tested.

Table 6-4**.** Total production LCGM solutions with the SAS 9.2- and R 2.7.2-based LCGM solvers

	SAS 9.2- Based LCGM Solver						R 2.7.2- Based LCGM Solver					
Cutting Bill	FAS	SEL	1C	2AC	3AC	Cost	FAS	SEL	1C	2AC	3AC	Cost
A			20		80	2096			20		80	2096
B			20		80	2176			20		80	2176
C	20				80	2796	20				80	2796
D			20		80	2456			20		80	2456
E	80			20		3087	80			20		3087
F	20				80	3575	20				80	3575
G	80			20		2585	80			20		2585
H	80			20		2564	80			20		2564
I			100			2120			100			2120
J			20		80	1775			20		80	1775
Buehlmann	20				80	2388	20				80	2388

6.5 Discussion

The SAS 9.2- and R 2.7.2- based least-cost lumber grade-mix solvers both used ROMI-3.0, the method of least squares, canonical analysis, and ridge analysis to calculate lumber yield, to create a quadratic cost response surface model, to determine the shape of the cost response surface, and to determine the absolute minimum of the response surface, respectively. It was expected that the R-based solutions would be equivalent or similar to that 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.

TablesTable 6-3 andTable 6-4 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 6-3, the least-cost lumber grade-mix solution for cutting bill A included 20 percent 2AC and 80 percent 3AC lumber with a raw material cost of $1614/mbf for both the SAS 9.2-based and the R 2.7.2-based least-cost lumber grade-mix solver. Similarly, in Table 6-4, the least-cost lumber grade-mix solution for cutting bill A included 20 percent 1C and 80 percent 3AC lumber with a total production cost (raw material plus processing) of $2096 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 (ANOVA at the 95 percent of significance level) was necessary.

Least-cost lumber grade-mix solver solutions for raw material only favor using 80 percent 3AC lumber showing that processing costs are important in determining true least-cost lumber grade-mix solutions. In the original set-up for the least-cost lumber grade-mix model by Buehlmann et al. (2004) and Zuo (2003), 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 when lumber is continuously being cut to obtain the missing larger parts, thereby skewing the response surface and leading to unrealistic least-cost lumber grade-mix solution (Buehlmann et al. 2004, Zuo 2003). However, the trend of the model to use the maximum amount of 3AC lumber is expected since lower grade lumber has lower raw material cost. However, lower grade lumber contains a larger number of defects and, thus, 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 6-3) is 20 percent 2C and 80 percent 3AC. However, the least-cost lumber grade mix solution with processing cost included (Table 6-4) is 20 percent 1C and 80 percent 3AC. 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). Thus, when including processing costs, input lumber grade quality requested either increased or stayed the same. Some of the more difficult cutting bills (cutting bill G, H, and I) required substantially more higher quality lumber for a least-cost lumber grade-mix solution when processing costs of $200 per thousand bdft were added. However, 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 industry's efforts to minimize those costs.

6.6 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 decision support systems (DSS) that describe the lumber grade or grade-mix that minimizes raw material or total dimension parts production costs (raw material plus processing cost).

The first least-cost lumber grade-mix solvers used linear models to predict least-cost lumber grade-mix solutions. However, 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 the USDA Forest Service's rough mill simulator, 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 internet. However, this research project investigated the possibility to eliminate 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 indicate 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 of ROMI 3.0 including the R-based least-cost lumber grade-mix solver can be installed and executed from a personal computer with no external computing resources.

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CHAPTER 7 General Results, Discussion, and Future Research

Initial comparisons of the eleven scenarios were performed using ROMI 3.0 and either one of the two statistical packages considered in this research (e.g. SAS 9.2 or R 2.7.2). The minimum raw material cost solutions for the SAS 9.2-based and the R 2.7.2-based least-cost lumber grade-mix solvers are shown in Table 7-1.

Table 7-1. Yield and raw material cost for the SAS-based and R-based LCGM solvers

Cutting	ROMI-3.0 & SAS 9.2					Average	Average	ROMI-3.0 & R 2.7.2					Average	Average
Bill	FAS	SEL	1C	2AC	3AC	Yield	Cost	FAS	SEL	1C	2AC	3AC	Yield	Cost
A				20	80	34.06	1614				20	80	34.06	1614
B			20		80	36.82	1632			20		80	36.82	1632
C			20		80	25.21	2381			20		80	25.21	2381
D			20		80	32.57	1842			20		80	32.57	1842
E	80			20		52.24	2702	80			20		52.24	2702
F	20				80	25.60	2793	20				80	25.60	2793
G	20				80	25.98	2753	20				80	25.98	2753
H	20				80	22.11	3230	20				80	22.11	3230
I	20				80	30.77	2321	20				80	30.77	2321
J			10	10	80	42.77	1344			10	10	80	42.77	1344
Buehl.			20		80	32.54	1844			20		80	32.54	1844

The minimum production (raw material and processing cost) cost solutions for the SAS 9.2-based and the R 2.7.2-based least-cost lumber grade-mix solvers are shown in Table 7-2.

Table 7-2. Yield and production cost for the SAS-based and R-based LCGM solvers

Cutting	ROMI-3.0 & SAS 9.2					Average	Average	ROMI-3.0 & R 2.7.2					Average	Average
Bill	FAS	SEL	1C	2AC	3AC	Yield	Cost	FAS	SEL	1C	2AC	3AC	Yield	Cost
A			20		80	38.18	2096			20		80	38.18	2096
B			20		80	36.82	2176			20		80	36.82	2176
C	20				80	32.70	2796	20				80	32.70	2796
D			20		80	32.57	2456			20		80	32.57	2456
E	80			20		52.24	3087	80			20		52.24	3087
F	20				80	25.60	3575	20				80	25.60	3575
G	80			20		62.12	2585	80			20		62.12	2585
H	80			20		62.62	2564	80			20		62.62	2564
I			100			56.62	2120			100			56.62	2120
J			20		80	45.07	1775			20		80	45.07	1775
Buehl.	20				80	38.28	2388	20				80	38.28	2388

The results of Table 7-1 and Table 7-2 indicate that no difference exists between SAS 9.2-based and R 2.7.2-based least-cost lumber grade-mix solutions.

Additional comparisons were performed using ROMI-RIP 2.0 and the statistical package SAS 8.2 (Zuo et al. 2004) and ROMI 3.0 and statistical package R 2.7.2 to indicate any differences in the underlying rough mill simulation programs used to derive the necessary yield data. If differences between the original least-cost lumber grade-mix solver solution by Buehlmann et al. (2004) and Zuo (2003) using ROMI-RIP 2.0 (Thomas 1999a, 1999b) and SAS 8.2 (SAS 2002) and the newly created solver using ROMI 3.0 (Thomas and Weiss 2006, Weiss and Thomas 2005), and R 2.7.2 (Venables et al. 2008) are detected, these differences can be uniquely assigned to the rough mill simulation programs, since no significant difference was found between SAS and R (Table 7-1 and Table 7-2). Table 7-3 compares minimum raw material cost solutions of the original, ROMI-RIP 2.0-based and the new ROMI 3.0-based least-cost lumber grade-mix solvers. Table 7-4 compares minimum raw material and processing cost solutions between these two least-cost lumber grade-mix solutions.

Table 7-3. Yield and raw material cost for the ROMI-RIP 2.0-based and ROMI-3.0 based LCGM solvers

Cutting	ROMI-RIP 2.0 & SAS 8.2					Average	Average	ROMI-3.0 & R 2.7.2					Average	Average
Bill	FAS	SEL	1C	2AC	3AC	Yield	Cost	FAS	SEL	1C	2AC	3AC	Yield	Cost
A				100		43.24	1730				20	80	34.06	1614
B				100		55.58	1346			20		80	36.82	1632
C				20	80	44.17	1244			20		80	25.21	2381
D				20	80	37.16	1479			20		80	32.57	1842
E	30		50	20		59.84	1873	80			20		52.24	2702
F		50	20		30	52.16	1965	20				80	25.60	2793
G			80		20	50.72	1775	20				80	25.98	2753
H			70		30	53.23	1597	20				80	22.11	3230
I			80	20		58.62	1620	20				80	30.77	2321
J	40		40	20		57.53	2047			10	10	80	42.77	1344
Buehl.			70		30					20		80	32.54	1844

Table 7-4. Yield and production cost for the ROMI-RIP 2.0-based and ROMI 3.0-based LCGM solvers

Cutting	ROMI-RIP 2.0 & SAS 8.2					Average	Average	ROMI-3.0 & R2.7.2					Average	Average
Bill	FAS	SEL	1C	2AC	3AC	Yield	Cost	FAS	SEL	1C	2AC	3AC	Yield	Cost
A			100			57.11	2101			20		80	38.18	2096
B				100		54.49	1740			20		80	36.82	2176
C				20	80	44.17	1697	20				80	32.70	2796
D				100		48.18	1968			20		80	32.57	2456
E	50		30		20	61.36	2253	80			20		52.24	3087
F		60	10		30	52.42	2405	20				80	25.60	3575
G			90		10	59.85	1922	80			20		62.12	2585
H			70		30	53.23	1973	80			20		62.62	2564
I			80	20		58.39	1969			100			56.62	2120
J	60		10	30		62.84	2334			20		80	45.07	1775
Buehl.			80		20			20				80	38.28	2388

Results from Table 7-3 and Table 7-4 indicate that in some cases differences between the least-cost solutions derived by either ROMI-RIP 2.0 or ROMI 3.0 exist. Table 7-5 shows the difference between the ROMI-RIP 2.0 and the ROMI 3.0-based least-cost lumber grade-mix solutions.

Table 7-5. Difference in raw material and production cost of ROMI-RIP 2.0 and ROMI 3.0

	Raw Material Cost			Production Cost		
Cutting	ROMI-RIP 2.0	ROMI 3.0	Difference	ROMI-RIP 2.0	ROMI 3.0	Difference
Bill	SAS 8.2	R 2.7.2	(SAS-R)	SAS 8.2	R 2.7.2	(SAS-R)
A	1730	1614	116	2101	2096	5
B	1346	1632	-286	1740	2176	-436
C	1244	2381	-1137	1697	2796	-1099
D	1479	1842	-363	1968	2456	-488
E	1873	2702	-829	2253	3087	-833
F	1965	2793	-828	2405	3575	-1171
G	1775	2753	-979	1922	2585	-663
H	1597	3230	-1633	1973	2564	-591
I	1620	2321	-701	1969	2120	-151
J	2047	1344	703	2334	1775	559

The Buehlmann cutting bill is not included in this table (Table 7-5) since cost data was not reported by either Buehlmann et al. (2004) or Zuo (2003). Table 7-5 shows that the ROMI-RIP 2.0-based least-cost lumber grade-mix solver gives lower cost solutions in eight of the ten cutting bills tested for both options, raw material cost only or raw material plus processing cost solutions. The reason for the cost differences in Table 7-5 is unknown and beyond the scope of this thesis.

Contributing factors may include changes to the lumber cut-up optimization algorithm and to the all blades movable arbor algorithm of ROMI 3.0 (Thomas 2009b). Zuo (2003) also used a different 25 lumber grade combination data set to create the response surface models for cutting bills G, I, and J (Appendix D).

Additional research should focus on resolving those issues resulting in inferior least-cost lumber grade-mix solutions between ROMI-RIP 2.0 and ROMI 3.0. The research should focus on why ROMI 3.0 produces higher cost results that ROMI-RIP 2.0. A description of changes made to ROMI can be found in Thomas and Weiss (2006) and Weiss and Thomas (2005).

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CHAPTER 8 Summary and Conclusions

In recent years, the least-cost lumber grade-mix solution has been a topic of interest to both the secondary hardwood industry and to academia. The least-cost lumber grade-mix solution details the lumber grade and percentage of each lumber grade that a rough mill should purchase to minimize raw material or total production cost (raw material plus processing cost). The least-cost lumber grade-mix solution also provides information regarding expected lumber yield and raw material or total production cost estimates. Previous research has shown raw material cost may comprise up to 70 percent of all rough mill expenses for manufacturers of the secondary wood products industry. Thus, even small changes in raw material cost can contribute to a substantial reduction in rough mill expenses.

The original least-cost lumber grade-mix solvers used linear modeling to find least-cost lumber grade-mix solutions. In 2004, Zuo et al. tested the assumption of linearity and found that a linear relationship between lumber grades or grade mixes and yield does not always exist and thus that linear modeling was not applicable in 9 of 10 cutting bills tested. Therefore, a statistical model was developed by Zuo (2003) that used a second order polynomial equation to find the least-cost lumber grade-mix solution. The new technique which used ROMI-RIP 2.0 (Thomas 1999a, 1999b) and SAS 8.2 (SAS 2002) was validated by Buehlmann et al (2008). Zuo's (2003) least-cost lumber grade-mix solver was incorporated into ROMI 3.0 (Thomas and Weiss 2006, Weiss and Thomas 2005), an updated version of ROMI-RIP 2.0, and relied on the statistical package SAS 8.2 (SAS 2002) to perform statistical calculations. To provide SAS 8.2 at no charge to the industry, the USDA Forest Service purchased a SAS server license to allow free access to least-cost lumber grade-mix solver users. However, users were reluctant to submit individual cost and yield information to a government server. Thus, the goal of this research was to incorporate the least-cost lumber grade-mix solver into

ROMI using the free open source statistical package R 2.7.2 (Venables et al. 2008) to perform statistical calculations. It was hypothesized that if R 2.7.2 is capable of replacing SAS 8.2, the least-cost lumber grade-mix solver could be made available on each user's personal computer. This new R-based least-cost lumber grade-mix solver would assist users in finding optimal least-cost lumber grade-mix solutions without connection to a government server.

Existing literature and initial results revealed that R 2.7.2 is capable of replacing SAS 8.2 in the least-cost lumber grade-mix solver. Thus, the newly created R-based least-cost lumber grade-mix solver was compared with the original SAS-based least-cost lumber grade-mix solver. No differences were found in the least-cost lumber grade-mix solutions from either solver. Thus, a new least-cost lumber grade mix solver using the R 2.7.2 open source statistical package was created. R 2.7.2 is installed on each personal computer on which the USDA Forest Service's ROMI rough mill simulation software is installed and, thus, no external computing resources need to be consulted when solving the least-cost lumber grade-mix problem.

The limitation of using ROMI 3.0 is that ROMI 3.0 often provides inferior yield solutions to ROMI-RIP 2.0. This limitation is beyond the scope of this thesis. Future research is needed to determine why ROMI 3.0 provides inferior yield solutions and what the implications are for least-cost lumber grade-mix users.

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APPENDIX A. SAS LEAST-COST LUMBER GRADE-MIX SOLVER CODE

```
/*****************************************************
* SAS code for LEAST_COST LUMBER GRADE_MIX problem   *
*                          XiaoqiuZuo                *
*               Necessary modifications by John Brown        *
*****************************************************/
/*input experimental results from a text file, I dropped only those variables being used.*/
data grid(keep=fasselonectwocthreec yield cost);
   infile“c:program files/romi 3.0 beta/lcg-res.txt”;
      input fasselonectwocthreec yield fascselconecomctwocomcthreecomc process
      fasnewselnewonecomnewtwocomnewthreecomnew MBF cost;
run;

/*Check to make sure the correct df are there for a full model with four terms.*/
proc iml;
use grid;
read all var {fasselonectwoc} into a;
rank_tmp=round(trace(ginv(a)*a));
create rank from rank_tmp[colname='rank'];
   append from rank_tmp;
quit;

data statement;
        set rank;
        ifrank ne 5 then statement='There are linearly dependent grades';
                else statement='Grade matrix is full rank';
run;

data _temp;
dofas=0 to 1 by 0.1;
        dosel=0 to 1 by 0.1;
                doonec=0 to 1 by 0.1;
                        dotwoc=0 to 1 by 0.1;
                                dothreec=0 to 0.8 by 0.1;
                                yield=.;
                                        cost=.;
                                        output;
                                end;
                        end;
                end;
        end;
end;
run;

proc append data=_temp(where=(fas+sel+onec+twoc+threec=1)) base=grid;
run;
```

```
/*search for the optimal results using rsreg (response surface methodology) odsouputsdf (among other
information).  */
proc rsreg data=grid out=costout;
          model yield cost=fasselonectwocthreec / lackfit predict;
run;

/*export the rank test to a text file*/
proc export data=statement
          outfile="c:/program files/SAS Foundation/9.2/linear_dependent_check.txt"/*give the file name
          and directory*/
          replace;
run;

/*export the results to a text file-Data includes new predictions and original data*/
proc export data=costout
    outfile="c:/program files/SAS Foundation.9.2/sas-output.txt"/*give the file name and directory*/
          replace;
run;
```

APPENDIX B. R LEAST-COST LUMBER GRADE-MIX SOLVER CODE

```
#Sets file containing data.
setwd("C:/Program Files/Romi 3.0 beta/")

#Reads in the data.
dat<-read.table("lcg-res.txt",col.names=c("fas", "sel", "onec", "twoc", "threec", "yield", "fasc", "selc", "onecomc", "twocomc",
"threecomc", "process", "fasnew", "selnew", "onecomnew", "twocomnew", "threecomnew", "MBF", "cost"))

#Loads the rsm library.
library (rsm)

#Fits the response surface models.
dat.rsm.y = rsm (yield ~ FO(fas, sel, onec, twoc, threec)+TWI(fas, sel, onec, twoc, threec) -1, data = dat)
dat.rsm.c = rsm (cost ~ FO(fas, sel, onec, twoc, threec)+TWI(fas, sel, onec, twoc, threec) -1, data = dat)

#Displays ANOVA table and some other goodies.
summary(dat.rsm.y)
summary(dat.rsm.c)

#Saves the coefficients from the ANOVA tables for predictions.
beta.y<-coef(dat.rsm.y)
beta.c<-coef(dat.rsm.c)

#The following creates the output lumber combination matrix.
col1<-NULL
for(i in seq(0,1,by=.1)){
        col1<-c(col1,rep(i,11979))
}
col2<-NULL
for(i in seq(0,1,by=.1)){
        col2<-c(col2,rep(i,11979/11))
}
col2.<-NULL
for(i in 1:11){
```

```
		col2.<-c(col2.,col2)
}
col2<-col2.
col3<-NULL
for(i in seq(0,1,by=.1)){
		col3<-c(col3,rep(i,11979/(11*11)))
}
col3.<-NULL
for(i in 1:(11*11)){
		col3.<-c(col3.,col3)
}
col3<-col3.
col4<-NULL
for(i in seq(0,1,by=.1)){
		col4<-c(col4,rep(i,11979/(11*11*11)))
}
col4.<-NULL
for(i in 1:(11*11*11)){
		col4.<-c(col4.,col4)
}
col4<-col4.
col5<-seq(0,.8,by=.1)
col5.<-NULL
for(i in 1:(11*11*11*11)){
		col5.<-c(col5.,col5)
}
col5<-col5.
p<-cbind(col1,col2,col3,col4,col5)
p<-cbind(p,p%*%rep(1,5))
p.<-NULL
for(i in 1:length(p[,6])){
		if(p[i,6]==1) p.<-rbind(p.,p[i,])
}

p<-p.
```

```
p<-p[,-6]
p<-cbind(p,p[,1]*p[,2],p[,1]*p[,3],p[,1]*p[,4],p[,1]*p[,5],p[,2]*p[,3],p[,2]*p[,4],p[,2]*p[,5],p[,3]*p[,4],p[,3]*p[,5],p[,4]*p[,5])
#End of matrix.

#Predicts yield and cost for all values in the matrix.
y.pred<-p%*%beta.y
c.pred<-p%*%beta.c

#Creates a new data frame out of the matrix and the predicted cost and yield.
p<-cbind(p,y.pred,c.pred)
p<-data.frame(p)
names(p)<-c("fas", "sel", "onec", "twoc", "threec",
"fas:sel","fas:onec","fas:twoc","fas:threec","sel:onec","sel:twoc","sel:threec","onec:twoc","onec:threec","twoc:threec","Predicted Yield","Predicted Cost")

#Creates a new matrix where the observations are ordered by cost and then yield.
p.order<-p[do.call(order,p[,17:16]),]
names(p.order)<-c("fas", "sel", "onec", "twoc", "threec",
"fas:sel","fas:onec","fas:twoc","fas:threec","sel:onec","sel:twoc","sel:threec","onec:twoc","onec:threec","twoc:threec","Predicted Yield","Predicted Cost")

#Plots the ordered yield and cost.
par(mfrow=c(2,1))
plot(p.order[,16],main="Yield",ylab="Predicted",xlab="Row of ordered matrix, p.order",type="l")
plot(p.order[,17],main="Cost",ylab="Predicted",xlab="Row of ordered matrix, p.order",type="l")

#Writes a .txt file containing the ordered yield and cost in the directory and filename specified.
#write.table(p.order,file="C:/Program Files/R/R-2.9.0/R-output.txt")

#create and dump brief Results to output
lcg<- cbind(p.order[,1], p.order[,2], p.order[,3], p.order[,4], p.order[,5], p.order[,16], p.order[,17])
colnames(lcg) <-c("fas","sel","onec","twoc","threec","pYield","pCost")

#print(lcg);
write.table(lcg, row.names = FALSE, file="lcg-results.txt")
```

APPENDIX C. CUTTING BILLS

CUTTING BILL A

Width	Length	Quality
2.00	25.50	625
2.25	20.75	750
2.25	27.00	2250
2.75	16.25	1500
2.75	32.50	1500

CUTTING BILL B

Width	Length	Quantity
1.50	12.00	1000
1.50	16.50	5000
1.50	27.00	260
2.00	19.75	500
2.00	27.00	125
2.00	48.00	400
2.25	29.25	500
2.75	13.75	1000
2.75	28.75	800
2.75	44.00	1000

CUTTING BILL C

Width	Length	Quantity
1.50	18.00	900
1.50	24.00	900
1.50	28.00	900
1.5	44.00	1170
1.50	72.00	540
3.00	36.00	900
3.00	60.00	630

CUTTING BILL D

Width	Length	Quantity
2.00	25.50	625
2.50	25.50	50
2.50	40.75	50
2.75	16.25	1500
2.75	32.50	1500

CUTTING BILL E

Width	Length	Quantity
4.00	29.00	23
4.00	81.00	40
5.00	29.00	10
5.00	84.00	10
5.50	29.00	11
6.00	29.00	11
6.00	84.00	11

CUTTING BILL F

Width	Length	Quantity
2.00	11.00	200
2.00	26.00	200
2.00	30.00	100
2.00	42.00	400
2.50	26.00	800
2.50	28.50	100
2.50	30.00	500
3.25	11.00	400
3.25	26.00	400
3.25	30.00	500
3.25	53.00	600
4.75	53.00	400

CUTTING BILL G

Width	Length	Quantity
2.00	15.00	325
2.00	18.00	100
2.00	25.00	250
2.00	33.00	300
2.00	50.00	400
2.75	15.00	175
2.75	25.00	250
2.75	45.00	600
2.75	72.00	150
3.50	15.00	250
3.50	38.00	250
3.50	50.00	600
3.50	60.00	100
4.25	29.00	400
4.25	50.00	200
4.25	72.00	300

CUTTING BILL H

Width	Length	Quantity
2.00	29.00	108
2.00	84.00	108
2.25	29.00	108
2.25	84.00	108
3.75	29.00	100
3.75	84.00	100
4.25	16.00	145
4.25	27.00	94
4.50	27.00	94
4.50	16.00	267

CUTTING BILL I

Width	Length	Quantity
1.50	30.00	605
1.50	48.25	480
2.25	22.75	100
2.25	30.00	203
2.25	48.25	240
2.25	64.50	67
2.25	80.50	67
2.25	87.50	135
2.75	19.50	156
2.75	30.00	203
2.75	48.25	240
3.00	28.25	240
3.00	30.00	203
3.00	33.25	120
3.25	30.00	405
3.25	48.25	120
3.25	56.00	617
4.00	23.25	617
4.25	21.00	183
4.25	33.25	281

CUTTING BILL J

Width	Length	Quantity
1.75	10.00	100
1.75	12.25	50
1.75	15.00	550
1.75	18.75	400
1.75	20.50	100
1.75	24.75	1150
1.75	27.75	500
2.00	15.00	1000
2.00	18.75	200
2.00	20.50	50
2.00	24.75	650
2.00	31.50	100
2.25	13.00	200
2.25	14.50	75
2.25	18.75	400
2.25	21.00	450
2.25	22.50	400
2.25	24.75	1150
2.25	28.75	700
3.75	13.50	50
3.75	28.25	200
4.50	21.00	150
5.00	14.50	25
5.25	12.25	200
5.25	15.00	200

BUEHLMANN CUTTING BILL

Width	Length	Quantity
1.50	10.00	136
150	17.50	297
1.50	27.50	433
1.50	47.50	243
1.50	72.50	103
2.50	10.00	152
2.50	17.50	298
2.50	27.50	480
2.50	47.50	262
2.50	72.50	98
3.50	10.00	46
3.50	17.50	102
3.50	27.50	146
3.50	47.50	88
3.50	72.50	57
4.25	10.00	49
4.25	17.50	99
4.25	27.50	458
4.25	47.50	85
4.25	72.50	40

APPENDIX D. 25 LUMBER COMBINATIONS USED TO CREATE RESPONSE SURFACES

R 2.7.2-BASED LCGM SOLVER

FAS	SEL	1C	2AC	3AC
0	0	0	20	80
0	0	0	60	40
0	0	0	100	0
0	0	20	0	80
0	0	50	50	0
0	0	50	50	0
0	0	60	0	40
0	0	100	0	0
0	20	0	0	80
0	50	0	50	0
0	50	0	50	0
0	50	50	0	0
0	50	50	0	0
0	60	0	0	40
0	100	0	0	0
50	0	0	50	0
50	0	0	50	0
50	0	50	0	0
50	0	50	0	0
50	50	0	0	0
50	50	0	0	0
60	0	0	0	40
60	0	0	0	40
100	0	0	0	0
100	0	0	0	0

SAS 9.2-BASED LCGM SOLVER

FAS	SEL	1C	2AC	3AC
0	0	0	20	80
0	0	0	60	40
0	0	0	100	0
0	0	20	0	80
0	0	50	50	0
0	0	50	50	0
0	0	60	0	40
0	0	100	0	0
0	20	0	0	80
0	50	0	50	0
0	50	0	50	0
0	50	50	0	0
0	50	50	0	0
0	60	0	0	40
0	100	0	0	0
50	0	0	50	0
50	0	0	50	0
50	0	50	0	0
50	0	50	0	0
50	50	0	0	0
50	50	0	0	0
60	0	0	0	40
60	0	0	0	40
100	0	0	0	0
100	0	0	0	0

SAS 8.2-BASED LCGM SOLVER
for cutting bills A, B, C, D, E, F, H,
and Buehlmann

FAS	SEL	1C	2AC	3AC
0	0	0	20	80
0	0	0	60	40
0	0	0	100	0
0	0	20	0	80
0	0	50	50	0
0	0	50	50	0
0	0	60	0	40
0	0	100	0	0
0	20	0	0	80
0	50	0	50	0
0	50	0	50	0
0	50	50	0	0
0	50	50	0	0
0	60	0	0	40
0	100	0	0	0
50	0	0	50	0
50	0	0	50	0
50	0	50	0	0
50	0	50	0	0
50	50	0	0	0
50	50	0	0	0
60	0	0	0	40
60	0	0	0	40
100	0	0	0	0
100	0	0	0	0

SAS 8.2-BASED LCGM SOLVER
for cutting bills G, I, and J

FAS	SEL	1C	2AC	3AC
0	0	0	40	60
0	0	0	70	30
0	0	0	100	0
0	0	40	0	60
0	0	50	50	0
0	0	50	50	0
0	0	70	0	30
0	0	100	0	0
0	0	100	0	0
0	40	0	0	60
0	50	0	50	0
0	50	0	50	0
0	50	50	0	0
0	50	50	0	0
0	70	0	0	30
100	0	0	0	0
40	0	0	0	60
50	0	0	50	0
50	0	0	50	0
50	0	50	0	0
50	0	50	0	0
50	50	0	0	0
50	50	0	0	0
70	0	0	0	30
100	0	0	0	0

APPENDIX E. RAW MATERIAL COST

YIELD AND RAW MATERIAL COST FOR SAS 9.2- AND R 2.7.2-BASED LCGM SOLVER

Cutting Bill	ROMI 3.0 & SAS 9.2					Yield (%)	Average Yield	Average Cost ($/mbf)	ROMI 3.0 & R 2.7.2					Yield (%)	Average Yield	Average Cost ($/mbf)
	FAS	SEL	1C	2AC	3AC				FAS	SEL	1C	2AC	3AC			
1				20	80	34.38	34.06	1614				20	80	34.38	34.06	1614
				20	80	33.66						20	80	33.66		
				20	80	34.13						20	80	34.13		
2			20		80	36.63	36.82	1632			20		80	36.63	36.82	1632
			20		80	35.10					20		80	35.10		
			20		80	38.74					20		80	38.74		
3			20		80	24.65	25.21	2381			20		80	24.65	25.21	2381
			20		80	26.15					20		80	26.15		
			20		80	24.84					20		80	24.84		
4			20		80	32.64	32.57	1842			20		80	32.64	32.57	1842
			20		80	32.42					20		80	32.42		
			20		80	32.65					20		80	32.65		
5	80			20		56.59	52.24	2702	80			20		56.59	52.24	2702
	80			20		48.14			80			20		48.14		
	80			20		52.00			80			20		52.00		
6	20				80	24.50	25.60	2793	20				80	24.50	25.60	2793
	20				80	26.76			20				80	26.76		
	20				80	25.53			20				80	25.53		
7	20				80	24.38	25.98	2753	20				80	24.38	25.98	2753
	20				80	26.69			20				80	26.69		
	20				80	26.88			20				80	26.88		
8	20				80	22.18	22.11	3230	20				80	22.18	22.11	3230
	20				80	22.01			20				80	22.01		
	20				80	22.13			20				80	22.13		
9	20				80	30.85	30.77	2321	20				80	30.85	30.77	2321
	20				80	31.29			20				80	31.29		
	20				80	30.17			20				80	30.17		
10			10	10	80	43.10	42.77	1344			10	10	80	43.10	42.77	1344
			10	10	80	42.14					10	10	80	42.14		
			10	10	80	43.07					10	10	80	43.07		
Buehl-mann			20		80	32.08	32.54	1844			20		80	32.08	32.54	1844
			20		80	32.65					20		80	32.65		
			20		80	32.89					20		80	32.89		

YIELD AND RAW MATERIAL COST FOR SAS 8.2- AND R 2.7.2-BASED LCGM SOLVER

Cutting	ROMI-RIP 2.0 & SAS 8.2					Yield	Average	Average	ROMI-3.0 & R 2.7.2					Yield	Average	Average
Bill	FAS	SEL	1C	2AC	3AC	(%)	Yield	Cost ($/mbf)	FAS	SEL	1C	2AC	3AC	(%)	Yield	Cost ($/mbf)
1				100		43.70	43.24	1730				20	80	34.38	34.06	1614
				100		42.64						20	80	33.66		
				100		43.38						20	80	34.13		
2				100		55.06	55.58	1346			20		80	36.63	36.82	1632
				100		55.84					20		80	35.10		
				100		55.83					20		80	38.74		
3				20	80	44.29	44.17	1244			20		80	24.65	25.21	2381
				20	80	44.29					20		80	26.15		
				20	80	43.94					20		80	24.84		
4				20	80	37.18	37.16	1479			20		80	32.64	32.57	1842
				20	80	37.14					20		80	32.42		
				20	80	37.17					20		80	32.65		
5	30		50	20		60.07	59.84	1873	80			20		56.59	52.24	2702
	30		50	20		60.49			80			20		48.14		
	30		50	20		58.96			80			20		52.00		
6		50	20		30	52.45	52.16	1965	20				80	24.50	25.60	2793
		50	20		30	51.75			20				80	26.76		
		50	20		30	52.29			20				80	25.53		
7			80		20	51.07	50.72	1775	20				80	24.38	25.98	2753
			80		20	50.86			20				80	26.69		
			80		20	50.23			20				80	26.88		
8			70		30	52.45	53.23	1597	20				80	22.18	22.11	3230
			70		30	53.48			20				80	22.01		
			70		30	53.75			20				80	22.13		
9			80	20		58.54	58.62	1620	20				80	30.85	30.77	2321
			80	20		58.93			20				80	31.29		
			80	20		58.40			20				80	30.17		
10	40		40	20		57.07	57.53	2047			10	10	80	43.10	42.77	1344
	40		40	20		57.56					10	10	80	42.14		
	40		40	20		57.95					10	10	80	43.07		
Buehl-mann			70		30						20		80	32.08	32.54	1844
			70		30						20		80	32.65		
			70		30						20		80	32.89		

APPENDIX F. PRODUCTION COST

YIELD AND PRODUCTION COST FOR SAS 9.2- AND R 2.7.2-BASED LCGM

Cutting Bill	ROMI 3.0 & SAS 9.2					Yield (%)	Average Yield	Average Cost ($/mbf)	ROMI 3.0 & R 2.7.2					Yield (%)	Average Yield	Average Cost ($/mbf)
	FAS	SEL	1C	2AC	3AC				FAS	SEL	1C	2AC	3AC			
1			20		80	37.77	38.18	2096			20		80	37.77	38.18	2096
			20		80	37.85					20		80	37.85		
			20		80	38.92					20		80	38.92		
2			20		80	36.63	36.82	2176			20		80	36.63	36.82	2176
			20		80	35.10					20		80	35.10		
			20		80	38.74					20		80	38.74		
3	20				80	33.09	32.70	2796	20				80	33.09	32.70	2796
	20				80	31.91			20				80	31.91		
	20				80	33.10			20				80	33.10		
4			20		80	32.64	32.57	2456			20		80	32.64	32.57	2456
			20		80	32.42					20		80	32.42		
			20		80	32.65					20		80	32.65		
5	80			20		56.59	52.24	3087	80			20		56.59	52.24	3087
	80			20		52.00			80			20		52.00		
	80			20		48.14			80			20		48.14		
6	20				80	24.50	25.60	3575	20				80	24.50	25.60	3575
	20				80	26.76			20				80	26.76		
	20				80	25.53			20				80	25.53		
7	80			20		62.84	62.12	2585	80			20		62.84	62.12	2585
	80			20		62.01			80			20		62.01		
	80			20		61.52			80			20		61.52		
8	80			20		63.60	62.62	2564	80			20		63.60	62.62	2564
	80			20		62.46			80			20		62.46		
	80			20		61.81			80			20		61.81		
9			100			56.07	56.62	2120			100			56.07	56.62	2120
			100			57.06					100			57.06		
			100			56.73					100			56.73		
10			20		80	44.61	45.07	1775			20		80	44.61	45.07	1775
			20		80	45.20					20		80	45.20		
			20		80	45.39					20		80	45.39		
Buehlmann	20				80	37.70	38.28	2388	20				80	37.70	38.28	2388
	20				80	38.24			20				80	38.24		
	20				80	38.91			20				80	38.91		

YIELD AND PRODUCTION COST FOR SAS 8.2- AND R 2.7.2-BASED LCGM

Cutting	ROMI-RIP 2.0 & SAS 8.2					Yield	Average	Average	ROMI-3.0 & R 2.7.2					Yield	Average	Average
Bill	FAS	SEL	1C	2AC	3AC	(%)	Yield	Cost ($/mbf)	FAS	SEL	1C	2AC	3AC	(%)	Yield	Cost ($/mbf)
1			100			56.67	57.11	2101			20		80	37.77	38.18	2096
			100			57.53					20		80	37.85		
			100			57.14					20		80	38.92		
2				100		55.34	54.49	1740			20		80	36.63	36.82	2176
				100		53.41					20		80	35.10		
				100		54.71					20		80	38.74		
3				20	80	44.29	44.17	1697	20				80	33.09	32.70	2796
				20	80	44.29			20				80	31.91		
				20	80	43.94			20				80	33.10		
4				100		48.03	48.18	1968			20		80	32.64	32.57	2456
				100		48.48					20		80	32.42		
				100		48.02					20		80	32.65		
5	50		30		20	61.40	61.46	2253	80			20		56.59	52.24	3087
	50		30		20	61.50			80			20		52.00		
	50		30		20	61.48			80			20		48.14		
6		60	10		30	53.89	52.42	2405	20				80	24.50	25.60	3575
		60	10		30	51.73			20				80	26.76		
		60	10		30	51.64			20				80	25.53		
7			90		10	59.72	59.85	1922	80			20		62.84	62.12	2585
			90		10	59.31			80			20		62.01		
			90		10	60.53			80			20		61.52		
8			70		30	52.45	53.23	1973	80			20		63.60	62.62	2564
			70		30	53.48			80			20		62.46		
			70		30	53.75			80			20		61.81		
9			80	20		58.81	58.39	1969			100			56.07	56.62	2120
			80	20		57.93					100			57.06		
			80	20		58.44					100			56.73		
10	60		10	30		61.61	62.84	2334			20		80	44.61	45.07	1775
	60		10	30		64.07					20		80	45.20		
	60		10	30		62.84					20		80	45.39		
Buehl-mann			80		20				20				80	37.70	38.28	2388
			80		20				20				80	38.24		
			80		20				20				80	38.91		