Simulating Optimal Part Yield from No. 3A Common Lumber

By:

Brian Patrick Shepley

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Dr. Robert L. Smith, Chairman

Dr. D. E. Kline

Dr. Janice K. Wiedenbeck

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Brian Patrick Shepley
Graduate Research Assistant

ABSTRACT

The percentage of low-grade material composing the annual hardwood lumber production in the U.S. is on the rise. As a result, finding markets for low-grade and low-value lumber has been identified as a top priority by researchers and industry associations. Computer simulation has been used by the manufacturing industry for several decades as a decision support tool. Simulation programs are commonly used and relied on by researchers and the industry alike to conduct research on various aspects of the rough mill from processing to recovery efficiency. This research used the ROMI-RIP and ROMI-CROSS simulation programs to determine specific conditions that led to optimal part yield when processing No. 3A Common, 4/4-thickness, kiln-dried, red oak lumber in rip-first and crosscut-first operations. Results of the simulations indicated that cutting bills with narrow part widths and short part lengths are conducive to obtaining optimal part yield while processing No. 3A Common lumber. Furthermore, it was found that as the percent of No. 3A Common lumber in a grade mix increases, part yields and sawing efficiencies decrease. The results also indicated that higher part yields will be obtained when processing short-length No. 3A Common lumber between 6 and 8 feet in length.

DEDICATION

This thesis is dedicated to my mother and father, John and Mary Jane Shepley, who have sacrificed so much so that I could live well. They have always believed in me and supported me in whatever I wanted to do. I owe all of my life's accomplishments to them. To my Grandpa, Grand Dad, Nanna, Uncle Joel, and Uncle Brian who did not survive my college education but would have been proud of my accomplishments. To my country and the men and women in our armed forces, past and present, who have provided me with the freedom to pursue and education and enjoy life.

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PREFACE

This thesis is broken into five chapters. Chapter 1 defines the problem, summarizes the hardwood lumber industry, reviews related literature, and introduces the subject matter related to the objectives. Chapter 2 describes the methodology and results of the Objective 1 simulations that looked at the part yield and sawing efficiency results when processing five industry representative cutting bills. Chapter 3 describes the methodology and results of the Objective 2 simulations that look at differences in part yield and sawing efficiency when processing different grade mixes. Chapter 4 describes the methodology and results of the Objective 3 simulations that looked at differences in part yield and sawing efficiency when processing different lengths of No. 3A Common lumber. Chapter 5 contains a summary of the research, suggests areas of future research, and discusses the limitations of this research.

TABLE OF CONTENTS

ABSTRACT .... **ii**
DEDICATION .... **iii**
AKNOWLEDGEMENTS .... **iv**
PREFACE .... **v**
TABLE OF CONTENTS .... **vi**
TABLE OF TABLES .... **viii**
GLOSSARY OF SIMULATION TERMS .... **x**

CHAPTER 1. LITERATURE REVIEW **1**
- PROBLEM STATEMENT AND JUSTIFICATION 1
- HARDWOOD INDUSTRY 3
- HARDWOOD MARKETS 6
- HARDWOOD LUMBER GRADING 8
- SMALL-DIAMETER MATERIAL 11
- LOW GRADE LUMBER 14
- SIMULATION 17
- ROMI SIMULATION PROGRAMS 20
- OBJECTIVES 23
- METHODOLOGY 23
- OBJECTIVE 1 26
- OBJECTIVE 2 26
- OBJECTIVE 3 27
- LITERATURE CITED 28

CHAPTER 2. DETERMINATION OF TWO FEASIBLE CUTTING BILLS **34**
- INTRODUCTION 34
- OBJECTIVE 1 36
  - *Research Hypothesis # 1 .... 36*
  - *Null Hypothesis # 1 .... 36*
  - *Research Hypothesis # 2 .... 36*
  - *Null Hypothesis # 2 .... 36*
- METHODOLOGY 37
- PART QUALITY DEFINITION (1) 38
- CUTTING BILLS (2) 39
- ARBOR SETUP (3) 41
- CHOPSAWS (4) AND OVERALL PROCESSING AND CONTROL OPTIONS (5) 43
- SALVAGE PARTS (6) 45
- BOARD DATA SELECTION (7) 45
- SIMULATIONS (9) 49
- RESULTS AND DISCUSSION 49
- CONCLUSION 53
- LITERATURE CITED 54
- APPENDIX 2 56

CHAPTER 3. THE EFFECTS OF GRADE-MIX ON PART YIELD AND SAWING EFFICIENCY 66
INTRODUCTION 66
OBJECTIVE 2 68
Research Hypothesis # 1 68
Null Hypothesis # 1 68
Research Hypothesis # 2 68
Null Hypothesis # 2 68
METHODOLOGY 68
CROOK 69
LENGTH 70
WIDTH 71
GRADE MIX FILES 72
CUTTING BILL MODIFICATION 74
SIMULATIONS 74
RESULTS AND DISCUSSION 75
CONCLUSION 82
LITERATURE CITED 84
APPENDIX 3 85

CHAPTER 4. NO. 3A COMMON LUMBER LENGTH ANALYSIS 100
INTRODUCTION 100
OBJECTIVE 3 102
Research Hypothesis # 1 102
Null Hypothesis # 1 102
Research Hypothesis # 2 102
Null Hypothesis # 2 102
METHODOLOGY 102
BOARD FILES 103
CUTTING BILL MODIFICATIONS 107
SIMULATIONS 108
RESULTS AND DISCUSSION 110
CONCLUSION 115
LITERATURE CITED 117
APPENDIX 4 118
CHAPTER 5. SUMMARY OF RESEARCH 129
RESEARCH CONCLUSIONS 129
FUTURE RESEARCH 134
LIMITATIONS OF STUDY 136
VITA 138

TABLE OF TABLES

CHAPTER 1

Table 1-1. Summary of NHLA Hardwood Lumber Grading Rules. 10
Table 1 - 2. Board defects and codes. 25

CHAPTER 2

Table 2-1. Width distributions.. 42
Table 2-2. Arbor sequences for cutting bills.. 43
Table 2-3. ROMI-RIP simulation parameters held constant for all simulations..... 43
Table 2-4. ROMI-CROSS simulation parameters held constant for all simulations. 44
Table 2-5. Average part yields and sawing efficiencies for ROMI-RIP and ROMI-CROSS simulations.. 50
Table 2-A. Original Cutting Bill A and modified versions used in ROMI-RIP and ROMI-CROSS simulations. 56
Table 2-B. Original Cutting Bill B and modified versions used in ROMI-RIP and ROMI-CROSS simulations. 56
Table 2-C. Original Cutting Bill C and modified versions used in ROMI-RIP and ROMI-CROSS simulations.. 57
Table 2-D. Original cutting bill D and modified versions used in ROMI-RIP and ROMI-CROSS simulations.. 57
Table 2-E. Original cutting bill E and modified versions used in ROMI-RIP and ROMI-CROSS simulations. 58
Table 2-F. Summary of ROMI-RIP results for cutting bill simulations.................. 59
Table 2-G. Summary of ROMI-CROSS results for cutting bill simulations........... 59
Table 2-H. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP part yields in Objective 1. 60
Table 2-I. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP sawing efficiencies in Objective 1.. 61
Table 2-J. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-CROSS part yields for Objective 1.. 63
Table 2-K. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-CROSS sawing efficiencies for Objective 1...................... 64

CHAPTER 3

Table 3-1. Length distribution of No. 3A boards after adjustment for crook.......... 71
Table 3-2. Board files for Objective 2 simulations... 73
Table 3-3. Summary of part requirement modifications made to cutting bills........ 74
Table 3-4. Average part yields and sawing efficiencies for the................................. 76
rip-first grade mix simulations. 76
Table 3-5. Average part yield and sawing efficiencies for the 76
crosscut-first grade mix simulations. 76
Table 3-A. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on board length in the grade-mix files for Objective 2. 85
Table 3-B. Summary of descriptive statistics and ANOVA conducted on the width of boards in new grade-mix files for Objective 2. 88

Table 3-C. Summary of descriptive statistics and 2nd ANOVA conducted on length of boards in new grade-mix files for Objective 2. 89
Table 3-D. Summary of descriptive statistics and 2nd ANOVA conducted on width of boards in new grade-mix files for Objective 2. 89
Table 3-E. Summary of the ROMI-RIP results for the grade-mix simulations in Objective 2. 91
Table 3-F. Summary of the ROMI-CROSS results for the grade-mix simulations in Objective 2. 91
Table 3-G. Summary of descriptive statistics, ANOVA, and Tukey’s HSD conducted on ROMI-RIP part yields for Objective 2... 92
Table 3-H. Summary descriptive statistics,ANOVA, and Tukey’s HSD conducted on ROMI-RIP sawing efficiency results for Objective 2. 94
Table 3-I. Summary of descriptive statistics, ANOVA, and Tukey’s HSD conducted on ROMI-CROSS part yield results for Objective 2. 96
Table 3-J. Summary of descriptive statistics, ANOVA, and Tukey’s HSD conducted on ROMI-CROSS sawing efficiency results for Objective 2. 98

CHAPTER 4

Table 4-1. Width distribution of the long boards (14-16 ft.). 104
Table 4-2. Length files after being modified to width distribution of long length board file. 104
Table 4-3. Board files after being modified to match the width and crook distributions of the limiting data set (the long-length board population). 107
Table 4-4. Cutting bills and modifications ROMI-RIP and ROMI-CROSS for Objective 3. 107
Table 4-5. Board files used in simulations and board samples available as a result. 109
Table 4-6. Average part yield and sawing efficiency results for the Objective 3 rip-first and crosscut first simulations. 111
Table 4-A. Crook distribution in long length lumber file. 118
Table 4-B. Summary of descriptive statistics and ANOVA conducted on width distribution of board files in Objective 3. 119
Table 4-C. Summary of the ROMI-RIP results produced from Objective 3 simulations. 120
Table 4-D. Summary of ROMI-CROSS results produced from Objective 3 simulations. 121
Table 4-E. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP part yield results for Objective 3. 121
Table 4-F. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP sawing efficiency results for Objective 3. 123
Table 4-G. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on the ROMI-CROSS part yield results for Objective 3.. 125
Table 4-H. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on the ROMI-CROSS sawing efficiency results for Objective 3.... 127

GLOSSARY OF SIMULATION TERMS

Board data file - a file of digitally described boards

Crosscut-first - operation in which boards are crosscut to length first and ripped to width second

Cutting bill – A part order that defines the different part sizes to be cut from the lumber being processed.

Files.gr - a source file of digitally described lumber used when making board files with the *Makefile* program

Makefile - a program that comes standard with ROMI-RIP and ROMI-CROSS that allows the user to construct board files by selecting individual boards or specifying percentages of different sizes and grades of boards.

Mix-master - a program that comes with ROMI-RIP and ROMI-CROSS which randomly reorders boards in a certain board data file.

Part yield - ratio of the board feet of parts produced to the board feet of lumber processed

Primary part - parts produced that have only been ripped once and crosscut one

Rip-first - operation in which boards are ripped to width s first and chopped to length second

ROMI-RIP - a rip-first rough mill simulation program

ROMI-CROSS - a crosscut-first rough mill simulation program

Salvage parts -parts produced that have been ripped or crosscut more then once; may be cut to primary sizes or salvage specific sizes

Sawing efficiency - the total number of cuts (rip and crosscut) required to produce one board foot of parts. **Note: this measure is based on actual saw kerfs (sawlines) not time.**

CHAPTER 1. LITERATURE REVIEW

Problem Statement and Justification

There are several major challenges facing the forest products industry as it enters the 21st century. One of these challenges is improving efficiency and resource utilization. To improve in this area, the industry must focus on low-grade lumber. More specifically, what can low-grade hardwood lumber be used for and how can it be produced and manufactured in an efficient and economically feasible manner?

In the 1996 Hardwood Symposium Proceedings, the NHLA stated that out of 322 identified research needs of the industry *"identifying and developing new and better markets for low-value, low-grade lumber and products, including smaller pieces was their number one priority"* (NHLA 1996). Likewise, the Research Steering Committee for the Center for Forest Products Marketing and Management at Virginia Tech identified finding profitable markets for low-grade lumber as their number one priority (CFPMM 2001). Cumbo et al. (2001) showed that the majority of the sawmills in the U.S. agree with these statements. Hardwood manufacturers need strong and reliable markets for their low-grade and low-value lumber. As the availability of higher-grade hardwood lumber decreases, manufacturers will have to be able to sell their low-grade material to stay in business (Meyer 1996). New harvesting and manufacturing techniques will be required in order for the production of low-grade material to be economically feasible.

Current forests in the United States are seriously over populated with small-diameter timber (SDT), a primary source of low-grade lumber (Gatchell 1993, Senft et al. 1985, Patterson and Xie 1998). Developing markets for low-grade hardwood lumber would increase the value of small diameter timber (SDT) and thus provide more incentive for loggers to harvest this portion of the resource. This could result in improved forest health and increase the supply of harvestable timber.

Furthermore, as low-grade hardwood lumber production volume rises (Cumbo et al. 2001), consumption numbers are holding steady, creating a surplus of low-grade lumber. Finding markets for low-grade hardwood lumber will benefit the forest products industry as a whole, improving efficiency and resource utilization and providing a broader spectrum of forest management options. The hardwood resource is changing and it is vital to companies that process hardwood lumber that they can adapt to these changes. However, to adapt to a changing resource, they need information regarding the raw material and its processing capabilities.

Research has been conducted to investigate the potential of all NHLA grades of lumber in a rough mill, except No. 3A Common. There is a lack of research and information on the capabilities of No. 3A Common lumber. Yet, it is important that those who process hardwood lumber, especially those that process lower grade lumber, know what can be expected while processing No. 3A Common lumber. This research focuses on No. 3A Common red oak lumber in a rough mill. The results of this research will provide data for rough mill managers concerning yield information and the sawing efficiency of No. 3A Common red oak lumber.

Hardwood Industry

The primary use of hardwood lumber is for remanufacture into furniture, cabinetwork, and pallets, or for direct use in millwork, paneling, moulding, and flooring (Forest Products Laboratory 1999). Annually in the U.S., the hardwood lumber industry produces approximately 13 billion board feet (bdft.) of lumber (Miller-Freeman 1999). The largest proportion of the production is red oak (*Quercus rubra*), white oak (*Quercus alba*), and yellow-poplar (*Liliodendron tulipifera*). The balance of the production consists of ash, gum, cherry, soft and hard maple, beech, walnut, and several other species (Irland 1996). In 1997, the estimated hardwood lumber consumption by sector was 4.5 billion bdft. for pallets, 3.0 billion bdft. for furniture, 2.5 billion bdft. for dimension products, 1.4 billion bdft. for exports, 1.3 billion bdft. for moulding and millwork, 1.2 billion bdft. for cabinets, and 0.8 billion bdft. for the flooring and railroad tie industries (Hansen and West 1998). Accordingly, the pallet industry consumes 4.5 billion bdft., or roughly 30 percent of the 1997 hardwood lumber production. The most current research indicates that the pallet industry consumes roughly 30 percent of all hardwood production in a year, most of which is low-grade (Bejune 2001).

In 1992, a respected hardwood sawmill analyst reported that "for sawmills, the lack of logs and insufficient profitability remain the paramount concerns" (Hardwood Publishing Co., Inc. 1992). Shortage of quality logs, high log prices, and profitability are still major concerns for sawmills today. Large hardwood producing sawmills are moving away from traditional cost and production-oriented strategies toward a marketing strategy that emphasizes product differences, while keeping pricing competitive. These companies are adding value to much of their production through secondary processing

(Bush and Sinclair 1991). However, today there are high volumes of hardwood lumber not suited for making the traditional higher valued products associated with hardwoods (Wiedenbeck and Araman 1994). This is largely due to decreases in overall log quality and worsening logging conditions (Meeks 2001; Serrano and Cassens 2000). As a result of rising lumber prices, lower log quality, and environmental constraints, the hardwood industry is being forced to look at nontraditional wood sources and processing methods (Gephart et al. 1995). Likewise, due to dwindling sources of raw materials and competition from synthetic wood substitutes, the U.S. hardwood forest products industry must seek to improve its productivity and processing efficiency (Lin et al. 1994; Mendoza et al. 1991; Youngquist and Hamilton 1999). In order to improve productivity and processing efficiency, certain activities must be performed at various stages including grading, cutting, and ripping (Mendoza et al. 1991; Youngquist and Hamilton 1999). There are several methods that have been, and are currently being studied as possible alternatives for efficiently manufacturing products from today’s low-grade hardwood lumber supply. Some of these include green dimensioning, different composite materials, modified sawmilling operations, finger-jointing, and structural hardwood lumber.

Most wood components used to meet the needs of the major hardwood markets are manufactured in a rough mill. Rough mills process hardwood lumber in a number of different ways, but the typical process is as follows. Rough lumber is dried and graded. The second step is to plane the lumber and cut the lumber to remove defects and produce the right size pieces for the finished product. This usually involves ripping and chopping the lumber. Prior to 1990, the conventional method of producing dimension hardwood parts had been crosscut-first processing (Thomas 1998). Today, a significant percentage of rough mills use rip-first processing. Ripping the lumber first may provide a better solution to yields from low-grade lumber. After the lumber is ripped or chopped, the pieces are usually sorted by size or color and sometimes both depending on the end product. The steps described thus far are fairly consistent in most rough mills, but after these steps operations vary quite a bit depending on the end product (edge-glued panels, finger-jointing, stair treads, mouldings, flooring, etc.). In 1996, Wiedenbeck surveyed 38 different companies investigating rough mill yields. The majority of respondents reported overall yields from 50-59 percent. The highest yield reported was between 85-89% (Wiedenbeck and Scheerer 1996). Based on these results, it is clear that there is room to improve efficiency in the rough mill process.

With current trends towards environmentalism and forest use for recreation, more timber will become unavailable for harvest. This will make efficient use of hardwood resources even more critical. It is important to make the most of the resources that are available by using them as efficiently as possible. This includes efficient production of low-grade material. In 1990, the National Research Council stated,

> "*Wood is a leading industrial raw material in the U.S., accounting for about 25% of the value of all major industrial materials. The demand for forest products is growing. The global demand for timber products grew by 90% in the past three decades . . . and is projected to grow by another 45% by the year 2000. These increased demands, if imposed on limited supplies, will result in increased prices of products and could have a dramatic effect on the affordability of housing, furniture, paper and other forest products. In addition, the impact of the environment of growing trees for wood in intensive wood-production systems could be reduced if the properties of the wood could be modified to increase yields through more efficient processing. In this way, less land could produce the same amount of wood so that the impact on local or regional environments would diminish."* (National Research Council 1990).

Efficient use of our wood has been a serious topic for a long time. By producing forest products more wisely and efficiently, less stress could be put on the environment from forest related operations. In addition, hardwood manufacturers would be able to save money in the production process and produce more products more efficiently.

Hardwood Markets

Hardwood lumber is grade marketed in three major categories: factory lumber, dimension parts, and finished market products. Araman et al. (1982) further broke down the market into eight solid segments. These markets were pallets, furniture, dimension and components, exports, millwork, cabinets, flooring, and railroad ties. Consumption by the flooring industry between 1991 and 1997 increased 120 percent. With the exception of pallets, hardwood lumber consumption within the other segments was estimated to have increased anywhere from 30 to 100 percent in the last decade. Despite being the largest single market for hardwood lumber, the pallet industry experienced no increase in lumber consumption between 1991 and 1997 (Hansen and West 1998).

In recent years, advances in technology and the available hardwood resource have prompted some industries to consume lower grades of lumber then they would typically. In general, the flooring industry consumes No. 2A and No. 3A Common grades, the furniture industry consumes FAS and No.1 Common grades, the moulding and millwork industry consumes FAS and No. 1 Common grades, the cabinet industry consumes FAS and No. 1 Common grades (Hansen et al. 1999, Araman and Tansey 1991), and the dimension and components industry consumes No. 1 Common and No. 2 Common grades (Lin 1993, Araman and Tansey 1991). Typically the pallet, mine prop, flooring, and railroad tie sectors are responsible for the majority of the low-grade, No. 3A

Common lumber consumption (Araman and Tansey 1991). The export market consists mainly of the highest grade material, FAS (Lin 1993).

Hardwood components, or hardwood dimension components, are wood parts used in the construction of furniture, cabinets, millwork, and related decorative wood products (Lawser 1994). They are processed from logs, cants, bolts, or rough boards and can fall into several different categories including fully-machined, semi-machined, or rough dimension. Although the quality of dimension lumber is declining, recent technologies have helped to process some high-grade components and dimension parts from lower grade material. Domestically, the furniture industry is the largest consumer of hardwood components. It is followed by the cabinet industry, the building products industry, and the decorative and specialty items industry. In 1994, Haas and Smith (1997) conducted a survey of the hardwood dimension and flooring industries. For domestic sales, respondents indicated that the mouldings and millwork were the most commonly sold hardwood component products, making up 22 percent of all hardwood component shipments. They were followed by cut to size blanks, hardwood flooring, edge glued panels, dowels, turnings, cabinet parts, chair parts, staircase, and upholstered furniture frame stock. For the same year, in both domestic and international markets, the species mix was led by red oak, followed by white oak, maple, yellow-poplar, ash, hickory, and cherry (Haas and Smith 1997). Combined, the pallet, furniture, dimension parts, exports, mouldings and millwork, flooring, cabinets, and railroad tie industries consume over 90 percent of all hardwood lumber produced in the U.S. (Cumbo 2000).

The hardwood industry is being forced to work with a much smaller supply of high-grade material then in the past. The use of high-grade lumber went from 49 percent

FAS in 1989 (Bush et al. 1991) to approximately 15.7 percent FAS in 1995 (Anonymous 1995). This decrease in high-grade lumber has greatly increased the use of common boards by the industry (Olah et al. 2000). Several markets present good opportunities for low-grade lumber, especially those that can use small pieces of wood or do not require clear pieces. As a result, pallets, flooring, mouldings and millwork (paint-grade), and cabinets provide good opportunities for the use of low-grade lumber with new advances in technology. Except for pallets, all of these markets increased consumption during the last decade and should continue to do so in the future as demand rises along with population growth and the demographic shift that will place baby-boomers in peak spending years. Technological advances should make manufacturing and processing of low-grade lumber more plausible from both economic and safety perspectives.

Red oak is the dominant species in both the furniture (Bowe et al. 2000) and cabinet markets (Olah et al. 2000). It is also very popular in the moulding and millwork, flooring, and the hardwood dimension and component markets (Smith and Araman 1997). In 1996, Wiedenbeck reported red oak as the number one species (Wiedenbeck and Scheerer 1996). It has been known for a long time that the needs of the furniture and cabinet industries can be met with No. 2A Common lumber gang ripped-first (Gatchell 1993). As resources dwindle and prices rise, it is time to more fully investigate the potential of No. 3A Common lumber.

Hardwood Lumber Grading

The National Hardwood Lumber Association (NHLA) rulebook states *"Lumber should be properly manufactured of good, average width and lengths. It should be edged* *and trimmed carefully to produce the best possible appearance while conserving the usable product of the log"* (National Hardwood Lumber Association 1998). It is equally important that the usable product of the log be used as efficiently as possible. However, much of today's hardwood resource goes to waste or is discarded because there is not a significant economic value associated with processing it for secondary wood products.

Hardwood lumber is sold based on volume and NHLA grade. The NHLA grading system is accepted throughout the U.S. and around the world (Cumbo 2000). It is the recognized standard for grading hardwood lumber intended for cutting into smaller pieces to make a finished product. However, some special grading criteria (procurement specifications) may also be used for special applications. Table 1 provides a brief summary of the NHLA grades for hardwood lumber. The grades are assigned to lumber on the basis of the amount of clear cuttings that can be removed from the board

Table 1-1. Summary of NHLA Hardwood Lumber Grading Rules (National Hardwood Lumber Association 1998).

				Allowable Cuttings	
Grade and allowable lengths	Allowable width (in.)	Allowable surface measures of pieces (ft^2)	Minimum amount of pieces in clearface cuttings (%)	Maximum no.	Minimum size
FAS	6+	4 to 9	83-1/3	1	4 in. by 5 ft. or 3in. by 7 ft.
		10 to 14		2	
		15+		3	
F1F	6+	4 to 7	83-1/3	1	4 in. by 5 ft. or 3 in. by 7 ft.
		6 and 7	91-2/3	2	
		8 to 11	83-1/3	2	
		8 to 11	91-2/3	3	
		12 to 15	83-1/3	3	
		12 to 15	91-2/3	4	
		16+	83-1/3	4	
Selects 6 to 16 ft	4+	2 and 3	91-2/3	1	4 in. by 5 ft. or 3 in. by 7 ft.
		4+			
No.1 Common	3+	1	100	0	4 in. by 2 ft. or 3 in. by 3 ft.
		2	75	1	
		3 and 4	66-2/3	1	
		3 and 4	75	2	
		5 to 7	66-2/3	2	
		5 to 7	75	3	
		8 to 10	66-2/3	3	
		11 to 13	66-2/3	4	
		14+	66-2/3	5	
No. 2A Common	3+	1	66-2/3	1	3 in. by 2 ft.
		2 and 3	50	1	
		2 and 3	66-2/3	2	
		4 and 5	50	2	
		4 and5	66-2/3	3	
		6 and 7	50	3	
		6 and 7	66-2/3	4	
		8 and 9	50	4	
		10 and 11	50	5	
		12 and 13	50	6	
		14+	50	7	
No. 3A Common	3+	1+	33-1/3	unlimited	3 in. by 2 ft.
No. 3B Common	3+	1+	25	unlimited	1-1/2 in. by 2 ft.

and on board size. The cutting area is affected by the length of the board and the defects, such as knots, wane, crook, decay, and splits, in the board. The lumber is graded based on the worse face of the board, except in the case of Selects and FAS-1 Face. Higher grade lumber has fewer defects and bigger clear cutting areas then lower grade lumber. The grades from highest to lowest are FAS, FAS-1 Face, Selects, No. 1 Common, No. 2A Common, No. 2B Common, No. 3A Common, and No. 3B Common. For No. 3A Common lumber, the board can range from 4 to 16 feet and must be at least 3 inches wide. The smallest allowable surface measure is 1 square foot, the measurement for a 4' x 3" board. The minimum amount of clearface cutting in the board is 33-1/3 %. In addition, the minimum size of the cuttings must be at least 3 inches by 2 feet. The number of cuttings allowed is unlimited (NHLA 1998).

Small-Diameter Material

A very large portion of the hardwood raw material available is composed of small stems of inferior quality (Serrano and Cassens 2000). These small stem trees are typically referred to as small-diameter trees/timber (SDT). The USDA Forest Service defines small diameter timber as that with a diameter base height (d.b.h.) between 5 and 11 inches (Bumgardner et al. 2000). The main reason small-diameter timber's are a major source of low-grade lumber is they have large proportions of juvenile wood and growth stresses (Gatchell 1993, Senft et al. 1985, Patterson and Xie 1998). In addition, they produce a high proportion of lumber that is narrower than 6 inches. When using lumber containing juvenile wood and tension wood, several quality problems, primarily with dimensional instability, may occur (Senft et al. 1985, Patterson and Xie 1998).

Currently many short logs or bolts of low economic value are left in the forests after harvesting.

Small-diameter timber is generally left in the forest because it is not economical to remove (LeVan and Livingston 2001). Consequently, small-diameter trees are a primary constituent of overstocked timber stands (Wolfe and Moseley 2000) and have been identified by forest managers as a critical forest health issue (Wolfe 2000). The presence of large populations of small-diameter timber increases risk of insect, disease, fire, and drought damage and leads to overall unhealthy forests. One reason for the large population of small-diameter timber is it is relatively low in value (Paun and Jackson 2000). Much greater care is required to selectively remove small-diameter trees with no negative impact on the remaining timber (Wolfe 2000). In addition, high costs are associated with harvesting small diameter timber's and there is a lack of markets for the low-grade raw material they provide (Forest Products Laboratory 2000). While much of the current focus has been on softwood small diameter timber in the western U.S., similar economic issues affect hardwood small diameter timber. Expanding the markets where small-diameter timber can be used will increase its value and make it more appealing for harvesting (Paun and Jackson 2000). Methods need to be developed for processing low-grade material from SDT at lower costs and more efficiently then can be accomplished using conventional methods. As a result, the harvest of small diameter timber would be encouraged and waste would be reduced (Stewart et al. 1982).

The hierarchical use of small-diameter timber can be divided into three categories: value-added uses, traditional uses, and residue uses. Value-added uses include flooring, paneling, cabinets, furniture, and millwork. Traditional uses include sawlogs, structural lumber, nonstructural lumber, poles/posts, pallets, and pulp chips. Lastly, residue uses include biomass energy, ethanol, firewood, pulp, and composting (LeVan and Livingston 2001). The small part sizes required for the majority of hardwood value-added markets make them ideal candidates for the use of low-grade lumber found in SDT. Furthermore, the ripping and chopping operations involved with the manufacturing of hardwood components and dimension parts provide adequate opportunities for removal of the defects found in low-grade lumber. High cost of small-diameter harvesting must be offset somehow, possibly by short lumber and low-grade lumber (Wolfe 2000).

Processing small-diameter logs has been done successfully and profitably. The Ledwidge Lumber Company Ltd., a softwood producer, installed a small-log line in their sawmill to lower the minimum diameter of log they could handle. In just 2 years after installment, the overall mill production went from 30 million to 50 million board feet per year. The addition of their small-log line has also increased their timber supply since they can now cut small as well as large logs. For example, they can now handle logs from 3.3” in diameter up to 16” in diameter where before their lower limit was 5.5” (Kryzanowski 1999). In a market where there is strong competition for a limited number of resources, the ability to process smaller diameter logs can be a great advantage for a company.

Although the above example cites a softwood mill, the hardwood industry is beginning to look at the potential of processing small diameter timber as well. Management practices for eastern hardwood forests include the removal of small diameter timber (Baumgras 1992), thus providing a supply of small diameter timber. In a recent hardwood mill study conducted by the Center for Forest Products Marketing and Management at Virginia Tech (Cumbo and Smith 2002), the mill in question performed at or near the industry average in terms of yield and lumber recovery. The logs were processed with a chipper head rig and had an average small end diameter of 12” with a range from 10” to 14”. The Center is currently conducting a value analysis of lumber produced from small diameter timbers down to 7” in diameter.

Options that have been explored for improving the use of low-grade lumber and small diameter timber include green dimensioning (Bratkovich et al. 2000), structural lumber (Wiedenbeck and Araman 1994), machine stress rated lumber (Erikson et al. 2000), and direct processing (Lin et al. 1994). Green dimensioning is currently used in Europe and Japan (Gephart et al. 1995). All of these options provide opportunistic possibilities, but they meet with resistance in most instances due to lack of knowledge about the process and lack of marketing experience (Wiedenbeck and Araman 1994).

Low Grade Lumber

Araman and Tansey (1991) estimated that 38 percent of the potential select oak lumber from the eastern U.S. saw timber would be graded below No. 2A Common. In 1991 they also estimated that eastern U.S. hardwoods would yield about 12 percent FAS and Select, 50 percent No. 1 Common and 2A Common, and 38 percent below No. 2A Common. The National Forest land in the Appalachian region of the U.S. has considerably higher quality timber than private lands in the same area due to implementation of long-term management plans. However, hardwood timber sales from National Forest lands have been steadily decreasing since the early 1990’s due to logging restrictions that have been set in place. This forces the balance of timber to be harvested from adjacent private lands that have a lower quality timber supply (Luppold and Baumgras 1998). As a result, more low-grade lumber is produced. Acceptance of low-grade lumber is and will be forced in the future as the average size of logs fall, lumber quality decreases, and lumber prices increase (Wiedenbeck and Araman 1995).

Cumbo et al. (2001) surveyed 569 U.S. sawmills to investigate the U.S. low-grade hardwood market. Approximately 47 percent of the respondents reported increases in low-grade lumber production between 1995 and 2000 and 39 percent of the respondents reported no change. Between 1995 and 2000 approximately 86 percent of the respondents experienced consistent or increased low-grade lumber production. Approximately 60 percent of the respondents reported selling 50 percent or more of their low-grade production to a single market. In addition, roughly 85 percent of the respondents indicated a moderate to high level of priority for maintaining and developing markets for low-grade hardwood lumber. The average sawmill in the study reported spending 10 percent of their 2000 capital expenditures on maintaining this market and/or developing new markets. The study also addressed the issue of what is considered low-grade in the industry. Approximately 34 percent of the respondents classified low-grade lumber as No. 3A Common and below. According to production numbers reported by the respondents, on average, this grade made up roughly 18 percent of their overall production.

Increases in price and technological advances have led the cabinet, furniture, millwork, and dimension sectors to consume higher proportions of lower grade lumber (Hansen et al. 1999). However, technology for handling, drying, color matching, and machining that makes processing low-grade lumber economically acceptable and competitive are still big obstacles (Araman et al. 1982). Similar to any manufacturing change in the forest products industry, the most important factors in evaluating low-grade lumber are production rates, costs, and yields (Bingham 1976-77 and Reynolds and Schroeder 1978). Traditionally, most rough mills have not used No. 3A Common lumber due to lack of experience, quality consistency, and uncertainties surrounding production.

Frequently, a rough mill manager who decides to try No. 3A Common, runs it through the rough mill mixed with another grade such as No. 2A Common. After experiencing lower yield this way, most would say that No. 3A Common lowers their yield. However, the cutting bill used while running No. 2A Common may not necessarily be the best cutting bill to use while running No. 3A Common lumber. There may be specific cutting bills or piece sizes that can be cut from No. 3A Common lumber that result in high yields. Several scientists have conducted studies that have proved that yields and profits can be improved by processing shorter length lumber and lower grade logs (Araman et al. 1982 and Wiedenbeck and Araman 1995). Other studies have been conducted to analyzed the effects of lumber length and grade on yield and sawing efficiency (Hamner et al. 2002 and Steele et al. 1999). However, there still remains a strong need to determine if No. 3A Common lumber can be processed and manufactured to produce profitable yields and what type of rough mill environment promotes optimal part yield when processing No. 3A Common Lumber.

Simulation

Simulation is a valuable decision support tool used by many U.S. manufacturing engineers. It can be very quick and relatively inexpensive (Thomas et al. 1995). In definition, simulation is “the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system” (Wiedenbeck 1992). It has been used to model and evaluate industrial production systems since 1955. Since then it has been commonly accepted and used in many fields as a computer based management tool for determining differences between processing systems (Gazo and Steele 1995). Consequently, it has developed into an accepted analyst approach tool (Thomas et al. 1995).

Many systems cannot be physically manipulated without causing disruption to the process. Thus, simulation modeling offers a good alternative to running an actual experiment in a rough mill (Wiedenbeck 1992). The key to successful development of a simulation model is appropriately representing a manufacturing system’s complex material flows and process interactions. In addition, properly designed experimentation with the model is crucial if valid results are to be obtained (Wiedenbeck and Kline 1994 and Thomas et al. 1995). Numerous computer simulation programs have been used to simulate various aspects of rough mills including production impacts, production costs sensitivities (Gazo and Steele 1995), the effects of sorting lumber (Steele and Gazo 1995), the effects of equipment changes (Gazo and Steele 1995), and to evaluate yields, productivity, costs, and efficiency (Wiedenbeck and Araman 1995). Furthermore, questions and situations that can be answered or explored by simulation modeling include (Wiedenbeck 1992):

- How is rough mill production affected by lumber length, lumber grade, cutting quality, and cutting size?
- How should equipment be purchased?
- How do personnel shifts affect system productivity?
- What affect will machine set-up time have on material flow?
- Evaluation of a new system.
- Comparison of system alternatives.
- Prediction of performance under forecasted conditions.
- Sensitivity analysis: What factors have the greatest influence?
- Optimization: What scenarios produce the best system response?
- Relationships: How are system elements interrelated?
- Bottleneck analysis: Where are backups occurring? How can they be fixed?

Simulation research performed by Steele et al. (1999) indicated that lumber grade significantly affects the number of cuts required to fill various cutting bills. The general trend was that higher grade lumber requires less cuts, which corresponds to shorter processing time. In addition, reduction in lumber grade had greater impacts on crosscut saw productivity then on rip saw productivity. This impact on the crosscut saw and straight-line rip was much less when cutting shorter and narrower parts (Steele et al. 1999).

Buehlmann (1998) used ROMI-RIP to evaluate cutting bill requirements and yields. Buelhmann ran his simulations using a board databank of No. 1 Common, 4/4 thickness, kiln-dried red oak lumber. With the use of ROMI-RIP and statistical analysis, he arrived at several conclusions. Medium size parts of 17.50 inches in length and 2.50 inches in width were found to be the most advantageous part size for high yield. Larger parts, such as parts 72.50 inches in length and 2.50 inches in width are damaging to high yields. Further, since each board has clear areas of different sizes, cutting bills requiring many different sizes to be cut simultaneously allow for a better match of the clear area and the part area. As a result, yields increase. To gain maximum yield benefits from the different part sizes required by a cutting bill, part sizes should be diverse and not similar.

Wiedenbeck and Araman (1995) conducted simulations using short-length lumber in both crosscut-first and rip-first models. The crosscut-first model indicated no lumber length-based processing differences and was able to achieve high productivity. It was concluded that high productivity could be experienced by a rough mill processing short lumber into dimension. On the other hand, the gang rip-first model could not reach the same production levels with short-length lumber as with medium and longer length lumber (Wiedenbeck and Araman 1995).

While Steele and Gazo’s (1995) simulation research found both positive and negative affects of running hardwood lumber sorted by grade in both rip-first and crosscut-first rough mills, it was concluded that crosscut-first rough mills responded better to running lumber sorted by grade. For crosscut-first rough mill operations, yield was increased by1 percent, crosscut saw utilization increased 9.4 percent, and salvage crosscut saw utilization decreased 16.7 percent; total processing time was not influenced (Steele and Gazo 1995).

Hamner et al. (2002) used ROMI-RIP to evaluate the effects of lumber length on yield. Three length segments were evaluated: 7-8 foot, 11-12 foot, and 15-16 foot lumber. The grade mix run in each length category was composed of 80 percent No. 1 Common, 12 percent No. 2A Common, and 8 percent FAS. It was concluded that part yield improves as lumber length increases in a rip-first rough mill.

ROMI Simulation Programs

ROMI-RIP and ROMI-CROSS are computer simulation software packages designed by R. Edward Thomas, a research computer scientist with the Northeastern Research Station’s Forestry Sciences Laboratory at Princeton, West Virginia. ROMI-RIP version 2.0 is the most recently developed rip-first, rough mill analysis tool from the USDA Forest Service (Thomas 1999a). ROMI-CROSS was developed for use as a rough mill analysis tool as well, allowing the evaluation of different crosscut-first rough mill setups for different cutting bills (Thomas 1998).

ROMI-RIP is designed for use by rip-first rough mill operators and researchers. It allows users to examine aspects of rough mill operations, including the impact of grade mix, cutting bill requirements, and process design on yield. It processes data files that contain information about board sizes, defect types, and defect locations. This simulator reports the quantity of lumber cutting operations required to complete processing of a cutting bill. Furthermore, it also reports part tallies by lumber grade and overall. ROMI-RIP 2.0 simulates seven different fixed and movable-blade arbor types. Other features include a selective rip arbor, the ability to cut sizes specified to the nearest 1/16” or millimeter, adjustable rip and chop saw kerf sizes, and the ability to process cutting bills with as many as 600 part sizes. The general sequence of the program’s rough mill operations is as follows. The board is gang-ripped into strips. Next, these strips are crosscut to primary part lengths, either specified or random. Any additional strip sections are processed by further rips and crosscuts to salvage parts. The simulations can be set up to generate maximum yields or to meet cutting bill requirements (Thomas 1999b).

When researching and experimenting with computer simulation programs such as ROMI-RIP, a question comes to mind: Is the information generated by the simulation accurate, as compared to what would really happen if the real process was performed? Thomas and Buehlmann (2002) performed a study to determine the validity of ROMI-RIP results when simulating operations using 4/4 kiln dried red oak. They collected lumber from a sawmill in Appalachia, digitized the boards, ran ROMI-RIP with the database created from digitizing the boards, and ran the actual boards through a rough mill. They compared the overall ripsaw and chopsaw yields between the simulation results and the real results at the 95 percent level of significance ($\alpha = 0.05$). They found that ROMI-RIP 2.0 reasonably simulates actual rough mill and the results can be used with confidence for analytical purposes.

In rough mills, parts are organized into a cutting bill. A cutting bill is a part order that defines the different part sizes to be cut from the lumber being processed. The gang ripsaw and/or chopsaw will be configured in order to achieve the desired output of the cutting bill in the most efficient way possible. When processing according to a cutting bill, the objective is to cut all the required part sizes from a minimal amount of lumber while generating the least number of excess parts. This is difficult due to variations in lumber grades and dimensions. As a result, sometimes yield must be sacrificed to obtain the exact number of parts demanded by the cutting bill. ROMI-RIP 2.0 solves these problems by the use of part prioritization strategies. It provides seven different strategies. These strategies provide a method that gives each part a weighted value. Simple methods prioritize parts on the basis of length, area, or assigned value. These are referred to as nondynamic strategies in that the method stays consistent throughout the simulation. On the other hand, complex methods generate part priorities based on each part's size and current required quantity. With these dynamic strategies, part priorities are continually updated as parts are cut and the remaining required quantities decrease. This allows emphasis to be switched to other part sizes as the quantity requirements for one part are achieved (Thomas 1999b).

ROMI-CROSS is designed for use by crosscut-first rough mill operators and researchers. Until recently, the usual method of producing dimension parts has been crosscut-first processing. ROMI-CROSS processes board files that consist of digitized board images. The images represent dimensions and defect types from actual boards. Like ROMI-RIP, ROMI-CROSS simulations can be performed to produce optimal yield based on surface areas or to meet cutting bill requirements. ROMI-CROSS uses the same non-dynamic and dynamic strategies for prioritizing parts as ROMI-RIP (Thomas 1998).

A major advantage of rough mill simulation programs such as ROMI-RIP and ROMI-CROSS is that all the manufacturing sequences can be tested with the same raw material. This assures the user that any change in the test results is due to the process and not the raw material (Anderson et al. 1992).

OBJECTIVES

In accomplishing the overall goal of identifying potential opportunities for low-grade lumber, the following research objectives werecarried out.

1. Identify two feasible low-grade cutting bills for ROMI-RIP and ROMI-CROSS through a series of exploratory crosscut-first and rip-first simulation studies.
2. Compare yields and cutting operations when No. 2A Common, No. 3A Common, and a 50-50 grade mix of No. 2A and No. 3A are used on the two feasible cutting bills.
3. Compare yields for short (6-8 feet long), medium (10-12 feet long), and long length (14-16 feet long) No. 3A Common lumber using two feasible cutting bills to determine which No. 3A Common length grouping offers a more economically feasible lumber input alternative compared to mixed lengths and No. 2A Common yields.

METHODOLOGY

To expand the existing databank for kiln-dried red oak lumber, roughly 2,700 board feet (bdft) of No. 3A, 4/4 thickness, kiln-dried red oak lumber were obtained for digital board mapping. To obtain a good representation of the No. 3A Common red oak lumber available in the industry, the lumber was collected from four sources. The lumber obtained was collected from three sawmills and one flooring plant. The lumber was randomly selected from the lumber they had available at that time. The lumber was taken to the USDA Forest Service’s Northeastern Research Station in Princeton, WV where approximately 1,500 bdft. of the boards were digitally mapped.

Making a digital map of a board (digitizing) is a process whereby a map of the board’s dimensions and defects are created in a computer database. The digitizing was performed according to the procedures described by Anderson et al. (1992). For the purposes of the database and the ROMI simulation programs, rectangular representations of the boards and their defects are used. The boards are mapped in terms of an x, y grid and each board and the defects within it are described by a series of rectangular coordinates. A map of the board's dimensions is made using the smallest rectangle that can enclose the entire board. This can result in a digital board that is wider (and sometimes longer) than its real-life counter part. Defects such as crook, side bend, and taper will cause this. However, the difference in dimensions of the digital board and the actual board are recorded as a defect called void, and thus an accurate digital map of the board is created. After the boundaries of the board are mapped, the defects within the board are mapped in terms of the same x, y axis. Rectangular representations are used to identify the defects. The defects are identified and labeled using the codes in Table 1-2 (Moody et al. 1998). Large defects that are not well defined by a single rectangle are broken down into a series of smaller rectangles (Anderson et al. 1992 and Gatchel 1993). After digitizing the lumber, the digital board maps were plotted and double checked against the actual boards to ensure accuracy.

The next step was to grade the boards. This was done using the Ultimate Grading and Remanufacturing System (UGRS) according to the procedures and directions set forth by Moody et al. (1998). UGRS grades boards according to the 1998 NHLA grading rules (Moody et al. 1998). UGRS begins by verifying that there are no data errors. Then both faces are graded in order to determine the worst face of the board as per the grading rules (NHLA 1998). UGRS analyzes the board beginning with the highest grade, FAS, to

Table 1 - 2. Board defects and codes.

Defect	**Code**
Void	2
Pith	3
Decay	4
Shake	5
Wane or scant wood thickness, or both	8
Bark pocket	11
Grub hole	12
Unsound knot	13
Surface check	15
Sound knot	16
Incipient decay	19
Sticker stain	20
Sap stain/Mineral streak	23
Split	25
Shot worm hole	111
Pin worm hole	211

determine if any of the grades basic rules are violated (e.g., minimum board width). In instances where grading rules are violated, UGRS steps down to the next lower grade and again checks for basic rule violations. When there are no rule violations for the grade under consideration, UGRS inspects clear areas to determine if the required cutting units can be obtained. It then assigns a grade to the board. After grading the newly mapped boards using UGRS, all the No. 3A Common boards were combined into a database. This database was added to the 1998 Data Bank for Kiln-Dried Red Oak (Gatchell et al. 1998) for use in the rough mill simulations.

Objective 1

Cutting bills and relevant information (allowable defects) were gathered from various rough mills. The information was collected via phone, email, and several rough mill visits. The cutting bills collected will be those the rough mills use when running No. 3A Common red oak lumber or ones the rough mill considers to be “low-grade” cutting bills. Next, a series of experimental simulations will be conducted to find two feasible cutting bills. The collected cutting bills will be processed using the ROMI-RIP 2.0 and ROMI-CROSS simulation programs. The software program Gang Ripsaw Optimizer (GRO) will be used to generate the optimal arbor design for each of the cutting bills (Mitchell and Zuo 2001). The two most feasible cutting bills, considering both part yield and sawing efficiency, will be identified in this way. Sawing efficiency will be based on the actual number of saw kerfs. Statistical comparisons using Analysis of Variance (ANOVA) will be used to evaluate differences in yield between these candidate cutting bills. These two cutting bills will be used in the simulations to address Objectives 2 and 3.

Objective 2

Simulations using the two selected cutting bills will be performed using ROMI-RIP 2.01 (Thomas 1999b) and ROMI-CROSS (Thomas 1997). Three red oak lumber grade mixes will be examined: No. 2A Common, No. 3A Common, and a 50/50 grade mix of No. 2A and No. 3A Common lumber. The lumber grade mix files will be composed of similar size boards. Three to five repetitions of each simulation (depending on the level of yield variance between repetitions) will be conducted. If variances are the same or only slight differences are present, only three repetitions will be conducted Analysis of Variance (ANOVA) tests will be performed to test for any significant differences in yields between the three different grade mixes. The number of rip saw lines and crosscut saw lines required to accomplish the cutting bills will be analyzed to compare processing efficiencies of different grade mixes.

Objective 3

The cutting bills selected in Objective 1 will again be used to test for possible yield differences between different lengths of No. 3A Common red oak lumber. Three length groups will be tested: short (6-8 ft. long), medium (10-12 ft. long), and long length (14-16 ft. long). Three to five repetitions of each simulation (depending on the level of yield variance between repetitions) will be conducted. If variances are the same or only slight differences occur, only three repetitions will be conducted. Again, Analysis of Variance will be conducted to test for differences in yield between the different lumber length groups. If a statistically significant difference in part yields is discovered, Tukey's (HSD) multiple comparison test will be performed to attempt to distinguish differences between group means. The number of rip saw lines and crosscut saw lines required to accomplish the cutting bills will be analyzed to compare processing efficiencies of different lengths of lumber.

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CHAPTER 2. DETERMINATION OF TWO FEASIBLE CUTTING BILLS

Introduction

Annually in the U.S., the hardwood lumber industry produces approximately 13 billion board feet of lumber (Miller-Freeman 1999). Red oak (*quercus rubra*) makes up the largest proportion of this production volume, about 35 percent (U.S. Department of Commerce, Bureau of the Census, MA24T, 1998). A current challenge facing the forest products industry is finding markets for low-grade lumber. An increasing percentage of low-grade material is making up the annual U.S. production of hardwood lumber (Cumbo et al. 2001). Experts agree, acceptance of low-grade lumber is and will be forced in the future as the average size of logs available for harvest falls, lumber quality decreases, and lumber prices increase (Wiedenbeck and Araman 1995). Over time, the definition of low-grade material has changed and what was considered low-grade lumber 10 years ago is not necessarily considered low-grade lumber today. Today, both No. 2A Common and No. 3A Common lumber are referred to as low-grade lumber.

There has been a fair amount of research conducted and information produced to investigate the characteristics of and the manufacturing potential of No. 2A Common and better lumber (Hamner et al. 2002, Buehlmann et al. 1998, Steele and Gazo 1995, Wiedenbeck and Araman 1995). However, there is a lack of this same kind of research and information available for No. 3A Common lumber. To determine potential markets for and better understand the outcomes that can be realized when processing No. 3A Common lumber, it is important to understand how it interacts with manufacturing systems. A key manufacturing system in the value-added hardwood industry is the rough mill. In a rough mill boards are ripped and chopped to create dimension parts that will be used in the manufacture of secondary wood products such as furniture, flooring, cabinets, and stair parts. Conducting research in a rough mill can be very expensive and disruptive. As a result, programs have been developed to simulate rough mill operations.

Simulation is a valuable decision support tool used by many U.S. manufacturing engineers. It can be very quick and relatively inexpensive (Thomas et al. 1995). By definition, simulation is “the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system” (Wiedenbeck 1992). Simulation has been used to model and evaluate industrial production systems since 1955. Since then it has been commonly accepted and used in many fields as a computer-based management tool for determining differences between processing systems (Gazo and Steele 1995). Consequently, it has developed into an accepted analyst approach tool (Thomas et al. 1995). To establish validity, ROMI-RIP yield results were compared to real world rough mill results. ROMI-RIP was found to produce the same overall part yield results as a similar real world rough mill at the 95 percent level of siginificance (Thomas 2002).

ROMI-RIP and ROMI-CROSS are computer simulation software packages designed by R. Edward Thomas, a research computer scientist with the Northeastern Research Station’s Forestry Science Laboratory at Princeton, West Virginia. ROMI-RIP version 2.0 is the most recently developed rip-first, rough mill analysis tool from the USDA Forest Service (Thomas 1999a, 1999b). ROMI-CROSS was developed for use as a rough mill analysis tool as well, allowing the evaluation of different crosscut-first rough mill setups for different cutting bills (Thomas 1997).

Analyzing optimal part sizes and cutting bill parameters is an important step in assessing market fits for No. 3A Common lumber. These rough mill simulation programs provide a valid and powerful approach for assessing the production performance of No. 3A Common lumber. Production performance of No. 3A Common lumber is made up of several factors but yield and machine productivity are of principal importance. Simulations such as those used in this research assume as ideal and fully optimized operation.

Objective 1

Identify two feasible low-grade cutting bills, based on yield and sawing efficiency, through a series of exploratory crosscut-first and rip-first simulation studies, using ROMI-RIP and ROMI-CROSS.

Research Hypothesis # 1

At least one cutting bill's part yield will be different.

Null Hypothesis # 1

The part yields will be the same for all five cutting bills.

Research Hypothesis # 2

At least one cutting bill's sawing efficiency will be different.

Null Hypothesis # 2

The sawing efficiencies will be the same for all five cutting bills.

Methodology

The ROMI-RIP and ROMI-CROSS computer simulations were conducted using No. 3A Common, 4/4-thickness, kiln-dried, red oak lumber from the *1998 Data Bank for Kiln-Dried Red Oak Lumber* (Gatchell et al. 1998). In addition, approximately 1500 board feet (125 boards) of No. 3A Common kiln-dried 4/4 red oak lumber was collected from three sawmills and one flooring facility. The lumber was digitized and added to the existing population of No. 3A Common boards present in the *1998 Data Bank for Kiln-Dried Red Oak Lumber*. "Digitizing" is a procedure whereby a digital map of a board's dimensions and defects are created. The lumber in the *1998 Data Bank for Kiln-Dried Red Oak Lumber* (Gatchell et al. 1998) and the new lumber collected for this research were digitized according to the procedures described by Anderson et al. (1993). This procedure was explained in detail in the Methodology section in Chapter 1. The objective was to select the two most productive cutting bills based on part yield and sawing efficiency. Part yield is a ratio of the board feet of parts produced to the board feet of lumber input into the production process. In this study part yield was based only on primary parts, no salvage parts produced from salvage operations were included. Primary parts are those that are produced in the first two cutting stages (rip or crosscut) that meet cutting bill requirements. Sawing efficiency comparisons were calculated by dividing the total number of cuts (both rip and crosscut) by the board feet of parts produced. In this research, sawing efficiency was not a measure of time but a measure of the actual number of saw kerfs (sawlines) required to produce the amount of parts specified by the cutting bills.

All simulations were conducted according to the basic sequence of events suggested in the ROMI-RIP Users Guide (Thomas 1999a). This sequence is as follows:

1) Select or define a part quality definition file
2) Select or create a cutting bill
3) Set up the gang ripsaw arbor
4) Set up the chopsaws
5) Set up the overall processing and control options
6) Specify the salvage part sizes (if any)
7) Define output options
8) Select board data to process
9) Run and analyze simulation results.

Prior to conducting any simulations, several additional steps, mainly pertaining to the newly collected lumber data and cutting bill adjustments, had to be taken. These steps are described, as appropriate, throughout the methodology sections of this thesis; they did not necessarily occur in the order in which they are discussed.

Part Quality Definition (1)

The part quality definition describes the defects permitted in the face and/or back of the parts produced during a simulation. Part quality definitions are highly variable between different types of rough mills, cutting bills, and between different products. For the simulations in this research the same, clear two-face (C2F), part quality definition was used for all cutting bills. This part quality definition allows no defects on the face or the back of the parts produced. This is the most strict part quality definition. Therefore, the resulting part yields represent the lowest yields that should be expected when processing No. 3A Common lumber. By prohibiting all defects, biased results due to differences in part quality definitions were avoided. The C2F part quality definition is defined automatically in ROMI-RIP and ROMI-CROSS. Part quality definition options are explained in detail in the *ROMI-RIP 2.0 Users Guide* (Thomas 1999a).

Cutting Bills (2)

Four cutting bills were collected from industry operations for analysis with ROMI-RIP and ROMI-CROSS. The contributing operations included a flooring plant, a rough mill for cabinet parts, a rough mill for dimension parts, and a rough mill for moulding and millwork. In addition, the "easy" cutting bill used by Gatchell et al. (1999) was also used. This cutting bill got its name as a result of having lots of short lengths and narrow widths that are typically easy for rough mills to produce. These cutting bills are displayed in Tables 2-A, 2-B, 2-C, 2-D, and 2-E of Appendix 2 together with the modified versions of the cutting bills used in the simulations.

Cutting Bill *A* was obtained from a rough mill producing dimension parts, Cutting Bill *B* is the "easy" cutting bill, Cutting Bill *C* was obtained from a rough mill producing cabinet parts, Cutting Bill *D* was obtained from a rough mill producing flooring strips (these lengths of the strips being cut in this operation were very long; 3 to 6 feet), and Cutting Bill *E* was obtained from a rough mill producing parts for mouldings and millwork. Cutting Bill *A, B, C*, and *D* required only part quantity modifications for use with ROMI-RIP and ROMI-CROSS. Cutting Bill *E,* however, required several random length part descriptions that had to be modified. This was necessary because ROMI-RIP only allows one random length definition per width specified in the cutting bill and in

ROMI-CROSS no random length definitions are allowed. Another challenge faced in simulating Cutting Bill *E* was caused by the presence of some very long parts in the cutting bill. These long parts were nearly impossible to acquire with the No. 3A Common boards used in the simulation. To resolve this problem the long random length part definitions (45”- 96”) were removed as was the fixed long length part definition (98”). To bypass the random length limitations of the ROMI programs, random lengths were approximated by defining discrete lengths at 3-inch intervals over the range of acceptable lengths for each part width. For example, Part 1, 2.125 (2.13) inches wide with random lengths from 10 to 25 inches, was defined in Cutting Bill *E* as 7 individual parts with the same width (2.125) and lengths of 10, 13, 16, 19, 22, 25 (Table 2-E in Appendix 2). All random length part definitions were handled the same way. Cutting Bills *D* and *E* were from rough mill operations that required a continual supply of the part sizes listed in their cutting bills, thus, no specified quantities were assigned to the defined parts. This is the case in an operation producing few or identical products continuously, such as flooring operations. Cutting Bill *D* required 10 different part sizes but had no required quantities. An equal quantity was assigned to all 10 parts. Like Cutting Bill *D*, random quantities were assigned to the parts in Cutting Bill *E*. However, one part width (2.5 inches) was defined as the target width and the other two widths were defined as drop sizes. Drop sizes refers to parts to be cut only if the target size can not be obtained. Quantities were assigned for the part requirements such that the target width required twice as many parts as the drop widths.

Arbor Setup (3)

Saw blades in a circular-blade gang ripsaw like that simulated in ROMI-RIP are mounted on an arbor. An arbor is best described as a “series of combinations of saw spacings that overlap and interact” (Gatchell 1996). There are endless arbor configurations and some are better than others. Several methods exist which can be used to create optimal arbor setups based on a specific cutting bill. The Gang Ripsaw Arbor Design System (GRADS) (Fathi et al. 1996), Gang Ripsaw Arbor Solver (GanSolv) (Mitchell 1998), and the “pencil arbor design technique” (Gatchell 1996) are some of the existing procedures for determining optimal arbor setups. Another arbor design program was selected for this research. It is called Gang Ripsaw Optimizer (GRO) (Mitchell and Zuo 2001). GRO was written using the C++ programming language and was designed specifically to be used in conjunction with ROMI-RIP. When running a simulation, ROMI-RIP can determine the optimal feed position, in terms of producing the greatest possible strip widths from each board processed. These feed positions are stored in Arborgen output, a standard feature with ROMI-RIP, and ranked by frequency of which they occur (Thomas 1999b). GRO uses these feed positions, the total arbor width defined by the user, and the kerf thickness to design an optimal arbor (Mitchell and Zuo 2001).

Arbor type options available when running ROMI-RIP simulations include: best spacing sequence, fixed blade (no optimization), fixed blade best feed, fixed blade with floating outer blade, best spacing sequence with floating outer blade, all blades movable, and selective rip (Thomas 1998). When collecting the cutting bills to use for these simulations, the arbor type and saw blade spacing information was not acquired. All the arbor setups used in this research were designed using the GRO program in conjunction with ROMI-RIP. When using GRO, one of the user-defined variables is arbor width (e.g., 24” or 31”). This research is focused on optimal part yield and arbor width was undefined such that the most favorable arbor with regards to strip yield could be designed. For each of the five cutting bills, simulations were run using a No. 3A Common board file created according to width distribution B in Table 2-1, which is based on dry, No. 3A Common board widths measured at 14 rough mills (Wiedenbeck et al. 2003).

Table 2-1. Width distributions.

A[1]		B[2]	
Width	Percent	Width	Percent
< 5.00	17	3.00-4.75	17
5.00-6.75	43	5.00-6.75	43
7.00-8.75	27	7.00-8.75	27
9.00-10.75	9	9.00-10.75	10
11.00-12.75	2	11.00-12.75	2
13.00-14.75	1	13.00-14.75	1
15.00-16.75	0	15.00-16.75	0
17.00 +	0	17.00 +	0

[1] Width distribution from Wiedenbeck et al. (2003)
[2] Distribution used for this research.

Part quantities were adjusted so that the all the No. 3A Common boards in the file could be processed. Therefore, Arborgen’s frequency-ranked best-feed options were based on the board width distribution that would subsequently be used to generate all of the board files in this research. Table 2-2 shows a list of the cutting bills, the part widths, and the optimal arbor designed based on the GRO results. Note that all of the total arbor widths given in the rightmost column of Table 2-2 are less than 24 inches, a standard width arbor employed in rough mills.

Table 2-2. Arbor sequences for cutting bills.

Cut bill	Kerf	Part widths	Arbor spacing sequence	Arbor width
A	2/16	2.5	2.5, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5	18.25
B	2/16	1.5, 1.87, 2.62, 3.87, 4.25	1.87, 1.87, 2.62, 1.87, 4.25, 3.87, 1.5, 2.62	21.37
C	2/16	2.31	2.31, 2.31, 2.31, 2.31, 2.31, 2.31	14.48
D	2/16	2.5, 2.25	2.5, 2.5, 2.25, 2.5, 2.5, 2.5, 2.25, 2.25, 2.25	22.5
E	2/16	2.125, 2.5, 3.0	2.5, 3.0, 2.125, 2.5, 2.125, 3.0, 2.5, 2.5,	21.125

Chopsaws (4) and Overall Processing and Control Options (5)

Tables 2-3 and 2-4 display the chopsaw and overall processing and control options used for all ROMI-RIP and ROMI-CROSS simulations conducted in addressing Objectives 1, 2, and 3. The user-defined process control parameters that can be altered when running a simulation are summarized in these tables.

Table 2-3. ROMI-RIP simulation parameters held constant for all simulations.

All cutting/processing sizes are in inches to the nearest 1/16 - inch.
Primary strip yield optimized for best priority fit
Full strip scanned and optimized at once
Primary operations avoid producing orphan parts
Salvage operations cut to cutting bill requirements
Random width strip parts acceptable in panel production
Part priorities are continuously updated
Arbor type: Fixed-Blade-Best-Feed
Ripsaw kerf size: 2/16-inch
Left edger kerf size: 4/16-inch
Right edger kerf size: 4/16-inch
Board cutup solution optimized at every 1/16-inch position on the arbor
Endtrim allowance for each board end 16/16-inch
Chopsaw kerf size: 2/16-inch
Primary parts are: Clear two-face
Salvage parts are: Clear two-face

Table 2-4. ROMI-CROSS simulation parameters held constant for all simulations.

All part and processing measurements are in inches
Part lengths are specified
Primary operations avoid orphan parts
Salvage cuts to meet cutting bill
Crosscuts optimized for best length fitting to board features
Scanner optimizes for entire board length
Boards will be trimmed 1.0-inch on both ends
Chopsaw kerf is 2/16-inch. Ripsaw kerf is 2/16-inch
Primary parts are: Clear two-face
Salvage parts are: Clear two-face

All parts produced in ROMI-RIP and ROMI-CROSS were specified as C2F quality. An important parameter of the simulations is the part prioritization strategy. Part prioritization (Thomas 1997) strategy refers to the priority weighting that is placed on the different sizes of parts as the simulation progresses. Both the ROMI-RIP and ROMI-CROSS programs have several different strategies to choose from (Thomas 1997, 1999b). For this research the Complex Dynamic Exponent (CDE) strategy was used. A detailed description of the CDE part prioritization schedule, including equations for weighting factors, is given in Thomas (1996). The research conducted by Thomas looked at several different cutting bills and a wide spectrum of hardwood lumber grades, except No. 3A Common, and found the CDE strategy to be the best overall. The CDE strategy prioritizes parts based on their length, width, and the required quantity. Furthermore, the CDE strategy increases the priority of parts having low initial quantities as the simulation progresses. The CDE strategy operates by generating exponential weighting factors based on the required quantity of the part. The number of attained parts and the remaining quantity requirements are constantly analyzed and priorities are continually reassigned based on the progress up to that point. Thus, in three different runs using the same cutting bill, the same board may yield different parts depending on when it is cut and the part priorities at that time.

Salvage Parts (6)

Salvage parts were left undefined in the part quality definition and were not included in the final results of the simulations. However, since salvage cutting operations are cumbersome and represent an added processing cost, many rough mill managers are focused principally on primary yields.

Board Data Selection (7)

Before running the simulations in Objective 1, several preliminary steps pertaining to the addition of new board data and cutting bill modifications had to be completed. Thomas' *Makefile* program (Gatchell et al. 1998, Thomas 1997, Thomas 1999a) was used to create several board data files containing No. 3A Common red oak boards. *Makefile* is a program that comes standard with the ROMI-RIP and ROMI-CROSS software packages. It allows the user to create random board data files based on width and length distributions or to create custom files by selecting specific boards (Gatchell et al. 1998). A total of eight new board files resulted from digitizing the 1500 board feet of No. 3A Common red oak lumber that was collected for this research. Since 4-foot lumber was not included in this research, the 4-foot lumber data files were removed from the *Makefile* directory. As a result, the complete No. 3A Common board source for *Makefile* consisted of nine data files which contained 314 board maps (1627 board feet).

The “Grade/size mix file creation” option in *Makefile* was used to create a No. 3A Common board file according to the No. 3A Common width distribution set forth by Wiedenbeck et al. (2003). Table 2-1 gives this width distribution and the actual distribution used in this research. Only two differences exist between the two distributions. The distribution used in this research further defined the 5-inch width class by adding a lower limit of 3 inches. For *Makefile* to function the percentages of each width segment must add up to 100 percent. Consequently, the 9.00-10.75-inch width class was changed from a percentage of 9 to a percentage of 10. Board data files were created using width distribution B in Table 2-1.

To ensure that the boards contained in the created files have the same distribution as the population from which they are drawn, *Makefile* follows a procedure which randomly selects boards from the randomized subsets in the *Makefile* directory. A detailed description of the process is given in the *1998 Data Bank for Kiln-Dried Red Oak Lumber* (Gatchell et al. 1998). *Makefile* uses the same random selection procedure when selecting boards to fit a specified distribution.

Past research using ANOVA and Duncan’s multiple range test showed that only insignificant yield changes occur when more than 150 boards are processed in a simulation ($\alpha = .05$) (Buehlmann et al. 1998). As a result, simulations in this research were designed to process at least 150 boards per simulation to ensure accurate yield information. *Makefile* was used to create a file according to width distribution B in Table 2-1. The file contained 173 No. 3A Common red oak boards having a total volume of approximately 954 board feet. Though nearly half, 41 percent or 673 board feet, of the boards could not be used to attain distribution B, there were enough boards to ensure that 150 boards could be processed in the simulations.

The *Mix-Master* program (Thomas 1999a) which also comes with the ROMI simulation software was used to create two more board files containing the same boards. *Mix-Master* takes the boards from a selected file and randomly reorders them, creating a new file with the same boards in a different order. Thus, all three files used in addressing this objective had the same number of boards, the same amount of board feet, the same width and length distribution, and the same amount and distribution of crook. The three files were named WD#1A, WD#2A, and WD#3A. They all contained 173 boards totaling 954 board feet. All variables surrounding the simulations (see Table 2-3 and 2-4) were held constant as well, except for the actual part sizes and quantity requirements of the various cutting bills. This ensured that any differences in part yield or cutting efficiency between simulations were attributed only to the part sizes and their required quantities in the cutting bills.

Once the board files were created and the arbors for each of the cutting bills was designed, the part quantities for the cutting bills had to be adjusted so that all the requirements of the cutting bills could be met with the 173 boards contained in the No. 3A Common board files. In addition, it was equally important that at least 150 boards be used to meet the requirements so that accurate part yield estimations would result (Buehlmann et al. 1998). This determination of suitable part quantity was done by trial and error. Part quantity proportions for the parts in each cutting bill were maintained during this iterative process (e.g., if the initial requirements specified 100 parts for Part

A, 50 parts for Part B, and 30 parts for Part C, the adjusted quantities would still maintain this 10:5:3 ratio).

Sequentially, simulations were run with the three new board files, WD#1A, WD#2A, and WD#3A. For Cutting Bills A, B, and C, the part quantity requirements were gradually reduced by a percent until all the requirements were met and at least 150 boards were used. To reduce the part requirements for a certain cutting bill, the quantity required for each part would be reduced by a given percentage. For example, after the simulations were run, it was found that many of the quantity requirements for the cutting bill were still unmet and it was decided that they needed to be reduced. Then each original quantity for every part would be reduced by the same percentage of the original quantity required. This ensured that although the quantity changed, each part quantity still made up the same percentage of the total parts required by the cutting bill and the part prioritization strategy effects would not be changed. This procedure was done repeatedly until all cutting bill requirements could be met and no less than 150 boards were processed. The quantity requirement for Cutting Bills A, B, and C had to be reduced by 40, 92, and 60 percent for the ROMI-RIP simulations. Part quantity requirements were the same for ROMI-CROSS except for Cutting Bill A which had to be reduced by 47 percent. For Cutting Bills D and E, which were assigned a random quantity to begin with because they were continuous operations, simulations were run with the cutting bill and the required quantity was reduced until all cutting bill requirements could be met with the three new No. 3A Common files and at least 150 boards were processed. The final required quantities for all cutting bills are shown in Tables 2-A thru 2-E in Appendix 2.

Simulations (9)

Cutting Bills *A* thru *E* were each run once with each of the newly created No. 3A Common red oak lumber data files. As a result, each cutting bill was run three times for ROMI-RIP and three times for ROMI-CROSS. A total of 15 simulations were conducted with ROMI-RIP and 15 were conducted with ROMI-CROSS for a total of 30 simulations.

Results and Discussion

The two best cutting bills were to be determined for ROMI-RIP and ROMI-CROSS based on primary part yield and sawing efficiency. Part yield is the ratio of output volume to input volume. In this case, it was the total board feet of the parts produced divided by the total board feet of the lumber from which the parts were cut, multiplied by 100. In this research the sawing efficiency was calculated by dividing the total number of ripcuts and crosscuts by the board feet of parts produced. Thus, sawing efficiency is the average number of cuts required to process one board feet of lumber. A smaller number corresponds to higher sawing efficiency and a higher number corresponds to lower sawing efficiency. Again, sawing efficiency, in this research, is a measure of effort, not time.

The part yield equation and the sawing efficiency equation are shown in Figure 1. The average part yields and sawing efficiencies are displayed in Table 2-5. A complete list of all the ROMI-RIP and ROMI-CROSS simulation results can be found in in Tables 2-F and 2-G of Appendix 2.

$$\text{Part yield} = \frac{\text{Board feet of parts produced}}{\text{Board feet of lumber processed}} \times 100\%$$

$$\text{Sawing efficiency} = \frac{\text{Rip-cuts} + \text{Cross-cuts}}{\text{Board feet of parts produced}}$$

Figure 1. Calculations used to derive part yield and sawing efficiency results for each simulation.

ANOVA ($\alpha=0.05$) was conducted on the part yield and sawing efficiency results for both the ROMI-RIP and ROMI-CROSS simulations. Tukey's Honestly Significant Difference (HSD) multiple comparison test ($\alpha=0.05$) was conducted in cases where differences were indicated by the ANOVA (Appendix 2, Tables 2-H, I, J, and K). ANOVA and Tukey's multiple comparison tests were conducted using the Statistical Package for the Social Sciences (SPSS©).

Table 2-5. Average part yields and sawing efficiencies for ROMI-RIP and ROMI-CROSS simulations.

ROMI-RIP Results			ROMI-CROSS Results		
Rip-first bill	**Yield**	**Efficiency**	**Crosscut-first bill**	**Yield**	**Efficiency**
A	36.75	6.81	**A**	**31.39**	**7.60**
B	18.23	8.87	B	18.79	6.60
C	**38.41**	**7.79**	C	37.13	9.28
D	14.05	7.65	D	14.29	3.72
E	**37.24**	**6.15**	**E**	**36.43**	**6.37**

Highlighted in bold are the best cutting bills in terms of yield and sawing efficiency.

For the ROMI-RIP simulations, null hypothesis # 1 was rejected. Tukey's HSD indicated that the part yields were different for all five cutting bills except *A* and *E*. Cutting Bill *C* had the best part yield at about 38.4 percent and *A* and *E* were tied for the second best part yield at 36.8 percent and 37.2 percent. Cutting Bills *B* and *D* had much lower part yields at approximately 18.2 percent and 14.0 percent. Null hypothesis # 2 was also rejected for the rip-first results. Tukey's HSD indicated that all the sawing efficiencies were different except for *D* and *C*. The most efficient to process cutting bill from No. 3A Common lumber was *E*, followed by *A*, *D* and *C*, and lastly *B*. Cutting Bill *E* required approximately 6.2 cuts per board feet of parts produced, *A* required 6.8, *C* required 7.7, *D* required 7.8, and *B* required 8.9. Cutting Bills *A* and *E* exhibited no difference in part yields, however *E* was a more efficient cutting bill. As a result, Cutting Bills *C* and *E* were selected as the two best rip-first cutting bills in terms of yield and sawing efficiency. Cutting Bill *C* originated from a rough mill producing cabinet parts and Cutting Bill *E* originated from a rough mill producing parts for moulding and millwork.

For the ROMI-CROSS simulations, null hypothesis # 1 was rejected. Tukey's HSD indicated that all the part yields were different except for that of Cutting Bills *C* and *E*. The highest part yield was shared by Cutting Bills *C* and *E*, followed by *A*, *B*, and *D*. Their part yields were 37.1, and 36.4, 31.4, 18.8, and 14.3 percent, respectively. Null hypothesis # 2 was also rejected. Tukey's HSD indicated that all the sawing efficiencies were different. The most efficient crosscut-first cutting bill was *D*, followed by *E*, *B*, *A*, and *C*. Cutting Bill *D* required 3.7 cuts per board feet of parts produced, *E* required 6.4, *B* required 6.6, *A* required 7.6, and *C* required 9.3. Cutting Bills *C* and *E* exhibited no difference in their part yields, however E was more efficiently processed. As a result, Cutting Bills *A* and *E* were selected as the two best crosscut-first cutting bills. Cutting Bill *A* originated from a rough mill producing dimension parts.

There was a fairly distinct division of part yields in both the rip-first and crosscut-first simulations. Cutting Bills *A*, *C*, and *E* had much higher part yields then *B* and *D*. Looking for differences between these cutting bills, Cutting Bill *B* had several long parts between 50 and 80 inches and the required quantities for these parts were higher than those for the shorter parts. Cutting Bill *B* also had several parts over 3 inches wide as well as several panel parts. Cutting Bill *D* only had five different part lengths and they were all 3 feet in length or longer. Cutting Bills *A*, *C*, and *E* all had fairly narrow part widths and many different part lengths. Narrow part widths, 3 inches or less, and part lengths 40 inches or less were characteristic of the best cutting bills in terms of part yields and sawing efficiencies.

Araman (1982) conducted a survey of the furniture and cabinet industries to look at the rough part sizes needed to manufacture solid furniture, veneered furniture, upholstered furniture, recliners, and kitchen cabinets. Based on these results, many of the rough-part sizes required to manufacture these products could be produced from a cutting bill designed to achieve optimal part yield while processing No. 3A Common lumber. Interestingly, one of the best rip-first cutting bills selected in this objective originated from a rough mill producing cabinet parts. Both the cabinet and the furniture industries require many parts 3 inches wide or narrower and many parts less then 40 inches in length. Sixty-two percent of the parts used in the manufacture of kitchen cabinets are 4/4 parts 36 inches in length or shorter. Furthermore, 40 percent of the parts used in the manufacture of kitchen cabinets are 4/4 inch parts 3 inches wide or narrower. Looking at furniture, nearly half of the parts that go into the production of upholstered furniture and recliners are 4/4 lumber 36 inches long and shorter (Araman 1982).

Conclusion

Based on these results, it is clear that part yield and sawing efficiency are highly dependent on the cutting bill. In terms of part yield and sawing efficiency, the best two rip-first cutting bills are *C* and *E* and the best two crosscut-first cutting bills are *A* and *E*. Characteristics of the best cutting bills were parts 3 inches wide or narrower and various part lengths for each part width. As a result, cutting bills designed to achieve optimal part yield from No. 3A Common red oak lumber should not have part widths in excess of 3 inches and there should be at least 10 different part length definitions less then 40 inches for every part width in the cutting bill. Sectors which require parts of these sizes include furniture, cabinet, dimension, flooring, and finger-jointing.

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Appendix 2

Table 2-A. Original Cutting Bill A and modified versions used in ROMI-RIP and ROMI-CROSS simulations.

CUTTING BILL A (Width and length in inches)											
Original				**ROMI-RIP**				**ROMI-CROSS**			
Part	Width	Length	Quantity	Part	Width	Length	Quantity	Part	Width	Length	Quantity
1	2.5	40.13	233	1	2.5	40.13	140	1	2.5	40.13	123
2	2.5	34.13	116	2	2.5	34.13	70	2	2.5	34.13	61
3	2.5	28.13	215	3	2.5	28.13	129	3	2.5	28.13	114
4	2.5	22.13	172	4	2.5	22.13	103	4	2.5	22.13	91
5	2.5	16.13	56	5	2.5	16.13	34	5	2.5	16.13	30
6	2.5	15.63	28	6	2.5	15.63	17	6	2.5	15.63	15
7	2.5	13.5	14	7	2.5	13.5	8	7	2.5	13.5	7
8	2.5	13.13	56	8	2.5	13.13	34	8	2.5	13.13	30
9	2.5	13	441	9	2.5	13	265	9	2.5	13	234

Table 2-B. Original Cutting Bill B and modified versions used in ROMI-RIP and ROMI-CROSS simulations.

CUTTING BILL B (Width and length in inches)											
Original				**ROMI-RIP**				**ROMI-CROSS**			
Part	Width	Length	Quantity	Part	Width	Length	Quantity	Part	Width	Length	Quantity
1	4.25	32	44	1	4.25	32	4	1	4.25	32	4
2	4.25	15.88	125	2	4.25	15.88	10	2	4.25	15.88	10
3	3.88	61.88	135	3	3.88	61.88	11	3	3.88	61.88	11
4	3.88	14.63	105	4	3.88	14.63	8	4	3.88	14.63	8
5	2.63	57.38	215	5	2.63	57.38	17	5	2.63	57.38	17
6	2.63	22.88	100	6	2.63	22.88	8	6	2.63	22.88	8
7	1.88	44.63	300	7	1.88	44.63	24	7	1.88	44.63	24
8	1.5	55.38	250	8	1.5	55.38	20	8	1.5	55.38	20
9	1.5	23	1550	9	1.5	23	124	9	1.5	23	124
10	1.5	15	240	10	1.5	15	19	10	1.5	15	19
Panel				Panel				Panel			
1	20.63	19.88	125	1	20.63	19.88	10	1	20.63	19.88	10
2	17.63	54	26	2	17.63	54	2	2	17.63	54	2
3	6.25	28.38	30	3	6.25	28.38	2	3	6.25	28.38	2
4	4.5	78.88	30	4	4.5	78.88	2	4	4.5	78.88	2
5	4.5	11.88	110	5	4.5	11.88	9	5	4.5	11.88	9

Table 2-C. Original Cutting Bill C and modified versions used in ROMI-RIP and ROMI-CROSS simulations.

CUTTING BILL C (Width and length in inches)											
Original				**ROMI-RIP**				**ROMI-CROSS**			
Part	Width	Length	Quantity	Part	Width	Length	Quantity	Part	Width	Length	Quantity
1	2.31	3.88	12	1	2.31	3.88	5	1	2.31	3.88	5
2	2.31	6.88	33	2	2.31	6.88	13	2	2.31	6.88	13
3	2.31	8.38	205	3	2.31	8.38	82	3	2.31	8.38	82
4	2.31	11.38	21	4	2.31	11.38	8	4	2.31	11.38	8
5	2.31	12.88	184	5	2.31	12.88	74	5	2.31	12.88	74
6	2.31	14.38	109	6	2.31	14.38	44	6	2.31	14.38	44
7	2.31	15.88	52	7	2.31	15.88	21	7	2.31	15.88	21
8	2.31	16.25	42	8	2.31	16.25	17	8	2.31	16.25	17
9	2.31	18.88	88	9	2.31	18.88	35	9	2.31	18.88	35
10	2.31	21.75	504	10	2.31	21.75	202	10	2.31	21.75	202
11	2.31	25.25	174	11	2.31	25.25	70	11	2.31	25.25	70
12	2.31	28.25	327	12	2.31	28.25	131	12	2.31	28.25	131
13	2.31	40.25	42	13	2.31	40.25	17	13	2.31	40.25	17

Table 2-D. Original Cutting Bill D and modified versions used in ROMI-RIP and ROMI-CROSS simulations.

CUTTING BILL D (Width and length in inches)											
Original				**ROMI-RIP**				**ROMI-CROSS**			
Part	Width	Length	Quantity	Part	Width	Length	Quantity	Part	Width	Length	Quantity
1	2.25	36	N/A	1	2.25	36	13	1	2.25	36	13
2	2.25	48	N/A	2	2.25	48	13	2	2.25	48	13
3	2.25	60	N/A	3	2.25	60	13	3	2.25	60	13
4	2.25	72	N/A	4	2.25	72	13	4	2.25	72	13
5	2.25	84	N/A	5	2.25	84	13	5	2.25	84	13
6	2.5	36	N/A	6	2.5	36	13	6	2.5	36	13
7	2.5	48	N/A	7	2.5	48	13	7	2.5	48	13
8	2.5	60	N/A	8	2.5	60	13	8	2.5	60	13
9	2.5	72	N/A	9	2.5	72	13	9	2.5	72	13
10	2.5	84	N/A	10	2.5	84	13	10	2.5	84	13

Table 2-E. Original Cutting Bill E and modified versions used in ROMI-RIP and ROMI-CROSS simulations.

CUTTING BILL E (Width and length in inches **)**											
Original				**ROMI-RIP**				**ROMI-CROSS**			
Part	Width	Length	Quantity	Part	Width	Length	Quantity	Part	Width	Length	Quantity
1	2.13	10-25	N/A	1	2.13	10	13	1	2.13	10	13
2	2.13	35-45	N/A	2	2.13	13	13	2	2.13	13	13
3	2.13	45-96	N/A	3	2.13	16	13	3	2.13	16	13
4	2.13	98	N/A	4	2.13	19	13	4	2.13	19	13
5	2.5	10-25	N/A	5	2.13	22	13	5	2.13	22	13
6	2.5	35-45	N/A	6	2.13	25	13	6	2.13	25	13
7	2.5	45-96	N/A	7	2.13	28	13	7	2.13	28	13
8	2.5	98	N/A	8	2.13	31	13	8	2.13	31	13
9	3	10-25	N/A	9	2.13	34	13	9	2.13	34	13
10	3	35-45	N/A	10	2.13	37	13	10	2.13	37	13
11	3	45-96	N/A	11	2.13	40	13	11	2.13	40	13
12	3	98	N/A	12	2.13	43	13	12	2.13	43	13
				13	2.13	46	13	13	2.13	46	13
				14	2.5	10	26	14	2.5	10	26
				15	2.5	13	26	15	2.5	13	26
				16	2.5	16	26	16	2.5	16	26
				17	2.5	19	26	17	2.5	19	26
				18	2.5	22	26	18	2.5	22	26
				19	2.5	25	26	19	2.5	25	26
				20	2.5	28	26	20	2.5	28	26
				21	2.5	31	26	21	2.5	31	26
				22	2.5	34	26	22	2.5	34	26
				23	2.5	37	26	23	2.5	37	26
				24	2.5	40	26	24	2.5	40	26
				25	2.5	43	26	25	2.5	43	26
				26	2.5	46	13	26	2.5	46	13
				27	3	10	13	27	3	10	13
				28	3	13	13	28	3	13	13
				29	3	16	13	29	3	16	13
				30	3	19	13	30	3	19	13
				31	3	22	13	31	3	22	13
				32	3	25	13	32	3	25	13
				33	3	28	13	33	3	28	13
				34	3	31	13	34	3	31	13
				35	3	34	13	35	3	34	13
				36	3	37	13	36	3	37	13
				37	3	40	13	37	3	40	13
				38	3	43	13	38	3	43	13
				39	3	46	13	39	3	46	13

Table 2-F. Summary of ROMI-RIP results for cutting bill simulations.

Cutting bill	Board file	Boards	Board feet	Parts (Bdft)	Part yield	Rip count	X-Cut count	Total cuts	Sawing efficiency*
A1	Wd#1a	161	889.30	331.77	37.31	742	1509	2251	6.78
A2	Wd#2a	162	896.20	327.78	36.57	748	1483	2231	6.81
A3	Wd#3a	166	910.10	331.04	36.37	760	1503	2263	6.84
B1	Wd#1a	168	926.80	163.27	17.62	745	727	1472	9.02
B2	Wd#2a	163	902.20	167.22	18.53	721	724	1445	8.64
B3	Wd#3a	163	889.70	164.96	18.54	725	754	1479	8.97
C1	Wd#1a	161	889.30	344.12	38.7	774	1908	2682	7.79
C2	Wd#2a	161	884.50	340.07	38.45	778	1868	2646	7.78
C3	Wd#3a	164	898.70	342.25	38.08	784	1882	2666	7.79
D1	Wd#1a	162	895.00	130.15	14.54	703	263	966	7.42
D2	Wd#2a	171	940.00	126.65	13.69	736	259	995	7.86
D3	Wd#3a	170	937.60	130.42	13.91	737	263	1000	7.67
E1	Wd#1a	161	889.30	332.32	37.37	746	1304	2050	6.17
E2	Wd#2a	162	896.20	331.82	37.03	750	1295	2045	6.16
E3	Wd#3a	166	910.10	334.23	36.73	750	1295	2045	6.12

* Total Cuts/ Parts (bdft)

Table 2-G. Summary of ROMI-CROSS results for cutting bill simulations.

Cutting bill	Board file	Boards	Board feet	Parts (Bdft)	Part yield	Rip count	X-Cut count	Total cuts	Sawing efficiency*
A1	Wd#1a	167	922.4	290.12	31.45	1283	908	2191	7.55
A2	Wd#2a	170	936	294.45	31.46	1324	933	2257	7.67
A3	Wd#3a	171	944	295.13	31.26	1322	917	2239	7.59
B1	Wd#1a	171	945.1	167.28	17.7	688	429	1117	6.68
B2	Wd#2a	152	839.9	166.82	19.86	672	427	1099	6.59
B3	Wd#3a	159	872.6	164.22	18.82	649	423	1072	6.53
C1	Wd#1a	164	906.9	336.10	37.06	1915	1214	3129	9.31
C2	Wd#2a	167	921.2	338.80	36.78	1927	1217	3144	9.28
C3	Wd#3a	164	900.5	338.10	37.55	1922	1206	3128	9.25
D1	Wd#1a	170	940.2	129.48	13.77	254	221	475	3.67
D2	Wd#2a	168	928.3	128.65	13.86	253	228	481	3.74
D3	Wd#3a	156	852.4	129.83	15.23	258	229	487	3.75
E1	Wd#1a	172	949.8	345.28	36.35	1273	914	2187	6.33
E2	Wd#2a	169	931.7	339.79	36.47	1268	925	2193	6.45
E3	Wd#3a	170	939.7	342.66	36.47	1263	904	2167	6.32

* Total Cuts/ Parts (bdft)

Table 2-H. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP part yields in Objective 1.

Cutting bill	Number of simulations	Mean part yield	Standard deviation	Standard error	95% Confidence interval for mean		Minimum part yield	Maximum part yield
					Lower bound	Upper bound		
=A	3	36.75	0.50	0.29	35.52	37.98	36.37	37.31
=B	3	18.11	0.46	0.27	16.96	19.27	17.62	18.54
=C	3	38.41	0.31	0.18	37.64	39.18	38.08	38.70
=D	3	14.05	0.44	0.25	12.95	15.14	13.69	14.54
=E	3	37.24	0.06	0.03	37.09	37.39	37.18	37.30
Total	15	28.91	10.95	2.83	22.85	34.97	13.69	38.70

ANOVA results for part yields.

	Sum of Squares	df	Mean Square	F	Sig.
Between groups	1675.94	4	418.99	2772.17	<0.01
Within groups	1.51	10	.151		
Total	1677.45	14			

Tukey's HSD for part yields.

		Mean difference (I-J)	Standard error	Significance	95% Confidence interval	
(I) BILL	(J) BILL				Lower bound	Upper bound
=A	=B	18.64*	0.32	<0.01	17.59	19.68
	=C	-1.66*	0.32	<0.01	-2.70	-0.62
	=D	22.70*	0.32	<0.01	21.66	23.75
	=E	-.49	0.32	0.55	-1.54	0.55
=B	=A	-18.64*	0.32	<0.01	-19.68	-17.59
	=C	-20.30*	0.32	<0.01	-21.34	-19.25
	=D	4.07*	0.32	<0.01	3.02	5.11
	=E	-19.13*	0.32	<0.01	-20.17	-18.09
=C	=A	1.66*	0.32	<0.01	0.62	2.70
	=B	20.30*	0.32	<0.01	19.25	21.34
	=D	24.36*	0.32	<0.01	23.32	25.41
	=E	1.17*	0.32	0.03	0.12	2.21
=D	=A	-22.70*	0.32	<0.01	-23.75	-21.66
	=B	-4.07*	0.32	<0.01	-5.11	-3.02
	=C	-24.36*	0.32	<0.01	-25.41	-23.32
	=E	-23.20*	0.32	<0.01	-24.24	-22.15
=E	=A	.49	0.32	0.55	-0.55	1.54
	=B	19.13*	0.32	<0.01	18.09	20.17
	=C	-1.17*	0.32	0.03	-2.21	-0.12
	=D	23.20*	0.32	<0.01	22.15	24.24

* The mean difference is significant at the .05 level.

Homogeneous Subset results of Tukey's HSD[a] on part yield.

Cutting bill	Number of simulations	Subset for alpha = .05			
		1	2	3	4
=D	3	14.05			
=B	3		18.11		
=A	3			36.75	
=E	3			37.24	
=C	3				38.41
Sig.		1.00	1.00	.55	1.00

Means for groups in homogeneous subsets are displayed.

a Uses Harmonic Mean Sample Size = 3.000.

Table 2-I. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP sawing efficiencies in Objective 1.

Cutting bill	Number of simulations	Mean sawing efficiency	standard deviation	standard error	95% Confidence interval for mean		Minimum sawing efficiency	Maximum sawing efficiency
					Lower bound	Upper bound		
= A	3	6.81	0.03	0.02	6.74	6.88	6.78	6.84
= B	3	8.88	0.21	0.12	8.36	9.39	8.64	9.02
= C	3	7.79	0.01	0.00	7.77	7.80	7.78	7.79
= D	3	7.65	0.22	0.13	7.10	8.20	7.42	7.86
= E	3	6.15	0.03	0.02	6.08	6.22	6.12	6.17
Total	15	7.45	0.97	0.25	6.92	7.99	6.12	9.02

ANOVA results for sawing efficiency.

	Sum of squares	df	Mean square	F	Sig.
Between groups	12.87	4	3.22	172.97	< 0.01
Within groups	.19	10	.02		
Total	13.05	14			

Tukey HSD results for sawing efficiency.

		Mean difference (I-J)	Standard error	Significance	95% Confidence Interval	
(I) CUTBILL	**(J) CUTBILL**				**Lower bound**	**Upper bound**
= A	**= B**	-2.07*	0.11	<0.01	-2.43	-1.70
	= C	-.98*	0.11	<0.01	-1.34	-0.61
	= D	-.84*	0.11	<0.01	-1.21	-0.47
	= E	.66*	0.11	<0.01	0.29	1.03
= B	**= A**	2.07*	0.11	<0.01	1.70	2.43
	= C	1.09*	0.11	<0.01	0.72	1.46
	= D	1.23*	0.11	<0.01	0.86	1.59
	= E	2.73*	0.11	<0.01	2.36	3.09
= C	**= A**	.98*	0.11	<0.01	0.61	1.34
	= B	-1.09*	0.11	<0.01	-1.46	-0.72
	= D	.14	0.11	0.74	-0.23	0.50
	= E	1.64*	0.11	<0.01	1.27	2.00
= D	**= A**	.84*	0.11	<0.01	0.47	1.21
	= B	-1.23*	0.11	<0.01	-1.59	-0.86
	= C	-.14	0.11	0.74	-0.50	0.23
	= E	1.50*	0.11	<0.01	1.13	1.87
= E	**= A**	-.66*	0.11	<0.01	-1.03	-0.29
	= B	-2.73*	0.11	<0.01	-3.09	-2.36
	= C	-1.64*	0.11	<0.01	-2.00	-1.27
	= D	-1.50*	0.11	<0.01	-1.87	-1.13

* The mean difference is significant at the .05 level.

Homogeneous subsets results of Tukey's HSD[a] on sawing efficiency.

Cutting bill	Number of simulations	Subset for alpha = .05			
		1	**2**	**3**	**4**
= E	3	6.15			
= A	3		6.81		
= D	3			7.65	
= C	3			7.79	
= B	3				8.88
Sig.		1.00	1.00	0.74	1.00

Means for groups in homogeneous subsets are displayed.
a Uses Harmonic Mean Sample Size = 3.000.

Table 2-J. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-CROSS part yields for Objective 1.

Cutting Bill	Number of simulations	Mean part yield	Standard deviation	Standard error	95% Confidence interval for mean		Minimum part yield	Maximum part yield
					Lower bound	Upper bound		
= A	3	31.39	.11	.07	31.11	31.67	31.26	31.46
= B	3	18.79	1.08	.62	16.11	21.48	17.70	19.86
= C	3	37.13	.39	.22	36.16	38.10	36.78	37.55
= D	3	14.28	.89	.47	12.25	16.32	13.77	15.23
= E	3	36.43	.07	.04	36.26	36.60	36.35	36.47
Total	15	27.60	9.70	2.51	22.23	32.98	13.77	37.55

ANOVA result for part yield.

	Sum of squares	df	Mean square	F	Sig.
Between groups	1313.87	4	328.47	818.81	< 0.01
Within groups	4.012	10	.401		
Total	1317.88	14			

Tukey HSD results for part yield.

		Mean difference (I-J)	Standard error	Significance	95% Confidence interval	
(I) BILL	(J) BILL				Lower bound	Upper bound
= A	= B	12.60*	0.52	<0.01	10.89	14.30
	= C	-5.74*	0.52	<0.01	-7.44	-4.04
	= D	17.10*	0.52	<0.01	15.40	18.81
	= E	-5.04*	0.52	<0.01	-6.74	-3.34
= B	= A	-12.60*	0.52	<0.01	-14.30	-10.89
	= C	-18.34*	0.52	<0.01	-20.04	-16.63
	= D	4.51*	0.52	<0.01	2.80	6.21
	= E	-17.64*	0.52	<0.01	-19.34	-15.93
= C	= A	5.74*	0.52	<0.01	4.04	7.44
	= B	18.34*	0.52	<0.01	16.63	20.04
	= D	22.84	0.52	<0.01	21.14	24.55
	= E	.70*	0.52	0.67	-1.00	2.40
= D	= A	-17.10*	0.52	<0.01	-18.81	-15.40
	= B	-4.51*	0.52	<0.01	-6.21	-2.80
	= C	-22.84	0.52	<0.01	-24.55	-21.14
	= E	-22.14*	0.52	<0.01	-23.85	-20.44
= E	= A	5.04*	0.52	<0.01	3.34	6.74
	= B	17.64*	0.52	<0.01	15.93	19.34
	= C	-.70*	0.52	0.67	-2.40	1.00
	= D	22.14*	0.52	<0.01	20.44	23.85

* The mean difference is significant at the .05 level.

Homogeneous subset results from Tukey's HSD [a] on part yields.[a]

Cutting bill	Number of simulations	Subset for alpha = .05			
		1	2	3	4
= D	3	14.29			
= B	3		18.80		
= A	3			31.39	
= E	3				36.43
= C	3				37.13
Sig.		1.000	1.000	1.000	0.667

Means for groups in homogeneous subsets are displayed.
a Uses Harmonic Mean Sample Size = 3.000.

Table 2-K. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-CROSS sawing efficiencies for Objective 1.

Cutting bill	Number of simulations	Mean part yield	Standard deviation	Standard error	95% Confidence interval for mean		Minimum part yield	Maximum part yield
					Lower bound	Upper bound		
= A	3	7.60	0.06	0.04	7.45	7.76	7.55	7.67
= B	3	6.60	0.08	0.04	6.41	6.79	6.53	6.68
= C	3	9.28	0.03	0.02	9.21	9.35	9.25	9.31
= D	3	3.72	0.04	0.03	3.61	3.83	3.67	3.75
= E	3	6.37	0.07	0.04	6.19	6.55	6.32	6.45
Total	15	6.71	1.88	0.49	5.67	7.75	3.67	9.31

ANOVA results for sawing efficiency.

	Sum of squares	df	Mean square	F	Sig.
Between groups	49.42	4	12.36	3536.65	<0.01
Within groups	.04	10	.00		
Total	49.45	14			

Tukey's HSD results for sawing efficiency.

		Mean difference (I-J)	**Standard error**	**Significance**	**95% Confidence interval**	
(I) CUTBILL	**(J) CUTBILL**				**Lower bound**	**Upper bound**
= A	**= B**	1.00*	0.05	<0.01	0.84	1.16
	= C	-1.68*	0.05	<0.01	-1.84	-1.52
	= D	3.88*	0.05	<0.01	3.72	4.04
	= E	1.24*	0.05	<0.01	1.08	1.40
= B	**= A**	-1.00*	0.05	<0.01	-1.16	-0.84
	= C	-2.68*	0.05	<0.01	-2.84	-2.52
	= D	2.88*	0.05	<0.01	2.72	3.04
	= E	.23*	0.05	0.01	0.07	0.39
= C	**= A**	1.68*	0.05	<0.01	1.52	1.84
	= B	2.68*	0.05	<0.01	2.52	2.84
	= D	5.56*	0.05	<0.01	5.40	5.72
	= E	2.91*	0.05	<0.01	2.75	3.07
= D	**= A**	-3.88*	0.05	<0.01	-4.04	-3.72
	= B	-2.88*	0.05	<0.01	-3.04	-2.72
	= C	-5.56*	0.05	<0.01	-5.72	-5.40
	= E	-2.65*	0.05	<0.01	-2.81	-2.49
= E	**= A**	-1.24*	0.05	<0.01	-1.40	-1.08
	= B	-.23*	0.05	0.01	-0.39	-0.07
	= C	-2.91*	0.05	<0.01	-3.07	-2.75
	= D	2.65*	0.05	<0.01	2.49	2.81

* The mean difference is significant at the .05 level.

Homogeneous subset results Tukey's HSD[a] on sawing efficiency.

Cutting bill	**Number of simulations**	**Subset for alpha = .05**				
		1	**2**	**3**	**4**	**5**
= D	3	3.72				
= E	3		6.37			
= B	3			6.60		
= A	3				7.60	
= C	3					9.28
Sig.		1.00	1.00	1.00	1.00	1.00

Means for groups in homogeneous subsets are displayed.

a Uses Harmonic Mean Sample Size = 3.000.

CHAPTER 3. THE EFFECTS OF GRADE-MIX ON PART YIELD AND SAWING EFFICIENCY

Introduction

A common practice in rough mills, and other lumber manufacturing systems, is to process multiple grades of lumber. Grade mix is the term used to describe the grade content of the lumber used for raw material. A grade mix may consist of one grade or it may be composed of several different grades of lumber. Factors affecting the grade mix include the end product, the cost of lumber, the type of equipment used to process it, and the grade of lumber available in inventory. Many rough mills develop one or more standard grade mixes based on previous experiences running various grades of lumber (Wiedenbeck 2001). Similar to any manufacturing change in the forest products industry, the most important factors in evaluating low-grade lumber are production rates, costs, and yields (Bingham 1976-77 and Reynolds and Schroeder 1978). As a result, opportunities for processing low-grade lumber may arise when lumber prices change, the width and/or length of the lumber supply changes, equipment and/or rough mill supervision changes, or when there are additions or deletions of a certain product or product line (Wiedenbeck 2001).

Traditionally, most rough mills have not used No. 3A Common lumber due to lack of experience, quality consistency, and uncertainties surrounding production. Rough mill yield is one of the biggest measurements of rough mill productivity. Since raw material costs typically make up 60 to 80 percent of the production cost, increasing the amount of low-grade lumber in the grade mix does have good potential to reduce overall manufacturing cost. If the percentage of low-grade lumber in a grade mix can be increased without sacrificing rough mill yield, rough mill managers may be persuaded to use it to reduce raw material costs. It is fairly common to find rough mills running multi-grade grade mixes.

Steele et al. (1999) looked at the influence of grade on machine productivity when processing hardwood lumber in a crosscut-first operation. The *Cut-Sim* rough mill simulator was used to simulate a crosscut rough mill that used manually operated crosscut saws and straight-line ripsaws. The simulations processed digitized 4/4, kiln-dried, southern red oak lumber. They analyzed the total number of cuts, the number of crosscuts, the number of straight-line rip cuts, and the number of salvage cuts required to process the lumber with respect to 3 different cutting bills. FAS, First One Face, No. 1 Common, No. 2A Common, and No. 3A Common lumber were evaluated. It was concluded that the lumber grade significantly impacts the number of cuts required to fill various cutting bills. The general trend between simulations was that the number of cuts required to fulfill a cutting bill decreased as the lumber grade increased. Crosscut saw productivity was affected more than the rip saw productivity.

All of the operations from which the cutting bills for this research were obtained were rough mills running more than one grade. One rough mill was running a No. 2A Common / No. 3A Common grade mix and the others were running No. 1 Common / No. 2A Common grade mixes.

Objective 2

Compare part yields and sawing efficiencies when No. 2A Common, No. 3A Common, and a 50-50 grade mix of No. 2A Common and No. 3A Common are run with the two most feasible low-grade lumber cutting bills determined in Objective 1.

Research Hypothesis # 1

At least one of the grade mixes will exhibit a part yield different form the others.

Null Hypothesis # 1

The No. 2A Common, No. 3A Common, and the 50/50 mix of No. 2A Common and No. 3A Common grade mixes will exhibit the same part yields.

Research Hypothesis # 2

At least one of the grade mixes will exhibit a sawing efficiency different then the others.

Null Hypothesis # 2

The No. 2A Common, No. 3A Common, and the 50/50 mix of No. 2A Common and No. 3A Common grade mixes will exhibit the same sawing efficiencies.

Methodology

For Objective 2, the three grade mixes were analyzed using the ROMI-RIP and ROMI-CROSS simulation programs (Thomas 1997, 1999b). The simulation results were evaluated and compared based on both part yield and sawing efficiency. The same sequence of nine steps (Thomas 1999a) followed in Objective 1 was used to conduct the simulations in Objective 2. As a result, the same part quality definition (C2F), arbor setups, chopsaw setups, and overall processing and control options were used. The only difference in Objective 2 simulation parameters was the board files used. The "best" low-grade lumber cutting bills identified in Objective 1 (see Chapter 2) were used. Cutting Bills *C* and *E* were used for ROMI-RIP and cutting bills *A* and *E* were used for ROMI-CROSS. Part yields and sawing efficiencies were measured the same as in Chapter 2. Again, part yield was a ratio of the board feet of parts produced to the board feet of the lumber processed. Sawing efficiency was a ratio of the total number of cuts required to complete a simulation to the board feet of parts produced by the simulation.

Makefile was used to create board files with three different grade mixes; No. 2A Common, No. 3A Common, and a 50/50 mix of No. 2A Common and No. 3A Common. To make certain that the results of the ROMI simulations were attributed to the grade mix, several other variables had to be held constant in all the board files for all three grade mixes. These variables were lumber width, lumber length, and crook. The bulk of the boards used in the ROMI simulations were from the *1998 Data Bank for Kiln-Dried Red Oak Lumber* (Gatchell et al. 1998). The remainder of the boards was composed of the new No. 3A Common boards collected for this research. Lumber length and crook distributions were based on that exhibited by this lumber. These variables were addressed first. The lumber width variable was addressed last. The same width distribution guidelines used to create files in Objective 1 (Table 2-1) were used for the No. 2A Common grade mix, as well as the No. 3A Common and the 50/50 grade mix.

Crook

The No. 2A Common and No. 3A Common boards in the *1998 Data Bank for Kiln-Dried Red Oak Lumber* contained no more then 0.25 inch of crook. It is possible that just 0 .25 inch of crook can have a significant impact on yield if it is present in a large amount of the lumber being processed. However, boards with 0.25 inch of crook or less are considered straight in the *1998 Data Bank for Kiln-Dried Red Oak Lumber* (Gatchell et al. 1998). The new No. 3A Common lumber acquired for this research contained boards with various degrees of crook greater then 0.25 inch. To be consistent with the boards in the *1998 Data Bank for Kiln-Dried Red Oak Lumber,* all of the new No. 3A Common boards that contained more then 0.25 inch of crook were removed from the No. 3A Common board population. As a result, 63 of the new No. 3A Common boards were removed leaving a total of 62 new boards, 352 board feet, in the No. 3A Common board population. The resulting No. 3A Common board population contained 1,275 board feet of lumber in 251 boards. The No. 2A Common board population contained 4,450 board feet of lumber in 785 boards. All of the No. 2A Common and No. 3A Common boards available for use in the simulations had 0.25 inch of crook or less and were considered straight.

Length

After adjusting the board populations to have even crook distributions (all boards straight), there were considerably less No. 3A Common boards available than No. 2A Common boards. As a result, the length distribution of the No. 3A Common board population was calculated and the population of No. 2A Common boards was adjusted to equal it. This would allow all the No. 3A Common boards to be considered in the width distribution modification. Table 3-1 shows the length distribution of the No. 3A Common boards. *Makefile* was then used to adjust the length distribution of the No. 2A Common board population. After the length distribution was adjusted, the population of

No. 2A Common boards was reduced by 4.3 percent, 192 board feet. This left 4,257 board feet of No. 2A Common lumber available for use in composing the board sample files to address Objective 2.

Table 3-1. Length distribution of No. 3A boards after adjustment for crook.

No. 3A Common length distribution	
Length (ft.)	**Percent (%)**
6	21
7	0
8	12
9	8
10	22
11	3
12	23
13	1
14	6
15	1
16	3
Total	100

Width

The final variable that required adjusting in the board files for Objective 2 was lumber width. After modifying the No. 2A Common and No. 3A Common board populations to have equal crook and length distributions, the No. 2A Common board population consisted of 4,257 board feet of lumber and the No. 3A Common board population consisted of 1,275 board feet of lumber. The width distribution of the final board files for the three different grade mixes was adjusted using *Makefile*. However, now all the No. 2A Common lumber was in one file which was too big to serve as a source file for the M*akefile* program. The board file size limitation is 999 board feet and the No. 2A Common file contained over 4000 board feet. The problem with the size of the file was solved by breaking the No. 2A Common file down into smaller subsets as was done to create the subsets for the other lumber grades in the *1998 Data Bank for Kiln-Dried Red Oak Lumber*. The process is outlined in detail on page 17 of the *1998 Data Bank for Kiln-Dried Red Oak Lumber* (Gatchell et al. 1998). The boards are distributed from the large No. 2A Common file to the smaller subsets in order, exactly like dealing cards. This process ensured that the distribution of each of the subsets was the same as the large No. 2A Common file that was created according to the length distribution in Table 3-1. Eight new No. 2A Common subsets were created that contained approximately 530 board feet of lumber and between 93 and 95 boards each. The order of the boards in these subsets was randomized so that every board had an equal opportunity of being selected for inclusion in the grade mix files by *Makefile.*

Grade Mix Files

Three grade mixes were studied as described previously with three sample board files per grade mix. The files were created using the No. 3A Common width distribution described in Table 2-1 (See Chapter 2). The research conducted by Wiedenbeck et al. also contained a width distribution for No. 2A Common lumber. However, the No. 3A Common width distribution was used to create each of the new files to take advantage of as many of the No. 3A Common boards as possible. Since the primary goal under Objective 2 was to evaluate performance differences between lumber grade mixes, using the same width distribution to create these new files minimized differences in the width distributions of the input lumber files which would have confounded results making them harder to interpret.

Each of the factors (crook, length, and width) had been handled separately up to this point. To make sure that the length and width distributions had carried through to the final board files, Analyses of Variance ($\alpha = 0.05$) were conducted, using SPSS©, on the width and length of the new files. The null hypothesis that the average width in each file was the same was not rejected; the width distribution for all nine files was the same**.**

In contrast to the width comparison results, the null hypothesis that the average length in all the files was the same was rejected. Tukey's HSD ($\alpha = 0.05$) was conducted to see where the discrepancy was. The 2a3a21 file and the 2a21 (see Table 3-2) file had different average lengths. As a result, another 50/50 file of No. 2A Common and No. 3A Common boards was created using *Makefile*. Another ANOVA ($\alpha = 0.05$) was conducted using this new file in place of the original 2a3a21 file. This time the null hypothesis was not rejected and so the new 50/50 file replaced the older 2a3a21 file. Summaries of the ANOVA and Tukey's HSD multi-comparison test conducted on the length and width distribution can be viewed in Tables 3-A, 3-B, 3-C, and 3-D of Appendix 3. Information on the nine grade mix files for Objective 2 are listed in Table 3-2.

Table 3-2. Board files for Objective 2 simulations.

File name	**Grade mix**	**Boards**	**Board feet**
2a21	*2A*	165	887
2a22	*2A*	167	888
2a23	*2A*	164	886
3a21	*3A*	175	886
3a22	*3A*	177	882
3a23	*3A*	177	887
2a3a21	*2A/3A* *	175	895
2a3a22	*2A/3A* *	178	902
2a3a23	*2A/3A* *	174	888

* 50 percent No. 2A Common, 50 percent No. 3A Common

Cutting Bill Modification

Before any simulations were conducted the required part quantities for the cutting bills had to be modified. For ROMI-RIP, the two best cutting bills based on part yield and sawing efficiency from Objective 1 were Cutting Bills *C* and *E*. For ROMI-CROSS, the two best cutting bills were *A* and *E*. The required part quantities for each cutting bill had to be modified for each of the grade mixes so that all of the part requirements could be met and at least 150 boards would be used in the simulations. Table 3-3 summarizes the part quantity requirement modifications that had to be made for each of the cutting bills.

Table 3-3. Summary of part requirement modifications made to cutting bills.

ROMI-RIP		
Cutting bill	**Grade/mix**	**Modification**
C2	No. 2A	Original part requirements reduced by 18%
C3	No. 3A	Original part requirements reduced by 40%
C2/3	50/50*	Original part requirements reduced by 27%
E2	No. 2A	Target width = 19, Drop widths = 38
E3	No. 3A	Target width = 13, Drop widths = 26
E2/3	50/50*	Target width = 16, Drop widths = 32
ROMI-CROSS		
Cutting bill	**Grade/mix**	**Modification**
A2	No. 2A	Original part requirements reduced by 35%
A3	No. 3A	Original part requirements reduced by 50%
A2/3	50/50*	Original part requirements reduced by 39%
E2	No. 2A	Target width = 18, Drop widths = 36
E3	No. 3A	Target width = 12, Drop widths = 24
E2/3	50/50*	Target width = 15, Drop widths = 30

* 50/50 mix of No. 2A Common and No. 3A Common

Simulations

ROMI-RIP and ROMI-CROSS simulations were conducted with the two best cutting bills from Objective 1. Each of the cutting bills was processed through nine simulations, three replications for each of the three grade mixes. This resulted in 18 simulations for ROMI-RIP and 18 simulations for ROMI-CROSS. The same simulation parameters for Objective 1, shown in Tables 2-4 and 2-5 (Chapter 2), were held constant through all the simulations in Objective 2.

Results and Discussion

Tables 3-4 and 3-5 summarize the results of the simulations. A complete list of all the results can be found in Tables 3-E and 3-F in Appendix 3. SPSS© was used to conduct ANOVA ($\alpha = 0.05$) and Tukey's HSD ($\alpha = 0.05$) on the rip-first and crosscut-first simulation results. Since all boards with more then 0.25 inch of crook were removed form the board files used in these simulations, the rip-first yields obtained while processing No. 3A Common in this objective were a little higher then those obtained in Objective 1. Crook has much less, if any, impact on crosscut-first operation as indicated by the part yield results for the ROMI-CROSS simulations in this objective which are the same as those from Objective 1.. For the ROMI-RIP simulations, null hypothesis # 1 was rejected. Tukey's HSD indicated that the part yields for Cutting Bills *C* and *E* were different for each grade mix. In more detail, for both cutting bills, the highest part yield (primary yield only) was achieved while running No. 2A Common lumber, followed by the 50/50 mix of No. 2A Common and No. 3A Common lumber and lastly the No. 3A Common lumber. The part yields were approximately 54 percent, 49 percent, and 42 percent for Cutting Bill *C* and 60 percent, 51 percent, and 40 percent for Cutting Bill *E*. For Cutting Bill *C*, there was a 5 percent average difference in part yield between the No. 2A Common grade mix and the 50/50, a 7 percent average difference in part yield between the 50/50 grade mix and the No. 3A Common grade mix, and 12 percent average difference in part yield between the No. 2A Common and No. 3A Common grade-mixes. For Cutting Bill *E*, there was a 9 percent average difference in part yield between the No. 2A Common and 50/50 grade mixes, an 11 percent average difference in part yield between the 50/50 and No. 3A Common grade mixes, and a 20 percent average difference in part yield between the No. 2A Common and No. 3A common grade mixes.

Table 3-4. Average part yields and sawing efficiencies for the rip-first grade mix simulations.

ROMI-RIP			
Cutting bill	**Grade mix**	**Average yield**	**Average sawing efficiency**
C3	No. 3A	42.19	7.83
C2	No. 2A	54.27	6.55
C23	50/50*	48.58	7.06
E3	No. 3A	40.17	6.14
E2	No. 2A	59.87	4.97
E23	50/50*	50.99	5.42

* 50/50 grade mix of No. 2A and No. 3A

Table 3-5. Average part yield and sawing efficiencies for the crosscut-first grade mix simulations.

ROMI-CROSS			
Cutting bill	**Grade mix**	**Average yield**	**Average sawing efficiency**
A3	No. 3A	31.39	7.68
A2	No. 2A	46.04	6.78
A23	50/50*	39.11	6.97
E3	No. 3A	36.84	6.53
E2	No. 2A	54.71	5.63
E23	50/50*	46.83	6.01

* 50/50 Grade mix of No. 2A and No. 3A

In regards to the sawing efficiency of the rip-first simulations, null hypothesis # 2 was rejected. Tukey's HSD multiple comparison test indicated that the sawing efficiencies were different for all three grade mixes for both Cutting Bills *C* and *E*. Similar to the part yields, for both Cutting Bills *C* and *E*, the best sawing efficiency was experienced while running No. 2A Common lumber, followed by the 50/50 mix of No. 2A Common and No. 3A Common and the No. 3A Common lumber. For Cutting Bill *C* an average of approximately 5, 5.5, and 6 saw lines were required, respectively, per board foot of parts produced. Put in ratio format, the sawing productivity for Cutting Bill *C* for 2A Common versus 50/50 No. 2A – No. 3A Common versus No. 3A Common is 1:1.1:1.2. The 50/50 No. 2A – No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the 50/50 No. 2A – No. 3A Common grade mix. For Cutting Bill *E* an average of approximately 6.5, 7, and 8 sawlines were required, respectively, per board foot of parts produced. Again, put in ratio format, the sawing productivity for Cutting Bill *E* for No. 2A Common versus 50/50 No. 2A – No. 3A Common versus No.3A Common is 1:1.1:1.2. The 50/50 No. 2A – No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 1 additional sawline per board foot of parts produced compared to the 50/50 No. 2A – No. 3A Common grade mix.

For the ROMI-CROSS simulations, null hypothesis # 1 was rejected. Tukey's HSD ($\alpha = 0.05$) multi-comparison test indicated that the part yields for each grade mix were different for Cutting Bills A and E. Similar to the ROMI-RIP results, for both cutting bills, the highest part yield was achieved while running the No. 2A Common grade mix, followed by the 50/50 grade mix of No. 2A Common and No. 3A Common lumber, and lastly the No. 3A Common grade mix. For Cutting Bill *A*, the part yields were approximately 46 percent, 39 percent, and 31 percent. There was a 7 percent average difference in part yield between the No. 2A Common and 50/50 grade mixes, an 8 percent average difference between the 50/50 and No. 3A Common grade mixes, and a 15 percent average difference between the No. 2A Common and No. 3A Common grade mixes. For Cutting Bill *E*, the part yields were approximately 55 percent, 47 percent, and 37 percent. There was an 8 percent difference in part yield between the No. 2A Common and 50/50 grade mixes, a 10 percent difference in part yield between the 50/50 and No. 3A Common grade mixes, and a 18 percent difference between the No. 2A Common and No. 3A Common grade mixes.

In regards to the sawing efficiency, null hypothesis # 2 was rejected. Tukey's HSD ($\alpha = 0.05$) multi-comparison test indicated that the average sawing efficiency for each grade mix was different as well. The best sawing efficiency was experienced while running the No. 2A Common grade mix, followed by the 50/50 grade mix of No. 2A Common and No. 3A Common and lastly the No. 3A Common grade mix. For Cutting Bill *A*, approximately 6.8, 7, and 7.7 saw lines were required, on average, per board feet of parts produced. Put in ratio format, the sawing productivity for Cutting Bill *A* for No. 2A Common versus 50/50 No. 2A – No. 3A Common versus No. 3A Common is 1:1:1.1. The 50/50 2A-3A Common grade mix required 0.2 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 0.7 additional sawlines per board foot of parts produced compared to the 50/50 No. 2A – No. 3A Common grade mix. For Cutting Bill *E*, approximately 5.6, 6, and 6.5 saw lines were required, on average, per board feet of parts produced. Again, put in ratio format, the sawing productivity for Cutting Bill *E* for No. 2A Common versus

50/50 No. 2A – No. 3A Common versus No. 3A Common is 1:1.1:1.2. The 50/50 No. 2A – No. 3A Common grade mix required 0 .4 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the 50/50 No. 2A – No. 3A Common grade mix.

Recall that the part quality definition for the simulations is C2F. The decrease in sawing efficiency experienced when processing No. 3A Common lumber compared to No. 2A Common is probably due to the hardwood lumber grading rules. No 2A Common lumber is only allowed 7 cuttings, at the most, to obtain its minimal clearface (50%) area while the No. 3A Common lumber is allowed and unlimited number of cuttings. It is possible for a No. 3A Common board to have a higher percentage of clear area then a No. 2A Common board. Thus, it is possible that more cuts are required to remove the clearface cutting from a No. 3A Common board then a No. 2A Common board.

In both the rip-first and the crosscut-first simulations, the majority of the sawlines were made at the second cutup stage for all three grade mixes. This was the crosscut stage in the rip-first simulations and the ripping stage in the crosscut-first simulations. The second cutup stage is also where the majority of the differences in the total number of sawlines required between grade mixes occurred. As a result, differences in sawing efficiencies were mainly due to differences in the number of sawlines made at the second cutup stage. The number of cuts required for both cutting stages in each simulation as well as the total number of cuts required per simulation are shown in Tables 3-E and 3-F in the Appendix.

The crosscut-first sawing efficiency results of this research do not differ between grades as much as those experienced in the simulation experiments conducted by Steele et al. (1999). In that research, three cutting bills of different difficulties, in terms of fulfilling the part requirements, were evaluated. The sawing productivity for the three cutting bills for No. 2A Common lumber versus the No. 3A Common lumber was 1:1.4, 1:1.9, and 1.5.

Based on the primary part yield results produced by this research, the raw material cost to produce 1000 board feet of parts from No. 3A Common lumber was compared to the raw material cost to produce 1000 board feet of parts from No. 2A Common lumber for each cutting bill. The price assigned to No. 3A Common lumber was $485 MBF and the price assigned to No. 2A Common lumber was $545 MBF, based on Appalachian Hardwoods prices from November 17, 2003 (Hardwood Market Report 2002). For both rip-first cutting bills and both crosscut-first cutting bills the cost of producing 1000 MBF of parts was less expensive when processing the No. 2A Common lumber. For rip-first Cutting Bills C and E, the cost to produce 1000 board feet of parts was $146.65 and $276.30 less when processing No. 2A Common lumber compared to No. 3A Common lumber. Likewise, for crosscut-first Cutting Bills A and E, the cost associated with processing the No. 2A Common lumber was $359.65 and $321.85 less compared to the cost when processing the No. 3A Common lumber.

Based on the part yield results of this study and current market prices, No. 3A Common lumber is not a cost effective raw material alternative compared to No. 2A Common lumber. However, for cutting bills with smaller differences between their No. 2A Common part yield and their No. 3A Common part yield, using No. 3A Common lumber as a raw material can reduce cost. Also, as the price difference between No. 2A Common lumber and No. 3A Common increases, No. 3A Common lumber becomes a more viable raw material, especially in rip-first operations. For Cutting Bill C, as the price difference between No. 2A Common and No.3A Common lumber approaches $130 dollars, No.3A Common becomes a more viable raw material. For Cutting Bill E, the same occurs as the price difference between No. 2A Common and No. 3A Common approaches $230.

Based on Appalachian area red oak prices, No. 2A Common lumber is a less expensive raw material alternative compared to No. 3A Common lumber. However, for Northern area red oak prices, there is a $245 price difference between No. 2A Common and No. 3A Common (Hardwood Market Report 2002). Based on these prices and Objective 2 part yields, No. 3A Common lumber is a less expensive raw material alternative compared to No. 2A Common lumber. Furthermore, the same NHLA grade rules apply to all hardwood lumber manufactured in the U.S.. Thus the same part yield results experienced processing No. 3A Common red oak can be expected when processing No. 3A Common white oak, maple, cherry, and other species. Red oak is a popular strip flooring species and thus the No. 3A Common price is higher relative to No. 2A Common compared to some other species. Price differences between No. 2A Common lumber and No. 3A Common lumber for some of these species is much greater then for red oak. As a result, based on the results of the simulations conducted to address Objective 2, No. 3A Common lumber may be a less expensive raw material to process compared to No. 2A Common lumber for some of these species such as cherry and maple.

Conclusion

In both ROMI-RIP and ROMI-CROSS simulations, part yield decreased significantly as the amount of No. 3A Common lumber in the grade mix increased. Similarly, the sawing efficiency decreased significantly as well. In the ROMI-RIP simulations, Cutting Bill *E* produced higher part yields than *C* for all grade mixes except the No. 3A Common lumber grade mix. Cutting Bills *E* and *C's* part yields were the same when running the No. 3A Common grade mix. Cutting Bill *E* exhibited better sawing efficiency then Cutting Bill *C* while running all three grade mixes.

In the ROMI-CROSS simulations, Cutting Bill *E* produced higher part yields than *C* while running all three grade mixes. In addition, higher sawing efficiencies were measured for each of the three grade mixes when processing Cutting Bill *E*.

When working with grade mixes composed of both No. 2A Common and No. 3A Common lumber, lower part yields should be expected as the percentage of the grade mix composed of No. 3A Common lumber increases. Likewise, more wear and tear on machinery should be expected, as the number of saw lines required per board foot of parts produced will increase.

It would benefit a rough mill manager to know what the part yield of his/her operation is when processing No. 3A Common lumber. This would help him/her to make sound decisions concerning what grade lumber to process and could help to reduce raw material cost given appropriate market prices. Whether or not No. 3A Common lumber is a less expensive raw material compared to No. 2A Common lumber is dependent of the region in which the lumber is purchased, the part yield difference between No. 2A Common and No. 3A Common lumber for the mill in question, and the difference between the prices for No. 2A Common and No. 3A Common. If these conditions are appropriate and it becomes less expensive to manufacture an end product with No. 3A Common lumber compared to No. 2A Common lumber, the cost difference can be used to address costs associated with added wear and tear on machinery and longer processing times that are associated with processing lower grade lumber.

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Appendix 3

Legend for Table 3-A,3-B, 3-C, and 3-D :

g2f1 = Grade 2A, File 1**, g2f2 =** Grade 2A, File 2**, g2f3 =** Grade 2A, File 3
g3f1 = Grade 3A, File 1**, g3f2 =** Grade 3A, File 2, **g3f3 =** Grade 3A, File 3
g2/3f1 = Grade 2A/3A, File 1**, g2/3f2** = Grade 2A/3A, File 2**, g2/3f3 =** Grade 2A/3A, File 3

Table 3-A. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on board length in the grade-mix files for Objective 2.

Board files	**Number of boards**	**Mean length**	**Standard deviation**	**Standard error**	**95% Confidence interval for mean**		**Minimum length**	**Maximum length**
					Lower bound	**Upper bound**		
= g2f2	167	10.32	2.79	.216	9.90	10.75	6.04	16.13
= g2f3	164	10.34	2.74	.214	9.92	10.77	6.00	16.13
=g2f1	165	10.44	2.94	.229	9.98	10.89	6.04	16.13
= g3f1	175	9.96	2.70	.204	9.56	10.37	6.00	16.19
=g3f2	176	9.80	2.72	.205	9.39	10.20	6.00	16.19
=g3f3	177	9.90	2.75	.207	9.49	10.31	6.00	16.19
=g2/3f1	182	9.46	2.47	.183	9.10	9.83	6.00	16.15
=g2/3f2	178	9.77	2.75	.206	9.37	10.18	6.00	16.15
=g2/3f3	174	9.86	2.72	.206	9.45	10.27	6.04	16.13
Total	1558	9.97	2.74	.069	9.84	10.11	6.00	16.19

ANOVA results for lumber length.

	Sum of squares	**df**	**Mean square**	**F**	**Sig.**
Between groups	141.15	8	17.64	2.36	.02
Within groups	11602.57	1549	7.49		
Total	11743.73	1557			

Tukey HSD results on lumber length.

		Mean difference (I-J)	Standard error	Sig.	95% Confidence interval	
(I) FILE	**(J) FILE**				**Lower bound**	**Upper bound**
= g2f2	**= g2f3**	-0.01	0.30	1.00	-0.95	0.92
	=g2f1	-0.11	0.30	1.00	-1.05	0.82
	= g3f1	0.35	0.30	0.95	-0.56	1.28
	=g3f2	0.52	0.30	0.69	-0.39	1.45
	=g3f3	0.42	0.30	0.89	-0.50	1.34
	=g2/3f1	0.85	0.29	0.08	-0.05	1.77
	=g2/3f2	0.55	0.29	0.63	-0.36	1.47
	=g2/3f3	0.46	0.30	0.83	-0.46	1.38
= g2f3	**= g2f2**	0.01	0.30	1.00	-0.92	0.95
	=g2f1	-0.09	0.30	1.00	-1.03	0.84
	= g3f1	0.37	0.30	0.94	-0.55	1.30
	=g3f2	0.54	0.30	0.66	-0.38	1.47
	=g3f3	0.43	0.30	0.87	-0.48	1.36
	=g2/3f1	0.87	0.29	0.07	-0.04	1.79
	=g2/3f2	0.56	0.30	0.60	-0.35	1.49
	=g2/3f3	0.47	0.30	0.80	-0.45	1.40
=g2f1	**= g2f2**	0.11	0.30	1.00	-0.82	1.05
	= g2f3	0.09	0.30	1.00	-0.84	1.03
	= g3f1	0.47	0.30	0.81	-0.45	1.39
	=g3f2	0.64	0.30	0.43	-0.28	1.56
	=g3f3	0.53	0.30	0.68	-0.39	1.45
	=g2/3f1	.97*	0.29	0.03	0.06	1.89
	=g2/3f2	0.60	0.30	0.38	-0.25	1.58
	=g2/3f3	0.57	0.30	0.59	-0.35	1.50
= g3f1	**= g2f2**	-0.39	0.30	0.95	-1.28	0.56
	= g2f3	-0.38	0.30	0.94	-1.30	0.55
	=g2f1	-0.47	0.30	0.81	-1.39	0.45
	=g3f2	0.16	0.29	1.00	-0.74	1.08
	=g3f3	0.06	0.29	1.00	-0.84	0.97
	=g2/3f1	0.49	0.29	0.73	-0.40	1.40
	=g2/3f2	0.19	0.29	1.00	-0.71	1.10
	=g2/3f3	0.10	0.29	1.00	-0.81	1.01
=g3f2	**= g2f2**	-0.52	0.30	0.69	-1.45	0.39
	= g2f3	-0.54	0.30	0.66	-1.47	0.38
	=g2f1	-0.64	0.30	0.43	-1.56	0.28
	= g3f1	-0.16	0.29	1.00	-1.08	0.74
	=g3f3	-0.10	0.29	1.00	-1.01	0.80
	=g2/3f1	0.33	0.29	0.97	-0.57	1.23
	=g2/3f2	0.02	0.29	1.00	-0.88	0.93
	=g2/3f3	-0.06	0.29	1.00	-0.98	0.84
=g3f3	**= g2f2**	-0.42	0.30	0.89	-1.34	0.50
	= g2f3	-0.43	0.30	0.87	-1.36	0.48

Continued form previous page						
		Mean difference (I-J)	Standard error	Sig.	95% Confidence interval	
I) FILE	(J) FILE				Lower bound	Upper bound
	=g2f1	-0.53	0.30	0.68	-1.45	0.39
	= g3f1	-0.06	0.29	1.00	-0.97	0.84
	=g3f2	0.10	0.29	1.00	-0.80	1.01
	=g2/3f1	0.43	0.29	0.85	-0.46	1.34
	=g2/3f2	0.13	0.29	1.00	-0.77	1.03
	=g2/3f3	0.03	0.29	1.00	-0.87	0.95
=g2/3f1	= g2f2	-0.85	0.29	0.08	-1.77	0.05
	= g2f3	-0.87	0.29	0.07	-1.79	0.04
	=g2f1	-.97*	0.29	0.03	-1.89	-0.06
	= g3f1	-0.49	0.29	0.73	-1.40	0.40
	=g3f2	-0.33	0.29	0.97	-1.23	0.57
	=g3f3	-0.43	0.29	0.85	-1.34	0.46
	=g2/3f2	-0.30	0.29	0.98	-1.20	0.59
	=g2/3f3	-0.39	0.29	0.91	-1.30	0.50
=g2/3f2	= g2f2	-0.55	0.29	0.63	-1.47	0.36
	= g2f3	-0.56	0.30	0.60	-1.49	0.35
	=g2f1	-0.66	0.30	0.38	-1.58	0.25
	= g3f1	-0.19	0.29	1.00	-1.10	0.71
	=g3f2	-0.02	0.29	1.00	-0.93	0.88
	=g3f3	-0.13	0.29	1.00	-1.03	0.77
	=g2/3f1	0.30	0.29	0.98	-0.59	1.20
	=g2/3f3	-0.09	0.29	1.00	-1.00	0.82
=g2/3f3	= g2f2	-0.46	0.30	0.83	-1.38	0.46
	= g2f3	-0.47	0.30	0.80	-1.40	0.45
	=g2f1	-0.57	0.30	0.59	-1.50	0.35
	= g3f1	-0.10	0.29	1.00	-1.01	0.81
	=g3f2	0.06	0.29	1.00	-0.84	0.98
	=g3f3	-0.03	0.29	1.00	-0.95	0.87
	=g2/3f1	0.39	0.29	0.91	-0.50	1.30
	=g2/3f2	0.09	0.29	1.00	-0.82	1.00

* The mean difference is significant at the .05 level.

Homogeneous subset results of Tukey's HSD [a,b] on lumber length.

Board file	Number of boards	Subset for alpha = .05	
		1	2
=g2/3f1	182	9.47	
=g2/3f2	178	9.78	9.78
=g3f2	176	9.80	9.80
=g2/3f3	174	9.87	9.87
=g3f3	177	9.91	9.91
= g3f1	175	9.97	9.97
= g2f2	167	10.33	10.33
= g2f3	164	10.35	10.35
=g2f1	165		10.44
Sig.		.072	.37

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 172.905.

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Table 3-B. Summary of descriptive statistics and ANOVA conducted on the width of boards in new grade-mix files for Objective 2.

Board files	Number of boards	Mean width	Standard deviation	Standard error	95% Confidence interval for mean		Minimum width	Maximum width
					Lower bound	Upper bound		
= g2f2	167	6.20	1.78	0.14	5.93	6.47	3.50	13.00
=g2f3	164	6.23	1.79	0.14	5.96	6.51	3.50	13.00
=g2f1	165	6.20	1.84	0.14	5.92	6.48	3.50	13.00
=g3f1	175	6.19	1.72	0.13	5.93	6.45	3.50	13.75
=g3f2	176	6.20	1.71	0.13	5.95	6.46	3.50	13.75
=g3f3	177	6.15	1.72	0.13	5.90	6.41	3.50	13.75
=g2/3f1	174	6.28	1.96	0.15	5.98	6.57	3.50	13.75
=g2/3f2	178	6.29	1.99	0.15	5.99	6.58	3.50	13.75
=g2/3f3	174	6.26	1.98	0.15	5.96	6.55	3.50	13.75
Total	1550	6.22	1.83	0.05	6.13	6.31	3.50	13.75

ANOVA results on lumber width.

	Sum of squares	df	Mean square	F	Sig.
Between groups	2.77	8	.347	.10	.99
Within groups	5197.51	1541	3.37		
Total	5200.28	1549			

Table 3-C. Summary of descriptive statistics and 2nd ANOVA conducted on length of boards in new grade-mix files for Objective 2.

Board files	Number of boards	Mean length	Standard deviation	Standard error	95% Confidence interval for mean		Minimum length	Maximum length
					Lower bound	Upper bound		
=g2f2	167	10.33	2.80	0.22	9.90	10.76	6.04	16.13
=g2f3	164	10.35	2.75	0.21	9.92	10.77	6.00	16.13
=g2f1	165	10.44	2.94	0.23	9.99	10.89	6.04	16.13
=g3f1	175	9.97	2.71	0.20	9.56	10.37	6.00	16.19
=g3f2	176	9.80	2.73	0.21	9.39	10.21	6.00	16.19
=g3f3	177	9.91	2.76	0.21	9.50	10.32	6.00	16.19
=g2/3f1	174	9.92	2.66	0.20	9.52	10.32	6.00	17.73
=g2/3f2	178	9.78	2.75	0.21	9.37	10.18	6.00	16.15
=g2/3f3	174	9.87	2.73	0.21	9.46	10.28	6.04	16.13
Total	1550	10.03	2.76	0.07	9.90	10.17	6.00	17.73

ANOVA results on lumber length.

	Sum of squares	df	Mean square	F	Sig.
Between groups	90.00	8	11.25	1.48	.16
Within groups	11718.08	1541	7.60		
Total	11808.09	1549			

Table 3-D. Summary of descriptive statistics and 2nd ANOVA conducted on width of boards in new grade-mix files for Objective 2.

Board files	Number of boards	Mean width	Standard deviation	Standard error	95% Confidence interval for mean		Minimum width	Maximum width
					Lower bound	Upper bound		
= g2f2	167	6.20	1.78	0.14	5.93	6.47	3.50	13.00
=g2f3	164	6.23	1.79	0.14	5.96	6.51	3.50	13.00
=g2f1	165	6.20	1.84	0.14	5.92	6.48	3.50	13.00
=g3f1	175	6.19	1.72	0.13	5.93	6.45	3.50	13.75
=g3f2	176	6.20	1.71	0.13	5.95	6.46	3.50	13.75
=g3f3	177	6.15	1.72	0.13	5.90	6.41	3.50	13.75
=g2/3f1	174	6.28	1.96	0.15	5.98	6.57	3.50	13.75
=g2/3f2	178	6.29	1.99	0.15	5.99	6.58	3.50	13.75
=g2/3f3	174	6.26	1.98	0.15	5.96	6.55	3.50	13.75

ANOVA results for lumber width.

	Sum of squares	df	Mean square	F	Sig.
Between groups	2.77	8	.35	.10	.99
Within groups	5197.51	1541	3.38		
Total	5200.29	1549			

Table 3-E. Summary of the ROMI-RIP results for the grade-mix simulations in Objective 2.

Cutting bill	Grade mix	Boards	Board feet	Parts (Bdft)	Part yield	Rip count	X-Cut count	Total cuts	Sawing efficiency*
C	3A	156	796.80	340.14	42.69	711	1936	2647	7.78
C	3A	167	825.20	340.06	41.21	759	1950	2709	7.97
C	3A	158	795.40	339.34	42.66	711	1912	2623	7.73
C2	2A	161	864.20	471.48	54.56	710	2358	3068	6.51
C2	2A	164	867.90	466.61	53.76	735	2346	3081	6.60
C2	2A	160	853.90	465.31	54.50	713	2334	3047	6.55
C23	2A/3A	169	861.40	417.56	48.47	756	2168	2924	7.00
C23	2A/3A	169	861.90	420.60	48.80	762	2215	2977	7.08
C23	2A/3A	169	865.60	419.52	48.47	758	2231	2989	7.12
E	3A	161	817.80	336.19	41.11	721	1313	2034	6.05
E	3A	175	864.60	335.73	38.83	783	1321	2104	6.27
E	3A	164	827.80	335.81	40.57	733	1316	2049	6.10
E2	2A	160	858.10	506.81	59.07	710	1792	2502	4.94
E2	2A	160	848.70	506.72	59.70	710	1803	2513	4.96
E2	2A	156	834.00	507.36	60.83	697	1839	2536	5.00
E23	2A/3A	165	846.80	422.34	49.87	742	1557	2299	5.44
E23	2A/3A	160	816.30	421.78	51.67	715	1578	2293	5.44
E23	2A/3A	161	822.10	422.79	51.43	717	1558	2275	5.38

* Total cuts/ Parts (Bdft.)

Table 3-F. Summary of the ROMI-CROSS results for the grade-mix simulations in Objective 2.

Cutting bill	Grade mix	Boards	Board feet	Parts (Bdft)	Part yield	Rip count	X-Cut count	Total cuts	Sawing efficiency*
A	3A	168	855.20	273.68	32.00	1213	882	2095	7.65
A	3A	176	877.20	272.25	31.03	1206	890	2096	7.70
A	3A	176	882.80	274.89	31.14	1223	895	2118	7.70
A2	2A	160	859.80	387.05	45.02	1644	983	2627	6.79
A2	2A	157	839.80	388.55	46.27	1645	985	2630	6.77
A2	2A	154	824.10	385.98	46.84	1634	982	2616	6.78
A23	2A/3A	171	878.40	339.03	38.60	1443	908	2351	6.93
A23	2A/3A	168	858.90	337.91	39.34	1457	917	2374	7.03
A23	2A/3A	168	858.70	338.23	39.39	1441	910	2351	6.95
E	3A	165	842.40	313.77	37.24	1185	874	2059	6.56
E	3A	173	857.10	312.62	36.47	1178	871	2049	6.55
E	3A	169	852.30	313.62	36.80	1174	862	2036	6.49
E2	2A	164	882.50	476.82	54.03	1662	1017	2679	5.62
E2	2A	165	875.80	479.37	54.74	1674	1035	2709	5.65
E2	2A	160	855.60	473.76	55.37	1666	1002	2668	5.63
E23	2A/3A	168	860.30	397.80	46.24	1428	958	2386	6.00
E23	2A/3A	164	838.10	398.25	47.52	1437	952	2389	6.00
E23	2A/3A	166	846.50	395.48	46.72	1436	948	2384	6.03

* Total cuts/ Parts (Bdft.)

Table 3-G. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP part yields for Objective 2.

Cutting bill	Number of simulations	Mean part yield	Standard deviation	Standard error	95% Confidence interval for mean		Minimum part yield	Maximum part yield
					Lower bound	Upper bound		
=C	3	42.19	.85	.49	40.09	44.29	41.21	42.69
= C2	3	54.27	.45	.26	53.17	55.38	53.76	54.56
= C23	3	48.58	.19	.11	48.11	49.05	48.47	48.80
=E	3	40.17	1.19	.69	37.21	43.13	38.83	41.11
= E2	3	59.87	.89	.51	57.65	62.08	59.07	60.83
=E23	3	50.99	.98	.56	48.56	53.42	49.87	51.67
Total	18	49.34	6.98	1.65	45.87	52.82	38.83	60.83

ANOVA results on part yield.

	Sum of squares	df	Mean square	F	Sig.
Between groups	821.12	5	164.23	239.13	<0.01
Within groups	8.241	12	.69		
Total	829.36	17			

Tukey's HSD results on part yield.

		Mean difference (I-J)	Standard error	Sig.	95% Confidence interval	
(I) BILL	**(J) BILL**				**Lower bound**	**Upper bound**
=C	**= C2**	-12.09*	0.68	<0.01	-14.36	-9.81
	= C23	-6.39*	0.68	<0.01	-8.67	-4.12
	=E	2.02	0.68	0.09	-0.26	4.29
	= E2	-17.68*	0.68	<0.01	-19.95	-15.41
	=E23	-8.80 *	0.68	<0.01	-11.08	-6.53
= C2	**=C**	12.09*	0.68	<0.01	9.81	14.36
	= C23	5.69*	0.68	<0.01	3.42	7.97
	=E	14.10*	0.68	<0.01	11.83	16.38
	= E2	-5.59*	0.68	<0.01	-7.87	-3.32
	=E23	3.28*	0.68	<0.01	1.01	5.56
= C23	**=C**	6.39*	0.68	<0.01	4.12	8.67
	= C2	-5.69*	0.68	<0.01	-7.97	-3.42
	=E	8.41*	0.68	<0.01	6.14	10.68
	= E2	-11.28*	0.68	<0.01	-13.56	-9.01
	=E23	-2.41*	0.68	0.04	-4.68	-0.14
=E	**=C**	-2.01	0.68	0.09	-4.29	0.26
	= C2	-14.10*	0.68	<0.01	-16.38	-11.83
	= C23	-8.41*	0.68	<0.01	-10.68	-6.14
	= E2	-19.69*	0.68	<0.01	-21.97	-17.42
	=E23	-10.82*	0.68	<0.01	-13.09	-8.55
= E2	**=C**	17.68*	0.68	<0.01	15.41	19.95
	= C2	5.59*	0.68	<0.01	3.32	7.87
	= C23	11.29*	0.68	<0.01	9.01	13.56
	=E	19.70*	0.68	<0.01	17.42	21.97
	=E23	8.88*	0.68	<0.01	6.60	11.15
=E23	**=C**	8.80*	0.68	<0.01	6.53	11.08
	= C2	-3.28*	0.68	<0.01	-5.56	-1.01
	= C23	2.41*	0.68	0.04	0.14	4.68
	=E	10.82*	0.68	<0.01	8.55	13.09
	= E2	-8.88*	0.68	<0.01	-11.15	-6.60

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey's HSD[a] conducted on part yields.

Cutting bill	Number of part yields	Subset for alpha = .05				
		1	**2**	**3**	**4**	**5**
=E	3	40.17				
=C	3	42.19				
= C23	3		48.58			
=E23	3			50.99		
= C2	3				54.27	
= E2	3					59.87
Sig.		.093	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
a Uses Harmonic Mean Sample Size = 3.000.

Table 3-H. Summary descriptive statistics,ANOVA, and Tukey's HSD conducted on ROMI-RIP sawing efficiency results for Objective 2.

Cutting bill	Number of simulations	Mean sawing efficiency	Standard deviation	Standard error	95% Confidence interval for mean		Minimum sawing efficiency	Maximum sawing efficiency
					Lower bound	Upper bound		
= C	3	7.83	.13	.07	7.51	8.14	7.73	7.97
= C2	3	6.55	.05	.03	6.44	6.67	6.51	6.60
= C23	3	7.07	.06	.04	6.91	7.22	7.00	7.12
= E	3	6.14	.12	.07	5.85	6.43	6.05	6.27
= E2	3	4.97	.03	.02	4.89	5.04	4.94	5.00
= E23	3	5.42,	.03	.02	5.33	5.51	5.38	5.44
Total	18	6.33	.99	.23	5.83	6.82	4.94	7.97

ANOVA results for sawing efficiency.

	Sum of squares	df	Mean square	F	Sig.
Between groups	16.67	5	3.33	537.14	<0.01
Within groups	.07	12	.006		
Total	16.74	17			

Tukey HSD results for sawing efficiency.

		Mean difference (I-J)	Standard error	Sig.	95% Confidence interval	
(I) CUTBILL	**(J) CUTBILL**				**Lower bound**	**Upper bound**
= C	**= C2**	1.27*	0.06	<0.01	1.06	1.49
	= C23	.76*	0.06	<0.01	0.54	0.98
	= E	1.68*	0.06	<0.01	1.47	1.90
	= E2	2.86*	0.06	<0.01	2.64	3.08
	= E23	2.40*	0.06	<0.01	2.19	2.62
= C2	**= C**	-1.27*	0.06	<0.01	-1.49	-1.06
	= C23	-.51*	0.06	<0.01	-0.73	-0.30
	= E	.41*	0.06	<0.01	0.20	0.63
	= E2	1.59*	0.06	<0.01	1.37	1.80
	= E23	1.13*	0.06	<0.01	0.92	1.35
= C23	**= C**	-.76*	0.06	<0.01	-0.98	-0.54
	= C2	.51*	0.06	<0.01	0.30	0.73
	= E	.92*	0.06	<0.01	0.71	1.14
	= E2	2.10*	0.06	<0.01	1.88	2.32
	= E23	1.65*	0.06	<0.01	1.43	1.86
= E	**= C**	-1.69*	0.06	<0.01	-1.90	-1.47
	= C2	-.41*	0.06	<0.01	-0.63	-0.20
	= C23	-.93*	0.06	<0.01	-1.14	-0.71
	= E2	1.17*	0.06	<0.01	0.96	1.39
	= E23	.72*	0.06	<0.01	0.50	0.94
= E2	**= C**	-2.86*	0.06	<0.01	-3.08	-2.64
	= C2	-1.59*	0.06	<0.01	-1.80	-1.37
	= C23	-2.10*	0.06	<0.01	-2.32	-1.88
	= E	-1.17*	0.06	<0.01	-1.39	-0.96
	= E23	-.45*	0.06	<0.01	-0.67	-0.24
= E23	**= C**	-2.41*	0.06	<0.01	-2.62	-2.19
	= C2	-1.13*	0.06	<0.01	-1.35	-0.92
	= C23	-1.65*	0.06	<0.01	-1.86	-1.43
	= E	-.72*	0.06	<0.01	-0.94	-0.50
	= E2	.45*	0.06	<0.01	0.24	0.67

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey's HSD[a] sawing efficiencies.

Cutting bill	Number of simulations	Subset for alpha = .05					
		1	**2**	**3**	**4**	**5**	**6**
= E2	3	4.97					
= E23	3		5.42				
= E	3			6.14			
= C2	3				6.55		
= C23	3					7.07	
= C	3						7.83
Sig.		1.00	1.00	1.00	1.00	1.00	1.00

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 3.000.

Table 3-I. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-CROSS part yield results for Objective 2.

Cutting bills	Number of simulations	Mean part yield	Standard deviation	Standard error	95% Confidence interval for mean		Minimum part yield	Maximum part yield
					Lower bound	Upper bound		
=A	3	31.39	0.53	0.31	30.07	32.71	31.03	32.00
=A2	3	46.04	0.93	0.54	43.73	48.36	45.02	46.84
=A23	3	39.11	0.44	0.26	38.01	40.21	38.60	39.39
=E	3	36.84	0.39	0.22	35.88	37.80	36.47	37.24
=E2	3	54.71	0.67	0.39	53.05	56.38	54.03	55.37
=E23	3	46.83	0.65	0.37	45.22	48.43	46.24	47.52
Total	18	42.49	7.85	1.85	38.58	46.39	31.03	55.37

ANOVA results for part yield.

	Sum of squares	df	Mean gquare	F	Sig.
Between groups	1042.31	5	208.46	529.71	<0.01
Within groups	4.72	12	.39		
Total	1047.03	17			

Tukey's HSD results for part yield.

		Mean difference (I-J)	**Standard error**	**Sig.**	**95% Confidence interval**	
(I) CUTBILL	**(J) CUTBILL**				**Lower bound**	**Upper bound**
=A	**=A2**	-14.65*	0.51	<0.01	-16.37	-12.93
	=A23	-7.72*	0.51	<0.01	-9.44	-6.00
	=E	-5.45*	0.51	<0.01	-7.17	-3.73
	=E2	-23.32*	0.51	<0.01	-25.04	-21.60
	=E23	-15.43*	0.51	<0.01	-17.16	-13.72
=A2	**=A**	14.65*	0.51	<0.01	12.93	16.37
	=A23	6.93*	0.51	<0.01	5.21	8.65
	=E	9.21*	0.51	<0.01	7.49	10.93
	=E2	-8.67*	0.51	<0.01	-10.39	-6.95
	=E23	-.78	0.51	0.65	-2.50	0.94
=A23	**=A**	7.72*	0.51	<0.01	6.00	9.44
	=A2	-6.93*	0.51	<0.01	-8.65	-5.21
	=E	2.27*	0.51	0.01	0.55	3.99
	=E2	-15.60*	0.51	<0.01	-17.32	-13.88
	=E23	-7.72*	0.51	<0.01	-9.44	-6.00
=E	**=A**	5.45*	0.51	<0.01	3.73	7.17
	=A2	-9.21*	0.51	<0.01	-10.93	-7.49
	=A23	-2.27*	0.51	0.01	-3.99	-0.55
	=E2	-17.88*	0.51	<0.01	-19.60	-16.16
	=E23	-9.99*	0.51	<0.01	-11.71	-8.27
=E2	**=A**	23.32*	0.51	<0.01	21.60	25.04
	=A2	8.67*	0.51	<0.01	6.95	10.39
	=A23	15.60*	0.51	<0.01	13.88	17.32
	=E	17.88*	0.51	<0.01	16.16	19.60
	=E23	7.88*	0.51	<0.01	6.17	9.61
=E23	**=A**	15.44*	0.51	<0.01	13.72	17.16
	=A2	.78	0.51	0.65	-0.94	2.50
	=A23	7.72*	0.51	<0.01	6.00	9.44
	=E	9.99*	0.51	<0.01	8.27	11.71
	=E2	-7.89*	0.51	<0.01	-9.61	-6.17

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey's HSD[a] conducted on part yield.

Cutting bill	**Number of simulations**	**Subset for alpha = .05**				
		1	**2**	**3**	**4**	**5**
=A	3	31.39				
=E	3		36.83			
=A23	3			39.11		
=A2	3				46.04	
=E23	3				46.83	
=E2	3					54.71
Sig.		1.000	1.000	1.000	.654	1.000

Means for groups in homogeneous subsets are displayed.

a Uses Harmonic Mean Sample Size = 3.000.

Table 3-J. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-CROSS sawing efficiency results for Objective 2.

Cutting bills	Number of simulations	Mean sawing efficiency	Standard deviation	Standard error	95% Confidence interval for mean		Minimum sawing efficiency	Maximum sawing efficiency
					Lower bound	Upper bound		
= A	3	7.68	0.03	0.02	7.61	7.76	7.65	7.70
= A2	3	6.78	0.01	0.01	6.76	6.80	6.77	6.79
= A23	3	6.97	0.05	0.03	6.84	7.10	6.93	7.03
= E	3	6.53	0.04	0.02	6.44	6.63	6.49	6.56
= E2	3	5.63	0.02	0.01	5.60	5.67	5.62	5.65
= E23	3	6.01	0.02	0.01	5.97	6.05	6.00	6.03
Total	18	6.60	0.68	0.16	6.26	6.94	5.62	7.70

ANOVA results for sawing efficiency.

	Sum of squares	df	Mean square	F	Sig.
Between groups	7.89	5	1.58	1660.98	<0.01
Within groups	.011	12	.001		
Total	7.90	17			

Tukey's HSD results for sawing efficiency.

		Mean difference (I-J)	**Standard error**	**Sig.**	**95% Confidence interval**	
(I) CUTBILL	**(J) CUTBILL**				**Lower bound**	**Upper bound**
= A	**= A2**	.90*	0.03	<0.01	0.82	0.99
	= A23	.71*	0.03	<0.01	0.63	0.80
	= E	1.15*	0.03	<0.01	1.07	1.23
	= E2	2.05*	0.03	<0.01	1.97	2.13
	= E23	1.67*	0.03	<0.01	1.59	1.76
= A2	**= A**	-.90*	0.03	<0.01	-0.99	-0.82
	= A23	-.19*	0.03	<0.01	-0.27	-0.11
	= E	.25*	0.03	<0.01	0.16	0.33
	= E2	1.15*	0.03	<0.01	1.06	1.23
	= E23	.77*	0.03	<0.01	0.69	0.85
= A23	**= A**	-.71*	0.03	<0.01	-0.80	-0.63
	= A2	.19*	0.03	<0.01	0.11	0.27
	= E	.44*	0.03	<0.01	0.35	0.52
	= E2	1.34*	0.03	<0.01	1.25	1.42
	= E23	.96*	0.03	<0.01	0.88	1.04
= E	**= A**	-1.15*	0.03	<0.01	-1.23	-1.07
	= A2	-.25*	0.03	<0.01	-0.33	-0.16
	= A23	-.44*	0.03	<0.01	-0.52	-0.35
	= E2	.90*	0.03	<0.01	0.82	0.98
	= E23	.52*	0.03	<0.01	0.44	0.61
= E2	**= A**	-2.05*	0.03	<0.01	-2.13	-1.97
	= A2	-1.15*	0.03	<0.01	-1.23	-1.06
	= A23	-1.34*	0.03	<0.01	-1.42	-1.25
	= E	-.90*	0.03	<0.01	-0.98	-0.82
	= E23	-.38*	0.03	<0.01	-0.46	-0.29
= E23	**= A**	-1.67*	0.03	<0.01	-1.76	-1.59
	= A2	-.77*	0.03	<0.01	-0.85	-0.69
	= A23	-.96*	0.03	<0.01	-1.04	-0.88
	= E	-.52*	0.03	<0.01	-0.61	-0.44
	= E2	.38*	0.03	<0.01	0.29	0.46

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey's HSD[a] sawing efficiency results.

Cutting bill	**Number of Simulations**	**Subset for alpha = .05**					
		1	**2**	**3**	**4**	**5**	**6**
= E2	3	5.63					
= E23	3		6.01				
= E	3			6.53			
= A2	3				6.78		
= A23	3					6.97	
= A	3						7.68
Sig.		1.00	1.00	1.00	1.00	1.00	1.00

Means for groups in homogeneous subsets are displayed.

a Uses Harmonic Mean Sample Size = 3.000.

CHAPTER 4. NO. 3A COMMON LUMBER LENGTH ANALYSIS

Introduction

The majority of the hardwood lumber produced in the U.S. is between 8 and 16 feet in length. Lumber is typically purchased by even lengths within this spectrum; 8, 10, 12, 14, and 16 foot. Several studies have been conducted on the effects of lumber length on rough mill productivity, especially on short-length lumber. Wiedenbeck (1992) looked at the potential of short lumber as a raw material in the cabinet and furniture industries. This research consisted of both computer simulations and mill studies. Results indicated that yields of crosscut-first operations tend to increase as lumber length increases and rip-first yields tend to decrease as lumber length increases. It was also concluded that yield differences that resulted from lumber length were inconsistent between cutting bills.

In a 1993 technical session of the 21st Annual Hardwood Symposium, Wiedenbeck presented results of a study conducted to evaluate opportunities for short-length lumber (4-7ft.) within the furniture and cabinet industries. Several facts illustrated that short-length lumber is more valuable than the chips that are usually made from it, short-length lumber it is manageable, it is typically easy to generate, and profitable market opportunities for short lumber do exist. Wiedenbeck (1993) concluded that the benefits of using short-length lumber in the production of secondary forest products could be experienced throughout the hardwood industry. More specifically, new opportunities for timber management, sawmill productivity, and manufacturing systems would result (Wiedenbeck 1993).

Wiedenbeck and Araman (1995) looked at the productivity of processing short lumber in a rough mill. They used discrete-event system simulations to conduct investigations of short-length lumber used in the furniture and cabinet industries. The short-length lumber used in this study was between 4 and 7 feet in length. Their simulation results did not reveal any length-based processing differences in a crosscut-first rough mill and thus they concluded that high productivity could be experienced while processing short-length lumber. However, results obtained from experiments with the gang rip-first model indicated processing short lumber was less productive than processing medium (8-13 ft.) and longer (14-16 ft.) lengths of lumber (Wiedenbeck and Araman 1995).

Hamner et al. (2002) used ROMI-RIP to compare part yields when processing short (in this case defined as 7-8 ft.), medium (11-12 ft.), and long (15-16ft.) lumber lengths of the same grade mix. The grade mix consisted of 80 percent No. 1 Common, 12 percent No. 2A Common, and 8 percent FAS. Results of the study indicated that part yield increases as lumber length increases in a gang rip first rough mill. In addition, this study determined that differences in part-prioritization had minimal impacts on the part yield increases. Part yield increase in the study ranged from 2.5 to 5.8 percent per 4-foot increase in lumber length. Past research has shown that there is a relationship between lumber length and part yield. It is possible that a specific lumber length or lumber length segment will produce better part yields than others. Objective 3 will explore this possibility.

Objective 3

Compare yields for short (6-8 ft.), medium (10-12 ft.), and long-length (14-16 ft.) No. 3A Common lumber using two feasible cutting bills to determine which No. 3A Common length grouping offers a more economically feasible lumber input alternative compared to mixed lengths and No. 2A Common yields.

Research Hypothesis # 1

The part yield for at least one of the lumber lengths will be different from the others for a particular cutting bill.

Null Hypothesis # 1

The part yields experienced while processing different lumber lengths will be the same for a particular cutting bill.

Research Hypothesis # 2

The sawing efficiency for at least one of the lumber lengths will be different from the others for a particular cutting bill

Null Hypothesis # 2

The sawing efficiencies experienced while processing different lumber lengths will be the same for a particular cutting bill.

Methodology

In this objective, part yields and sawing efficiencies obtained when running three different length groups of No. 3A Common lumber were compared. The length groups were short (6-8 ft.), medium (10-12 ft.), and long (14-16 ft.). These length groups were evaluated using ROMI-RIP and ROMI-CROSS with the best two cutting bills identified in Objective 1. Cutting Bills *C* and *E* were used for ROMI-RIP and Cutting Bills *A* and *E* were used for ROMI-CROSS. In analyzing the effects of lumber length on yield and sawing efficiency, it was important that the width and crook distributions of the short, medium, and long No. 3A Common lumber files be the same. The same sequence followed in Objectives 1 and 2 was again used to conduct the simulations in Objective 3. As a result, the same arbor setups, chopsaw setups, salvage specifications, and overall processing and control options were used. Again, the part quality definition was clear two-face. The only difference in Objective 3 was the board files used.

Board Files

Three sets of board files were created: short, medium, and long length files. There were 82 boards in the short length file, 198 boards in the medium length file, and 33 boards in the long length file. All 9-foot and 13-foot boards were excluded from this objective. Since the total number of No. 3A Common boards between 14 and 16 feet in length was only 33, the short and medium length board files were modified to mirror the width and crook distributions of the boards in the long-length lumber group. This allowed the use of all the long No. 3A Common boards which were in limited supply. Thus, before using *Makefile,* the short and medium length files had to be modified. The new short and medium length board files were split in half, similar to dealing one stack of playing cards into two piles. The order of the boards in the new short and medium board files was randomized using the *Mix-master* program. This resulted in two short length files and two medium length files and ensured that every board had an equal opportunity of being selected when *Makefile* was run. These were used as the source files for *Makefile* when constructing new short and medium length files according to the width distribution of the long-length board file. Table 4-1 displays the width distribution of the long length board file.

Table 4-1. Width distribution of the long boards (14-16 ft.).

Width	Percent
3-4.75	3
5-6.75	85
7-8.75	9
9-10.75	0
11-12.75	3
13-14.75	0

Consequently, the short and medium length files lacked boards from 9 to 10.75 inches in width and boards from 14 to 14.75 inches in width. Table 4-2 contains a description of the long board population and the short and medium board population files after being modified to the width distribution of the long board in the No. 3A Common population.

Table 4-2. Length files after being modified to width distribution of long length board file.

Board file	Number of boards	Board feet
Short1 (6-8 ft.)	64	213.7
Med1 (10-12 ft.)	130	712.6
Long1 (14-16 ft.)	33	245.8

Similar to the width distribution modifications, the board populations in the short and medium lumber files were modified to mirror the crook distribution in the long length lumber file. The Short1, Med1, and Long1 files served as the source files when making crook modifications. The new short and medium-length files were constructed to have the same amount of crook in them as the long length file and the same percentage of boards with no crook (0” crook). The *1998 Data Bank for Kiln-Dried Red Oak Lumber* classifies boards with 0.25 inch of crook or less as straight boards, and crook is disregarded (Gatchell et al. 1998). However, in this study, 0.25 inch of crook was not disregarded but instead was included in the crook distribution tables. This also allowed greater board variability in our population of boards. Crook was measured in inches of crook per linear foot (plf) of lumber. This measure was obtained by dividing the inches of crook in a board by the length (in feet) of the board. Thus a 12-foot board with 0.75 inch of crook would have a plf measurement of 0.0625. Table 4-A in the Appendix contains every long board with its absolute crook measurement and its crook plf. The total amount of crook per linear foot for the long length lumber file was 0.77. Twenty seven percent of the boards in the long-length lumber set had no crook.

Makefile has no crook distribution assignment capabilities so the short and medium files had to be modified by hand. First, *Mix-master* was used to randomly reorder the boards in the short and medium length lumber files. Once this was done, every board had an equal opportunity of being selected in the making of the new width and crook modified board files. The same procedure was followed to create the short and the medium length board files based on the amount of crook plf contained in the long-length file. The procedure will be explained using the short board file (*short1*), containing 213.7 board feet of lumber in 64 boards, as an example.

Starting with the first board in the short board file, every other board was selected until the total amount of crook plf of the selected boards was close to 0.77 inch, the total crook plf in the long length file. An exact amount of crook plf equal to 0.77 inch could not be achieved without sacrificing random selection. Therefore, the total amount of crook plf in the short and medium-length input files was either slightly lower or slightly higher than 0.77 inch.

Once approximately 0.77 inch of crook plf was reached, board selection stopped. At this point, the percentage of crook-free boards selected was calculated. If this percentage was less than 27 percent of the total number of boards in the new file, more crook-free boards were selected until crook-free boards made up 27 percent of the total boards in the file. If, once selection stopped, the boards with no crook made up more than 27 percent of the total boards in the file, then the most recently selected board(s) with no crook were removed until this percentage fell to approximately 27 percent (getting the percentage of boards to be exactly 27 percent was difficult thus some files were off by 1 percent).

This procedure was conducted three times with both the short and medium-length board data sets to create three new short and medium length files that would serve as input files for the ROMI simulations. Different starting points were used for the systematic random sampling process when making each file. Using the *short1* file as an example, the board sampling for the first file started with the first board, sampling for the second file started with a randomly selected board from the middle of the file, and the sampling for the third file started with a randomly selected board located near the end of the file. Creating the files in this manner used every board from the short1 and med1 files. All of the new short and medium length files contained some boards that were the same and some boards that were different. On the other hand, all the long length lumber files contained the same 33 boards. The only difference between the three long-length lumber files was the order of the boards in each file. The *Mix-master* program was used to randomly order the boards in these files. Table 4-3 summarizes each of the new short and medium length board files as well as the long length files. The numbers in the

"Crook-free" column represent the number of boards in the files with no crook and the percentage they compose of all the boards in the file. All the files were made in ROMI-RIP format and than converted to ROMI-CROSS format to be used in the crosscut-first simulations.

Table 4-3. Board files after being modified to match the width and crook distributions of the limiting data set (the long-length board population).

Files	Number of boards	Number of crook-free boards and percent	Board feet
Short3A	26	7 (27%)	84.4
Short3B	26	7 (27%)	87.5
Short3C	26	7 (27%)	92.1
Med3A	23	6 (26%)	127.6
Med3B	21	6 (28%)	117.8
Med3C	22	6 (26%)	122
Long3A	33	9 (27%)	245.8
Long3B	33	9 (27%)	245.8
Long3C	33	9 (27%)	245.8

Cutting Bill Modifications

The cutting bills were modified the same as in Objectives 1 and 2. Table 4-4 contains the cutting bills and their modifications for ROMI-RIP and ROMI-CROSS.

Table 4-4. Cutting bills and modifications ROMI-RIP and ROMI-CROSS for Objective 3.

ROMI-RIP	Lumber length	Modification
Cshort	6-8 ft	Original part quantities reduced by 56%
Cmed	10-12 ft	Original part quantities reduced by 36%
Clong	14-16 ft	Original part quantities reduced by 16%
Eshort	6-8 ft	Target width = 18" parts, Drop widths = 9
Emed	10-12 ft	Target width = 26" parts, Drop widths = 13
Elong	14-16 ft	Target width = 30" parts, Drop widths = 15
ROMI-CROSS		**Modification**
Ashort	6-8 ft	Original part quantities reduced by 65%
Amed	10-12 ft	Original part quantities reduced by 50%
Along	14-16 ft	Original part quantities reduced by 40%
Eshort	6-8 ft	Target width = 16" parts, Drop widths = 8
Emed	10-12 ft	Target width = 26" parts, Drop widths = 13
Elong	14-16 ft	Target width = 32" parts, Drop widths = 16

A total of 12 new cutting bills, in regards to required part quantities, had to be built. The two best rip-first and the two best crosscut-first cutting bills from Objective 1 were modified for each lumber length test level. For example, from rip-first Cutting Bill *C,* Cutting Bills *Cs (short length), Cm (medium length)*, and *Cl (long length)* were created by adjusting the required part quantities for each lumber length. The part quantities were adjusted so that all the required part quantities could be satisfied and at least 150 boards would be used when processing the lumber length board files. Every other aspect of the cutting bills remained exactly the same as in the original Cutting Bill *C.*

Simulations

The simulations for Objective 3 had to be conducted differently then those for Objectives 1 and 2. As stated in the *Board Data Selection* section of Chapter 2, at least 150 boards must be run in a simulation before changes in part yield become insignificant (i.e., part yield results stabilize). The short, medium, and long-length lumber files for Objective 3 all contained substantially less than 150 boards. Recent research conducted by Zuo and Buehlmann (2002) looked at yield results achieved when using the same boards more than once. This study statistically compared ROMI-RIP part yields when running the same boards repeatedly in a simulation. The study compared yields for No. 1 Common lumber. Yields were obtained for input board data sets made up of 1,000 board feet of lumber, 500 board feet of lumber with each board used twice (for a total of 1,000 bdft.), 250 board feet of lumber with each board used four times, 62.5 board feet (approximately 10 boards) of lumber with each board used 16 times, and 31.25 board feet of lumber (approximately 5 boards) with each board used 32 times to once again construct an input file comprised of 1,000 board feet. Statistical analysis found that the part yield results were not statistically different until the number of No. 1 Common boards used dropped to five (31.25 board feet). Since greater between board variability is expected for No. 3A Common lumber than for No. 1 Common lumber, the minimum number of boards that could be used in a repeating sequence in a simulation input file was projected to be ten (Wiedenbeck 2002). Thus, the same boards were used repeatedly in simulating the influence of lumber length on part yield under Objective 3 so that at least 150 boards were used in a simulation. This allowed accurate yield predictions from simulations with the present population of boards in the different length files. For example, board file *short3a*, containing 26 boards, was processed seven times when conducting a simulation (26 x 7 = 182 boards). Table 4-5 shows how many times each board file had to be selected in order to ensure that a minimum of 150 boards were processed in each simulation.

Table 4-5. Board files used in simulations and board samples available as a result.

Board files	Boards	Number of times selected	Total boards
Short3A	26	7	182
Short3B	26	7	182
Short3C	26	7	182
Med3A	23	8	184
Med3B	21	8	168
Med3C	22	8	176
Long3A	33	5	165
Long3B	33	5	165
Long3C	33	5	165

Each of the 12 cutting bills from Table 4-5 was run three times, once for each of the board length files in Table 4-6. Therefore, a total of 36 simulations were conducted.

Results and Discussion

Table 4-6 contains a summary of the average part yields and sawing efficiencies resulting from simulations conducted in Objective 3. A complete summary table of all the ROMI-RIP and ROMI-CROSS results is located in Appendix 4, Tables 4-C and 4-D. Three simulations were conducted for each length segment with all four cutting bills. SPSS© was used to conduct statistical analyses. It should be noted that there were several inconsistencies while running the ROMI-CROSS simulations. Each cutting bill was processed three times, each time with a different board file. Cutting Bills *As* and *Es* both failed to meet the cutting bill requirements (not all parts in the cutting bill were produced) when processing the short length lumber board file *short3a*. In addition, Cutting Bill Es used less than 150 boards to fulfill the cutting bill requirements when running board file *short3c*. Cutting Bill *As* was fulfilled except for four pieces of the 40.13 x 2.5 inch part when run with board file *short3a*. Cutting Bill *Es* lacked five pieces of the 40 x 2.5 inch part, two pieces of the 43 x 2.13 inch part, and four pieces of the 46 x 2.13 inch part when run with board file *short3a*. Finally, Cutting Bill *Es* used 149 boards to meet its cutting bill requirements when running board file *short 3c.* It is possible that the failure to fulfill certain part requirements and using less then 150 boards created minor biases in the prediction of yield and sawing efficiency in these simulation tests. However, since these deviations are all quite minor, the results are not expected to be significantly biased.

Table 4-6. Average part yield and sawing efficiency results for the Objective 3 rip-first and crosscut first simulations.

ROMI-RIP				ROMI-CROSS			
Cutting bill	Board length	Part yield	Sawing efficiency[a]	Cutting bill	Board length	Part yield	Sawing efficiency[a]
Cs	6 - 8 ft.	44.97	8.65	**As**	6 - 8 ft.	34.49	8.01
Cm	10 - 12 ft.	41.79	7.56	**Am**	10 - 12 ft.	31.19	7.68
Cl	14 - 16 ft.	41.97	7.05	**Al**	14 - 16 ft.	27.89	7.96
Es	6 - 8 ft.	41.18	7.09	**Es**	6 - 8 ft.	36.09	6.86
Em	10 - 12 ft.	39.80	5.87	**Em**	10 - 12 ft.	36.34	6.55
El	14 - 16 ft.	37.18	5.41	**El**	14 - 16 ft.	35.76	6.57

[a] Total cuts/parts (Bdft).

ANOVA (α=0.05) was run on the part yields and sawing efficiencies for the ROMI-RIP and ROMI-CROSS. Tukey's Honestly Significant Difference (HSD) multiple comparison test (α=0.05) was conducted if differences were indicated by the ANOVA (Appendix 4, Tables 4-E, F, G, and H). For the rip-first part yields, null hypothesis # 1 was rejected for Cutting Bill C.

Tukey's HSD indicated that the medium and long length lumber had the same average part yield, about 42 percent, while the short lumber produced a slightly higher average yield of approximately 45 percent. Null hypothesis # 2 was also rejected. Tukey's HSD indicated that the sawing efficiency was different for all three lumber lengths. The best sawing efficiency was experienced while running the long length lumber followed by the medium and short length lumber, respectively. The long, medium, and short length lumber required an average of approximately 7, 8, and 9 saw lines per board foot of parts produced. Put in ratio format, the sawing productivity for Cutting Bill C for short-length lumber vs. medium-length lumber vs. long-length lumber was 1:1.1:1.1. Lumber length had minimal impact on the sawing efficiency of the No. 3A Common lumber.

For Cutting Bill *E*, null hypothesis #1 was rejected. Tukey's HSD indicated that the average rip-first part yields were not statistically different for the short and medium lumber lengths, 41.2 percent for the short and 39.8 percent for the medium. However, the long length lumber produced a slightly lower average part yield, approximately 37 percent. Null hypothesis # 2 was rejected. Tukey's HSD indicated the sawing efficiency was different for all three lumber lengths The best sawing efficiency occurred when running the long length lumber, followed by the medium length lumber and the short length lumber. The long, medium, and short-length lumber required an average of approximately 5, 6, and 7 saw lines per board foot of parts produced. Put in ratio format, the sawing productivity for Cutting Bill *E* for short-length lumber vs. medium-length lumber vs. long length lumber was 1:1.1:1.1. Again, lumber length had minimal impact on the sawing efficiency of the No. 3A Common lumber.

For the ROMI-CROSS (crosscut-first) simulation results, null hypothesis # 1 was rejected for Cutting Bill *A.* Null hypothesis # 2 was not rejected for Cutting Bill *A.* For Cutting Bill *A*, Tukey's HSD indicated that the average part yields for the long and medium-length lumber were statistically the same, approximately 28 percent for the long length lumber and 31 percent for the medium length lumber. The short length lumber produced a higher average yield compared to that of the long and medium length lumber, approximately 34.5 percent versus an average of 29.5 percent for the other two length groups. On the other hand, sawing efficiency was the same for all lumber lengths. Approximately 8 saw lines were required per board foot of parts produced.

For Cutting Bill *E,* neither null hypotheses were rejected. The average short, medium, and long lumber yields were statistically the same; 36.1 percent, 36.3 percent, and 35.8 percent, respectively. Similarly, the average sawing efficiencies obtained while running the short, medium, and long-length exhibited no statistical differences. For the short, medium, and long-length lumber the average saw lines required per board foot of parts produced was 6.9, 6.5, and 6.6, respectively.

Several factors could have contributed to part yield and sawing efficiency differences between lumber length segments that occurred in the rip-first and crosscut-first simulations. One of these factors is the amount of defects in the boards and how they were distributed in the boards. Fewer cuts may be required to obtain parts from a board who's defects are more concentrated in certain areas then one who's defects are dispersed throughout a board. Every defect that is removed from a board decreases the part yield potential as wood is removed that is not going into a required part. Thus, when defects are concentrated, fewer cuts are required to remove them and less wood may be removed form the board. If the defect arrangements in the boards of the different lumber length segments were different, this could have been a contributing factor to the part yield differences and sawing efficiency differences.

In addition, differences in part yield and sawing efficiencies between cutting bills could have been due to the percentage of smaller parts composing the cutting bill. In rip-first Cutting Bill *C*, approximately 92 percent of the part lengths were less than 30 inches compared to approximately 53 percent for Cutting Bill *E*. The high percentage of smaller parts could have allowed Cutting Bill *C* to better utilize certain clear areas in a board. For example, if there was a clear face section in a board that was 32 inches long, more of this wood could be used cutting two 15.5 inch parts from it then one 30 inch part. This could have helped Cutting Bill C to achieve better part yields then Cutting Bill *E* in some situations. Further, this would also have decreased the sawing efficiency of a cutting bill since it may take several small parts to produce the same area as one large part.

The general trends displayed by the part yield results of this objective share some similarities and some differences with earlier research conducted on the effects of lumber length on part yield. Wiedenbeck (1992) concluded that the part yields of crosscut-first operations tend to increase as lumber length increases and rip-first yields tend to decrease as lumber length increases**.** The rip-first results of this research indicated, similar to Wiedenbecks' results, that part yields tend to decrease as the lumber length increases. However, these results provided no evidence to support Wiedenbeck's conclusions regarding the crosscut-first part yields. It should be noted that Wiedenbeck defined short lumber as that between 4 feet and 8 feet in length vs. the 6 to 8 foot definition used in this research.

Results from Wiedenbeck and Araman's (1995) study indicated that there were no length-based processing differences in a crosscut-first rough mill. Results also indicated that processing short-length (4-7 ft.) lumber in a rip-first rough mill was less productive then processing medium length (8-13 ft.) and longer (14-16 ft.) lengths of lumber. The crosscut-first part yield results for Cutting Bill *A* contradict those produced from their study. However, the crosscut-first part yield results for Cutting Bill *E* indicated, similarly, that there are no length-based processing differences in a crosscut-first rough mill. On the other hand, the rip-first part yield results for both Cutting Bills *C* and *E* indicate, opposite of Wiedenbeck and Araman's (1995) results, that the part yield increases as the lumber length decreases. These differences are probably attributed to the inclusion of 4 and 5 foot lumber in Wiedenbeck and Araman's short-length lumber segment and the inclusion of 13 foot lumber in their medium-length lumber segment.

Hamner et al. (2002) concluded that part yield increases significantly in a rip-first rough mill as lumber length increases. A multi-grade lumber grade mix, not including No. 3A Common lumber, was used in this research and the lumber length segments were narrower: short-length lumber (7-8 ft.), medium-length lumber (11-12 ft.), and long-length lumber (15-16 ft.). Their results indicated an exact opposite relationship between lumber length and part yield in a rip-first rough mill then that indicated by the results of this research.

Conclusion

The results of tests to detect how part yields and sawing efficiencies vary by lumber length group are inconsistent between rip-first and crosscut-first cutting bills. However, the rip-first and crosscut-first cutting bills did exhibit a similar trend regarding part yield. When processing No. 3A Common red oak lumber, the length of the lumber processed did affect the part yield. Except for Cutting Bill *E* in the crosscut–first simulation, both the rip-first and the crosscut-first simulations exhibited increasing part yields as the lumber length decreased. As a result, to achieve the best part yield when processing No. 3A Common lumber, short lumber lengths should be used, more specifically, lumber between 6 and 8 feet in length. Depending on the cutting bill, 10-12 foot long lumber may produce part yields comparable to the short-length (6-8 ft) lumber.

Sawing efficiency exhibited a different trend than did part yield. In the rip-first simulations, the sawing efficiency improved as the lumber length increased. In the crosscut-first simulations, the lumber length had no affect on sawing efficiency.
As a result, in a rip-first rough mill, as the lumber length decreases, more wear and tear should be expected on processing equipment and higher processing costs owing to slower production rates can be expected. On the other hand, in a crosscut-first rough mill, neither the amount of wear and tear experienced on processing equipment nor the processing costs in the rough mill will be affected by the length of the lumber processed.

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Appendix 4

Table 4-A. Crook distribution in long length lumber file.

Board	Crook (in.)	Length (feet)	Crook per linear foot
3046	0	16	0
3260	0	14	0
3285	0	14	0
3287	0	16	0
3351	0	14	0
3397	0	14	0
3399	0	14	0
3402	0	15	0
3403	0	16	0
3024	0.25	14	0.02
3025	0.25	16	0.02
3034	0.25	16	0.02
3284	0.25	14	0.02
3286	0.25	14	0.02
3288	0.25	16	0.02
3349	0.25	14	0.02
3350	0.25	14	0.02
3352	0.25	15	0.02
3398	0.25	14	0.02
3400	0.25	14	0.02
3401	0.25	14	0.02
3404	0.25	16	0.02
3405	0.25	16	0.02
3424	0.25	14	0.02
3447	0.25	14	0.02
3039	0.5	14	0.04
3041	0.5	14	0.04
3035	0.75	14	0.05
3048	0.75	15	0.05
3049	0.75	15	0.05
3043	1	14	0.07
3044	1.5	16	0.09
3020	1.75	16	0.11
Total			**0.77**[a]

[a] This is the real crook plf total before the values were rounded to two significant digits.

Table 4-B. Summary of descriptive statistics and ANOVA conducted on width distribution of board files in Objective 3.

Cutting bill	Number of boards	Mean width	Standard deviation	Standard error	95% Confidence interval for mean		Minimum width	Maximum width
					Lower bound	Upper bound		
= long	33	5.98	1.32	.23	5.51	6.45	4.00	12.00
= shorta	32	5.83	.74	.13	5.57	6.10	4.00	8.00
= shortb	31	5.74	.90	.16	5.41	6.07	4.50	8.75
= shortc	30	5.90	1.32	.24	5.40	6.38	4.50	11.25
= meda	23	5.87	.60	.12	5.61	6.12	4.75	7.00
= medb	21	6.01	.90	.19	5.61	6.42	5.25	8.75
= medc	21	5.79	.56	.12	5.53	6.04	4.75	7.50
Total	191	5.87	.97	.07	5.73	6.01	4.00	12.00

ANOVA results for lumber width.

	Sum of squares	df	Mean square	F	Sig.
Between groups	1.511	6	.252	.260	.955
Within groups	178.221	184	.969		
Total	179.732	190			

Table 4-C. Summary of the ROMI-RIP results produced from Objective 3 simulations.

ROMI-RIP									
Cutting bill	**Board files**	**Number of boards**	**Board feet**	**Parts (Bdft.)**	**Part yield**	**Rip count**	**X-Cut count**	**Total cuts**	**Sawing efficiency***
Cs	short3a	168	544.70	250.91	46.07	719	1429	2148	8.56
Cs	short3b	165	558.80	248.22	44.42	744	1434	2178	8.77
Cs	short3c	158	561.20	249.20	44.41	728	1420	2148	8.62
Cm	med3a	154	852.90	360.09	42.22	702	2002	2704	7.51
Cm	med3b	155	869.40	362.13	41.66	757	1993	2750	7.59
Cm	med3c	157	872.70	362.13	41.50	721	2025	2746	7.58
Cl	long3a	152	1133.00	473.87	41.81	709	2646	3355	7.08
Cl	long3b	153	1136.00	476.75	41.97	711	2649	3360	7.05
Cl	long3c	152	1133.00	477.70	42.13	705	2657	3362	7.04
Es	short3a	167	541.90	232.15	42.84	724	931	1655	7.13
Es	short3b	169	571.40	232.01	40.60	727	921	1648	7.10
Es	short3c	165	579.80	232.46	40.09	719	919	1638	7.05
Em	med3a	165	917.40	368.01	40.12	729	1420	2149	5.84
Em	med3b	165	927.00	359.73	38.81	746	1392	2138	5.94
Em	med3c	162	900.80	364.61	40.48	719	1412	2131	5.84
El	long3a	152	1133.00	419.83	37.04	669	1607	2276	5.42
El	long3b	151	1122.00	418.08	37.26	666	1596	2262	5.41
El	long3c	150	1119.00	416.72	37.25	660	1588	2248	5.39

* Total cuts/ Parts (Bdft.)

S = bill modified for short lumber,,

M = bill modified for medium length lumber

l= bill modified for long length lumber

Table 4-D. Summary of ROMI-CROSS results produced from Objective 3 simulations.

ROMI-CROSS									
Cutting bill	Board file	Number of boards	Board feet	Parts (Bdft)	Total yield	Rip count	X-Cut count	Total cuts	Sawing efficiency*
As ***	short3a	182	592.5	187.826	31.7	834	699	1533	8.16
As	short3b	159	537.5	193.24	35.95	883	697	1580	8.18
As	short3c	154	547.4	196.126	35.83	866	640	1506	7.68
Am	med3a	158	877.9	277.164	31.57	1250	913	2163	7.80
Am	med3b	157	885.2	274.57	31.02	1192	841	2033	7.40
Am	med3c	162	902.5	279.609	30.98	1263	933	2196	7.85
Al	long3a	160	1196	334.842	27.99	1542	1141	2683	8.01
Al	long3b	159	1189	331.469	27.88	1515	1123	2638	7.96
Al	long3c	159	1187	330.139	27.8	1496	1113	2609	7.90
Es ***	short3a	182	592.5	199.429	33.66	761	616	1377	6.90
Es	short3b	173	586.2	206.149	35.17	793	659	1452	7.04
Es **	short3c	149	529.9	209.02	39.45	788	599	1387	6.64
Em	med3a	169	940.9	337.153	35.83	1266	965	2231	6.62
Em	med3b	158	890.8	338.34	37.98	1267	906	2173	6.42
Em	med3c	174	966.7	340.245	35.2	1282	965	2247	6.60
El	long3a	159	1187	422	35.55	1594	1187	2781	6.59
El	long3b	158	1181	423.323	35.84	1598	1177	2775	6.56
El	long3c	155	1154	414.226	35.88	1565	1156	2721	6.57

* Total cuts/ Parts (Bdft.)
** Less than 150 boards used
*** All part requirements not met

s= bill modified for short lumber,,
m= bill modified for medium length lumber
l=bill modified for long length lumber

Table 4-E. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP part yield results for Objective 3.

Cutting bill	Number of simulations	Mean part yield	Standard deviation	Standard error	95% Confidence interval for mean		Minimum part yield	Maximum part yield
					Lower bound	Upper bound		
=Cs	3	44.97	.96	.55	42.59	47.34	44.41	46.07
=Cm	3	41.80	.38	.22	40.85	42.73	41.50	42.22
=Cl	3	41.97	.16	.09	41.57	42.37	41.81	42.13
=Es	3	41.18	1.46	.84	37.54	44.81	40.09	42.84
=Em	3	39.80	.88	.51	37.62	41.99	38.81	40.48
=El	3	37.18	.12	.07	36.87	37.49	37.04	37.26
Total	18	41.15	2.52	.59	39.90	42.40	37.04	46.07

ANOVA results for part yields.

	Sum of squares	df	Mean square	F	Sig.
Between groups	99.61	5	19.92	29.81	<0.01
Within groups	8.02	12	.67		
Total	107.63	17			

Tukey's HSD results for part yield.

		Mean difference (I-J)	Standard error	Significance	95% Confidence interval	
(I) CUTBILL	**(J) CUTBILL**				**Lower bound**	**Upper bound**
=Cs	**=Cm**	3.17*	0.67	0.01	0.93	5.42
	=Cl	2.99*	0.67	0.01	0.75	5.24
	=Es	3.79*	0.67	<0.01	1.55	6.03
	=Em	5.16*	0.67	<0.01	2.92	7.41
	=El	7.78*	0.67	<0.01	5.54	10.03
=Cm	**=Cs**	-3.17*	0.67	0.01	-5.42	-0.93
	=Cl	-.18	0.67	1.00	-2.42	2.07
	=Es	.62	0.67	0.93	-1.63	2.86
	=Em	1.99	0.67	0.09	-0.25	4.23
	=El	4.61*	0.67	<0.00	2.37	6.85
=Cl	**=Cs**	-2.99*	0.67	0.01	-5.24	-0.75
	=Cm	.18	0.67	1.00	-2.07	2.42
	=Es	.79	0.67	0.83	-1.45	3.04
	=Em	2.17	0.67	0.06	-0.08	4.41
	=El	4.79*	0.67	<0.01	2.54	7.03
=Es	**=Cs**	-3.79*	0.67	<0.01	-6.03	-1.55
	=Cm	-.62	0.67	0.93	-2.86	1.63
	=Cl	-.79	0.67	0.83	-3.04	1.45
	=Em	1.37	0.67	0.37	-0.87	3.62
	=El	3.99*	0.67	<0.01	1.75	6.24
=Em	**=Cs**	-5.16*	0.67	<0.01	-7.41	-2.92
	=Cm	-1.99	0.67	0.09	-4.23	0.25
	=Cl	-2.17	0.67	0.06	-4.41	0.08
	=Es	-1.37	0.67	0.37	-3.62	0.87
	=El	2.62*	0.67	0.02	0.38	4.86
=El	**=Cs**	-7.78*	0.67	<0.01	-10.03	-5.54
	=Cm	-4.61*	0.67	<0.01	-6.85	-2.37
	=Cl	-4.79*	0.67	<0.01	-7.03	-2.54
	=Es	-3.99*	0.67	<0.01	-6.24	-1.75
	=Em	-2.62*	0.67	0.02	-4.86	-0.38

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey's HSD[a] conductd on part yields.

Cutting bill	Number of simulations	Subset for alpha = .05		
		1	2	3
=El	3	37.1833		
=Em	3		39.8033	
=Es	3		41.1767	
=Cm	3		41.7933	
=Cl	3		41.9700	
=Cs	3			44.9667
Sig.		1.000	0.060	1.000

Means for groups in homogeneous subsets are displayed.

a Uses Harmonic Mean Sample Size = 3.000.

Table 4-F. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on ROMI-RIP sawing efficiency results for Objective 3.

Cutting bill	Number of simulations	Mean sawing efficiency	Standard deviation	Standard error	95% Confidence interval for mean		Minimum sawing efficiency	Maximum sawing efficiency
					Lower bound	Upper bound		
= Cs	3	8.6500	.10817	.06245	8.3813	8.9187	8.56	8.77
= Cm	3	7.5600	.04359	.02517	7.4517	7.6683	7.51	7.59
= Cl	3	7.0567	.02082	.01202	7.0050	7.1084	7.04	7.08
= Es	3	7.0933	.04041	.02333	6.9929	7.1937	7.05	7.13
= Em	3	5.8733	.05774	.03333	5.7299	6.0168	5.84	5.94
= El	3	5.4067	.01528	.00882	5.3687	5.4446	5.39	5.42
Total	18	6.9400	1.09925	.25910	6.3934	7.4866	5.39	8.77

ANOVA results for sawing efficiency.

	Sum of squares	df	Mean square	F	Sig.
Between groups	20.504	5	4.101	1279.250	<0.01
Within groups	.038	12	.003		
Total	20.542	17			

Tukey's HSD results for sawing efficiency.

		Mean difference (I-J)	Standard error	Significance	95% Confidence interval	
(I) CUTBILL	(J) CUTBILL				Lower bound	Upper bound
= Cs	**= Cm**	1.09*	0.05	<0.01	0.93	1.25
	= Cl	1.59*	0.05	<0.01	1.44	1.75
	= Es	1.56*	0.05	<0.01	1.40	1.71
	= Em	2.78*	0.05	<0.01	2.62	2.93
	= El	3.24*	0.05	<0.01	3.09	3.40
= Cm	**= Cs**	-1.09*	0.05	<0.01	-1.25	-0.93
	= Cl	0.50*	0.05	<0.01	0.35	0.66
	= Es	0.47*	0.05	<0.01	0.31	0.62
	= Em	1.69*	0.05	<0.01	1.53	1.84
	= El	2.15*	0.05	<0.01	2.00	2.31
= Cl	**= Cs**	-1.59*	0.05	<0.01	-1.75	-1.44
	= Cm	-0.50*	0.05	<0.01	-0.66	-0.35
	= Es	-0.04	0.05	0.96	-0.19	0.12
	= Em	1.18*	0.05	<0.01	1.03	1.34
	= El	1.65*	0.05	<0.01	1.49	1.81
= Es	**= Cs**	-1.56*	0.05	<0.01	-1.71	-1.40
	= Cm	-0.47*	0.05	<0.01	-0.62	-0.31
	= Cl	0.04	0.05	0.96	-0.12	0.19
	= Em	1.22*	0.05	<0.01	1.06	1.38
	= El	1.69*	0.05	<0.01	1.53	1.84
= Em	**= Cs**	-2.78*	0.05	<0.01	-2.93	-2.62
	= Cm	-1.69*	0.05	<0.01	-1.84	-1.53
	= Cl	-1.18*	0.05	<0.01	-1.34	-1.03
	= Es	-1.22*	0.05	<0.01	-1.38	-1.06
	= El	0.47*	0.05	<0.01	0.31	0.62
= El	**= Cs**	-3.24*	0.05	<0.01	-3.40	-3.09
	= Cm	-2.15*	0.05	<0.01	-2.31	-2.00
	= Cl	-1.65*	0.05	<0.01	-1.81	-1.49
	= Es	-1.69*	0.05	<0.01	-1.84	-1.53
	= Em	-0.47*	0.05	<0.01	-0.62	-0.31

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey's HSD[a] concuted on sawing efficiency.

Cutting bill	Number of simulations	Subset for alpha = .05				
		1	2	3	4	5
= El	3	5.4067				
= Em	3		5.8733			
= Cl	3			7.0567		
= Es	3			7.0933		
= Cm	3				7.5600	
= Cs	3					8.6500
Sig.		1.000	1.000	0.963	1.000	1.000

Means for groups in homogeneous subsets are displayed.

a Uses Harmonic Mean Sample Size = 3.000.

Table 4-G. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on the ROMI-CROSS part yield results for Objective 3..

Cutting bill	Number of simulations	Mean Part yield	Standard deviation	Standard error	95% Confidence interval for mean		Minimum part yield	Maximum part yield
					Lower bound	Upper bound		
=As	3	34.49	2.42	1.40	28.48	40.50	31.70	35.95
=Am	3	31.19	0.33	0.19	30.37	32.01	30.98	31.57
=Al	3	27.89	0.10	0.06	27.65	28.13	27.80	27.99
=Es	3	36.09	3.00	1.73	28.63	43.55	33.66	39.45
=Em	3	36.34	1.46	0.84	32.72	39.96	35.20	37.98
=El	3	35.76	0.18	0.10	35.31	36.20	35.55	35.88
Total	18	33.63	3.49	0.82	31.89	35.36	27.80	39.45

ANOVA results for part yield.

	Sum of squares	df	Mean square	F	Sig.
Between groups	172.69	5	34.54	12.08	<0.01
Within Groups	34.30	12	2.86		
Total	206.99	17			

Tukey’s HSD results for part yields.

		Mean difference (I-J)	Standard error	Sig.	95% Confidence interval	
(I) CUTBILL	**(J) CUTBILL**				**Lower bound**	**Upper bound**
=As	**=Am**	3.30	1.38	0.23	-1.33	7.94
	=Al	6.60*	1.38	0.01	1.97	11.24
	=Es	-1.60	1.38	0.85	-6.24	3.04
	=Em	-1.84	1.38	0.76	-6.48	2.79
	=El	-1.26	1.38	0.94	-5.90	3.37
=Am	**=As**	-3.30	1.38	0.23	-7.94	1.33
	=Al	3.30	1.38	0.23	-1.34	7.94
	=Es	-4.90*	1.38	0.04	-9.54	-0.27
	=Em	-5.15*	1.38	0.03	-9.78	-0.51
	=El	-4.57	1.38	0.05	-9.20	0.07
=Al	**=As**	-6.60*	1.38	0.01	-11.24	-1.97
	=Am	-3.30	1.38	0.23	-7.94	1.34
	=Es	-8.20*	1.38	<0.01	-12.84	-3.57
	=Em	-8.45*	1.38	<0.01	-13.08	-3.81
	=El	-7.87*	1.38	<0.01	-12.50	-3.23
=Es	**=As**	1.60	1.38	0.85	-3.04	6.24
	=Am	4.90*	1.38	0.04	0.27	9.54
	=Al	8.20*	1.38	<0.00	3.57	12.84
	=Em	-0.24	1.38	1.00	-4.88	4.39
	=El	0.34	1.38	1.00	-4.30	4.97
=Em	**=As**	1.84	1.38	0.76	-2.79	6.48
	=Am	5.15*	1.38	0.03	0.51	9.78
	=Al	8.45*	1.38	<0.00	3.81	13.08
	=Es	0.24	1.38	1.00	-4.39	4.88
	=El	0.58	1.38	1.00	-4.06	5.22
=El	**=As**	1.26	1.38	0.94	-3.37	5.90
	=Am	4.57	1.38	0.05	-0.07	9.20
	=Al	7.87*	1.38	<0.00	3.23	12.50
	=Es	-0.34	1.38	1.00	-4.97	4.30
	=Em	-0.58	1.38	1.00	-5.22	4.06

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey’s HSD[a] conducted on part yields.

Cutting bill	Number of simulations	Subset for alpha = .05		
		1	**2**	**3**
=Al	3	27.8900		
=Am	3	31.1900	31.1900	
=As	3		34.4933	34.4933
=El	3		35.7567	35.7567
=Es	3			36.0933
=Em	3			36.3367
Sig.		0.233	0.054	0.762

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 3.000.

Table 4-H. Summary of descriptive statistics, ANOVA, and Tukey's HSD conducted on the ROMI-CROSS sawing efficiency results for Objective 3.

Cutting bill	Number of simulations	Mean sawing efficiency	Standard deviation	Standard drror	95% Confidence interval for mean		Minimum sawing efficiency	Maximum sawing efficiency
					Lower bound	Upper bound		
= As	3	8.01	0.28	0.16	7.30	8.71	7.68	8.18
= Am	3	7.68	0.25	0.14	7.07	8.30	7.40	7.85
= Al	3	7.96	0.06	0.03	7.82	8.09	7.90	8.01
= Es	3	6.86	0.20	0.12	6.36	7.36	6.64	7.04
= Em	3	6.55	0.11	0.06	6.27	6.82	6.42	6.62
= El	3	6.57	0.02	0.01	6.54	6.61	6.56	6.59
Total	18	7.27	0.66	0.16	6.94	7.60	6.42	8.18

ANOVA results for sawing effciciency.

	Sum of squares	df	Mean square	F	Sig.
Between groups	7.085	5	1.417	43.034	<0.01
Within groups	.395	12	.033		
Total	7.480	17			

Tukey's HSD results for sawing efficiency.

		Mean difference (I-J)	Standard error	Sig.	95% Confidence interval	
(I) CUTBILL	(J) CUTBILL				Lower bound	Upper bound
= As	= Am	.32	0.15	0.31	-0.17	0.82
	= Al	.05	0.15	1.00	-0.45	0.55
	= Es	1.15*	0.15	<0.01	0.65	1.64
	= Em	1.46*	0.15	<0.01	0.96	1.96
	= El	1.43*	0.15	<0.01	0.94	1.93
= Am	= As	-.32	0.15	0.31	-0.82	0.17
	= Al	-.27	0.15	0.48	-0.77	0.22
	= Es	.82*	0.15	<0.01	0.33	1.32
	= Em	1.14*	0.15	<0.01	0.64	1.63
	= El	1.11*	0.15	<0.01	0.61	1.61
= Al	= As	-.05	0.15	1.00	-0.55	0.45
	= Am	.27	0.15	0.48	-0.22	0.77
	= Es	1.10*	0.15	<0.01	0.60	1.59
	= Em	1.41*	0.15	<0.01	0.91	1.91
	= El	1.38*	0.15	<0.01	0.89	1.88
= Es	= As	-1.15*	0.15	<0.01	-1.64	-0.65
	= Am	-.82*	0.15	<0.01	-1.32	-0.33
	= Al	-1.10*	0.15	<0.01	-1.59	-0.60
	= Em	.31	0.15	0.34	-0.18	0.81
	= El	.29	0.15	0.43	-0.21	0.78
= Em	= As	-1.46*	0.15	<0.01	-1.96	-0.96
	= Am	-1.14*	0.15	<0.01	-1.63	-0.64
	= Al	-1.41*	0.15	<0.01	-1.91	-0.91
	= Es	-.31	0.15	0.34	-0.81	0.18
	= El	-.03	0.15	1.00	-0.52	0.47
= El	= As	-1.43*	0.15	<0.01	-1.93	-0.94
	= Am	-1.11*	0.15	<0.01	-1.61	-0.61
	= Al	-1.38*	0.15	<0.01	-1.88	-0.89
	= Es	-.29	0.15	0.43	-0.78	0.21
	= Em	.03	0.15	1.00	-0.47	0.52

* The mean difference is significant at the .05 level.

Homogeneous subset results for Tukey's HSD[a] conducted on sawing efficiency.

Cutting bill	Number of simulations	Subset for alpha = .05	
		1	2
= Em	3	6.5467	
= El	3	6.5733	
= Es	3	6.8600	
= Am	3		7.6833
= Al	3		7.9567
= As	3		8.0067
Sig.		0.342	0.312

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 3.000.

CHAPTER 5. SUMMARY OF RESEARCH

Research Conclusions

The purpose of this research was to study the impacts of cutting bills grade mixes, and lumber lengths on the productivity of processing No. 3A Common lumber in rip-first and crosscut-first rough mills. Optimum processing conditions were assumed and red oak lumber was processed to make clear two-face parts. The two best rip-first cutting bills were *C* and *E*. Their part yields when processing mixed lumber lengths were approximately 38 and 37 percent. Cutting Bill *C* required approximately eight cuts per board foot of parts produced and Cutting Bill E required six. The two best crosscut-first cutting bills were *A* and *E*. Their part yields when processing mixed lumber lengths were approximately 31 and 36 percent. Cutting Bill *A* required approximately nine cuts per board foot of parts produced and Cutting Bill *E* required six.

Characteristics shared by the best cutting bills, rip-first and crosscut-first, were narrow part widths and short part lengths. More specifically, cutting bills that dictate the manufacture of 3 inch wide or narrower part widths to at least 10 different lengths less than 40 inches long will achieve optimal part yield when processing No. 3A Common lumber into clear two-face parts. As a result, operations that have a good opportunity for achieving optimal part yield while processing No. 3A Common lumber are those rough mills that produce dimension parts, parts for cabinets, parts for furniture, and parts that will be finger-jointed. The cabinet and furniture industries require many parts that could be produced from a cutting bill designed to achieve optimal part yields from No. 3A Common lumber. Finger-jointing operations provide a great opportunity for No. 3A Common lumber with the ability to use very short pieces.

In both the rip-first and crosscut-first simulations, the results of the grade mix yield simulations for Objective 2 indicated that part yield will decrease as the percentage of No. 3A Common lumber composing a grade mix increases. For rip-first Cutting Bill *C*, there was a 5 percent average difference in part yield between the No. 2A Common grade mix and the 50/50 No. 2A – No. 3A Common grade mix, a 7 percent average difference in part yield between the 50/50 No. 2A – No. 3A Common grade mix and the No. 3A Common grade mix, and a 12 percent average difference in part yield between the No. 2A Common and No. 3A Common grade mixes. The 50/50 No. 2A – No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the 50/50, No. 2A – No.3A Common grade mix. For rip-first Cutting Bill *E*, there was a 9 percent average difference in part yield between the No. 2A Common and 50/50 grade mixes, an 11 percent average difference in part yield between the 50/50 and No. 3A Common grade mixes, and a 20 percent average difference in part yield between the No. 2A Common and No. 3A common grade mixes. The 50/50 No. 2A – No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 1 additional sawline per board foot of parts produced compared to the 50/50 No. 2A – No. 3A Common grade mix.

For crosscut-first Cutting Bill *A*, there was a 7 percent average difference in part yield between the No. 2A Common and 50/50 No. 2A – No.3A Common grade mixes, an 8 percent average difference between the 50/50 No. 2A – No.3A Common and No. 3A

Common grade mixes, and an 15 percent average difference between the No. 2A Common and No. 3A Common grade mixes. The 50/50 No. 2A – No. 3A Common grade mix required 0.2 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 0.7 additional sawlines per board foot of parts produced compared to the 50/50 No. 2A – No. 3A Common grade mix. For crosscut-first Cutting Bill *E,* there was an 8 percent difference in part yield between the No. 2A Common and 50/50 grade mixes, a 10 percent difference in part yield between the 50/50 and No. 3A Common grade mixes, and a 18 percent difference between the No. 2A Common and No. 3A Common grade mixes. The 50/50 No. 2A – No. 3A Common grade mix required 0 .4 additional sawlines per board foot of parts produced compared to the No. 2A Common grade mix and the No. 3A Common grade mix required 0.5 additional sawlines per board foot of parts produced compared to the 50/50 No. 2A – No. 3A Common grade mix.

When changing grade mixes, differences in part yields are highly dependent on the cutting bill. Part yield differences between grade mixes were inconsistent within and between cutting bills. Further, changes in sawing efficiencies were also inconsistent between different cutting bills when altering the grade mix. Rough mill managers should be aware of the part yield that can be achieved when processing No. 3A Common lumber, as well as various grade combinations, in their rough mill. Rip-first operations that experience small differences, less then 6 percent based on current lumber prices and the part yields produced in this research, in part yields when processing No. 3A Common lumber compared to No. 2A Common lumber should investigate and compare the amount of No. 3A Common lumber and the amount of No. 2A Common lumber they need to fulfill their cutting bills and overall operating needs. For the rip-first cutting bills in this research, which experienced yield differences greater than 10 percent between No. 2A Common and No. 3A Common lumber, using No. 3A Common lumber instead of No. 2A Common became less expensive as the cost difference between the two grades became greater then $150/MBM. Again, this is based on red oak lumber prices.

The same NHLA grade rules apply to all hardwood lumber manufactured in the U.S. Thus the same part yield results experienced processing No. 3A Common red oak can be expected when processing No. 3A Common white oak, maple, cherry, and other species. Price differences between No. 2A Common lumber and No. 3A Common lumber for some of these species is much greater then for red oak. As a result, based on the results of the simulations conducted to address Objective 2, No. 3A Common lumber may be a less expensive raw material to process compared to No. 2A Common lumber for some of these species. Also, these lumber prices may vary for the same species depending on the region in which they are sold.

The results of Objective 3 indicated that when processing No. 3A Common lumber in rip-first and crosscut-first rough mills, the highest yields will be experienced when running short lumber between 6 and 8 feet in length. For rip-first Cutting Bill *C*, the part yield for the short-length lumber was approximately 3 percent higher then that of the medium and long-length lumber. The short-length lumber required 1 additional sawline per board foot of parts produced compared to the medium-length lumber and the medium length lumber required 1 additional sawline compared to the long-length lumber. For rip-first Cutting Bill *E*, the part yield for the short and medium length lumber was approximately 3 percent higher then that of the long-length lumber. The short-length lumber required 1 additional sawline per board foot of parts produced compared to the medium-length lumber and the medium length lumber required 1 additional sawline compared to the long-length lumber. For crosscut-first Cutting Bill *A*, the part yield for the short-length lumber was approximately 6 percent higher then that of the medium and long-length lumber. There was no difference in sawing efficiency between the lumber lengths. For crosscut first Cutting Bill *E*, there was no difference in part yield or sawing efficiency between lumber lengths.

Depending on the cutting bill, part yields similar to that experienced when running short length lumber may be experienced while running medium length lumber (10-12 foot). Unfortunately, rip-first rough mill running shorter No. 3A Common lumber should expect a decrease in sawing efficiency and more wear and tear on their equipment. On the other hand, sawing efficiency in a crosscut-first rough mill can be expected to stay the same regardless of the length of lumber being processed. Of course, the sawing efficiency will differ between different cutting bills.

For rough mills processing a grade mix of No. 2A Common and No. 3A Common lumber, part yield could be improved by adjusting their lumber-processing schedule, given the No. 2A Common and No. 3A Common are processed separately. For example, schedule the No. 3A Common lumber to be processed when cutting short narrow parts and process the No. 2A Common lumber when cutting longer wider parts. This may not be applicable in all rough mills, but an operation could increase their No. 3A Common part yield by scheduling their cutup process like this.

Below is a list of rough mill parameters that, based on tests conducted to address Objective 1, 2, and 3, are conducive to attaining optimal part yield when processing No. 3A Common lumber in both rip-first and crosscut-first operations:

- Part widths 3” wide or narrower;
- at least 10 length definitions, less then 40”, for every part width; and
- processing short lumber (6-8 foot)

Rough mill operations that process cutting bills made up mostly, or fully, by the part sizes listed above could increase their primary part yield by processing more lumber between 6 and 8 feet in length. This could have impacts throughout the No. 3A Common supply chain. Sawmillers who wanted to move their No. 3A Common lumber would make their lumber more attractive to rough mills by manufacturing it to the appropriate lengths, 6- 8 ft. As a result of this and the ability to obtain useable parts from lumber only 3 inches wide could be an increase in the demand for the raw material typically produced from short logs and bolts as well as SDL. The ability to profitably obtain a value-added product from these raw material sources could further promote forest management practices that had not been economically feasible before, and eventually even lead to improved forest health.

Future Research

There are several areas of future research that would help to determine the best overall conditions for achieving optimal part yield while processing No. 3A Common lumber. First would be to conduct a study in an actual rough mill. There are several options as to how to conduct a study of this sort. Using the same cut-up parameters and lumber specification as used in this research is one option. This could serve as another validation of the ROMI simulation software.

More rough mill simulations should be conducted using No. 3A Common lumber that incorporates salvage operations. It would be of interest to see if salvage cutup operations would significantly increase part yields and how much of the overall No. 3A Common part yield was made up of salvage parts compared to higher grades of lumber. In addition, it would be of interest to study the impact of cutting salvage parts to part grade definitions different than those required for the primary parts. For example, cutting clear two-face primary parts and cutting clear one-face salvage parts.

Similarly, in attempts to realize the true yield potential of No. 3A Common lumber, a study evaluating several different part grade definitions for primary parts, including lumber color, would be insightful. Part quality definitions are plentiful in the industry, both between and within industry sectors. A study of this nature could evaluate the maximum primary yield potential of No. 3A Common lumber and further specify which secondary manufacturers provide the best opportunities to achieve them.

An in depth cost analysis, comparing the costs of processing No. 2A Common lumber compared to No. 3A Common lumber based on historic and projected market prices would be insightful. It would be interesting to incorporate a comparison of reject rates for parts cut from No. 3A Common lumber compared to parts cut from No. 2A Common lumber into a study of this sort. Further, an evaluation of material handling rates at different machine centers in a rough mill, as well as maintenance and up keep costs, would provide additional valuable information for rough mill managers. This would shed more light on the production cost question.

Limitations of Study

The main limitation of this study was a lack of No. 3A Common digital board maps. As a result, part quantity requirements had to be modified for the simulations in each objective and for each cutting bill. Although ROMI-RIP has been validated as an accurate estimator of rough mill yield, ROMI-CROSS has not. The cutting bills used in this study were collected from the industry and were not designed to produce the highest yields possible when processing No. 3A Common lumber. In addition, although stain and mineral streak were addressed, color variation was not. Also, the yield results are all primary, meaning each part was only ripped and chopped once. Salvage operations were not used in these simulations. As a result of this and the clear two-face part grade definition, these part yields represent the lower end of the yield spectrum that can be expected processing No. 3A Common lumber. There may be potential for operations that use part quality definitions other than C2F to experience higher yields than those exhibited by these simulations.

The board files in Objective 2 lacked 7 foot lumber. Also, Objective 2 boards were all straight since all the No. 2A Common boards in the *1998 Data Bank for Kiln-Dried Red Oak Lumber* were free of crook and the use of No. 3A Common boards with crook could have created a bias.

For the purpose of this study there was a lack of No. 3A Common lumber available between 14 and 16 feet in length. Future research simulations dealing with ROMI-RIP or ROMI-CROSS should include the acquisition of at least 1500 to 2000 board feet of No. 3A Common lumber between 14 and 16 feet in length to be digitized. Several hundred more board maps between 6 and 8 feet in length would be helpful as well. Despite these limitations, there is confidence that the conclusions of this study are based on accurate simulation results.

VITA

Brian Patrick Shepley, son of John and Mary Jane Shepley, was born in Arlington, VA on June 12, 1978. After graduating from Annandale High School he attended Virginia Polytechnic Institute and State University where he earned his B.S. in Forest Products Marketing in 2000. Mr. Shepley continued his education at Virginia Tech and earned a M.S. degree in Wood Science and Forest Products in 2002. Mr. Shepley will begin his career in the wood products industry as Sales Manager with Morgan Lumber Company in Red Oak, VA.