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Development of a 3D log processing optimization system for small-scale sawmills to maximize profits and yields from central appalachian hardwoods

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DEVELOPMENT OF A 3D LOG PROCESSING OPTIMIZATION SYSTEM FOR SMALL-SCALE SAWMILLS TO MAXIMIZE PROFITS AND YIELDS FROM CENTRAL APPALACHIAN HARDWOODS

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ABSTRACT

DEVELOPMENT OF A 3D LOG PROCESSING OPTIMIZATION SYSTEM FOR SMALL-SCALE SAWMILLS TO MAXIMIZE PROFITS AND YIELDS FROM CENTRAL APPALACHIAN HARDWOODS

Wenshu Lin

The current status of log sawing practices in small hardwood sawmills across West Virginia was investigated and the effects of log sawing practices on lumber recovery evaluated. A total of 230 logs two species, red oak (*Quercus rubra)* and yellow-poplar (*Liriodendron tulipifera*), were measured in five typical hardwood sawmills in the state. Log characteristics such as length, diameter, sweep, taper, and ellipticality were measured. Additionally, the characteristics of sawing equipment such as headrig type, headrig kerf width, and sawing thickness variation were recorded. A general linear model (GLM) was developed using Statistical Analysis System (SAS) to analyze the relationship between lumber recovery and the characteristics of logs and sawing equipment for small sawmills in West Virginia. The results showed that the factors of log grade, log diameter, species, log sweep, log length, different sawmills, the interaction between log species and grade, and the interaction between log species and log length had significant impacts on volume recovery. Log grade, log species and headrig type had significant effects on value recovery.

Hardwood lumber production includes a sequence of interrelated operations. Methods to optimize the entire lumber production process and increase lumber recovery are important issues for forest products manufacturers. Therefore, a 3D log sawing optimization system was developed to perform 3D log generation, opening face determination, headrig log sawing simulation, cant resawing, and lumber grading. External log characteristics such as length, large-end and small-end diameters, diameters at each foot, and external defects were collected from five local sawmills in central Appalachia. The positions and shapes of internal log defects were predicted using a model developed by the USDA Forest Service. 3D modeling techniques were applied to reconstruct a 3D virtual log that included internal defects. Heuristic and dynamic programming algorithms were developed to determine the opening face and grade sawing optimization. The National Hardwood Lumber Association (NHLA) grading rules were computerized and incorporated into the system to perform lumber grading. Preliminary results have shown that hardwood sawmills have the potential to increase lumber value by determining the optimal opening face and optimizing the sawing patterns. Our study showed that without flitch edging and trimming, the average lumber value recovery in the sawmills could be increased by 10.01 percent using a heuristic algorithm or 14.21 percent using a dynamic programming algorithm, respectively.

An optimal 3D visualization system was developed for edging and trimming of rough lumber in central Appalachian. Exhaustive search procedures and a dynamic programming algorithm were employed to achieve the optimal edging and trimming solution, respectively. An optimal procedure was also developed to grade hardwood lumber based on the National Hardwood Lumber Association (NHLA) grading rules. The system was validated through comparisons of the total lumber value generated by the system as compared to values obtained at six local sawmills. A total of 360 boards were measured for specific characteristics including

board dimensions, defects, shapes, wane and the results of edging and trimming for each board. Results indicated that lumber value and surface measure from six sawmills could be increased on average by 19.97 percent and 6.2 percent, respectively, by comparing the optimal edging and trimming system with real sawmill operations.

A combined optimal edging and trimming algorithm was embedded as a component in the 3D log sawing optimization system. Multiple sawing methods are allowed in the combined system, including live sawing, cant sawing, grade sawing, and multi-thickness sawing. The system was tested using field data collected at local sawmills in the central Appalachian region. Results showed that significant gains in lumber value recovery can be achieved by using the 3D log sawing system as compared to current sawmill practices. By combining primary log sawing and flitch edging and trimming in a system, better solutions were obtained than when using the model that only considered primary log sawing. The resulting computer optimization system can assist hardwood sawmill managers and production personnel in efficiently utilizing raw materials and increasing their overall competitiveness in the forest products market.

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CHAPTER 1: INTRODUCTION

Maximizing the profits obtained in the conversion of hardwood logs into lumber is a primary concern of forest products companies. Trends of increased log costs and limited availability are forcing wood processors to become more efficient in their operations (Occeña et al. 2001). There exists an increasing need for sawmilling technology that can provide the most efficient method of optimizing the grade and yield of hardwood lumber (Zhu et al. 1996, Sarigul et al. 2001). Conventional log sawing practices rely on the manual inspection of log profiles and external defects. Logs are sawn during primary breakdown based on either maximum volume or the highest grade (Zhu et al. 1996, Lee et al. 2001). Similarly, edger and trimmer operators visually examine the board surfaces, and then make quick judgments regarding the placement of cuts during the secondary log breakdown. These practices have resulted in low lumber yields, inadequate lumber quality in respect to grade, slow production, and an inefficient utilization of forest resources (Thomas 2002, Regalado et al. 1992). In response to these issues, there is a growing need to advanced milling technology that can optimize hardwood lumber recovery and help increase business competitiveness and profitability (Zhu et al. 1996; Sarigul et al. 2001).

The implementation of an automated log scanning inspection system has the potential to improve the productivity, quality, and grade of the hardwood lumber being produced (Zhu et al. 1996). Although there have been many log internal scanning technologies developed (x-ray, computed tomography (CT), magnetic resonance imaging (MRI), etc.), most of the systems are not fast, efficient, or cost-effective when analyzing log internal defects. Three dimensional log shape scanners originally developed for softwood saw mills are becoming more common in hardwood mills. The USDA Forest Service, in cooperation with Virginia Tech and Concord University, has developed a full shape 3D log scanner and methods to detect severe defects on the log's surface. Given that the presence of surface defects on hardwood logs indicates internal defects for, the Forest Service developed models to predict internal defect characteristics based on external defect measurements (Thomas 2006, Thomas 2008).

The economic advantages of utilizing a log scanning system to detect internal or external defects in hardwood logs are important to large-scale production facilities, and possibly even more to smaller operations. Of the several hundred hardwood sawmills in the U.S., the majority are small- to medium-sized facilities operated as small businesses in rural communities (Occeña et al. 2001). Approximately 68.52 percent of the hardwood sawmills produce less than 4 million board feet (MMBF) of green hardwood lumber per year in West Virginia (West Virginia Division of Forestry 2004). These small sawmills are less able to adopt new, more efficient technologies because of initial cost, payback period, and modifications to operations (Occeña et al. 2001). Only 35 percent of all Pennsylvania hardwood sawmills used a computer-aided headrig (Smith et al. 2004). To survive in a highly competitive marketplace, these smaller mills should utilize defect-scanning and optimal sawing technology to increase production efficiency and profits. It is noted that the scanning technology needs to be cost-effective for smaller mills to implement new methods. Once the log profile, external defects, and internal defects are obtained by the scanning techniques and predicted model, a suitable sawing strategy combining the scanning information is required to conduct optimal log sawing.

The goal of this dissertation was to develop a 3D log processing optimization system to determine the opening face, optimize the headrig log sawing patterns, flitch edging and trimming, cant resawing, and lumber grading. Specially the objectives including: (1) Design a heuristic procedure to determine the opening face of log based on external defects and shape; (2) Design heuristic and dynamic programming algorithms at primary log breakdown based on obtained log, lumber information, and NHLA lumber grading rules; (3) Design exhaustive search and dynamic programming algorithms to deal with flitch edging and trimming, respectively, based on flitch profile and defects information, lumber information, and NHLA lumber grading rules; (4) Develop a software system to implement these optimal algorithms within a 3-D visual simulation environment; (5) Validate the optimal log processing system by comparing real sawmill production and the optimal log processing system in terms of lumber value gained for the same log.

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CHAPTER 2: LOG SAWING PARCTICES AND LUMBER RECOVERY OF SMALL HARDWOOD SAWMILLS IN WEST VIRGINIA *

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Abstract

A total of 230 logs in two species, red oak (*Quercus rubra)* and yellow-poplar (*Liriodendron tulipifera*), were measured in five typical hardwood sawmills across West Virginia to evaluate log sawing practices and lumber recovery. Log characteristics such as length, diameter, sweep, taper, and ellipticality were measured in sawmills while log scale and grade were determined by using the USDA Forest Service (USFS) grading rules. The characteristics of sawing equipment such as headrig type, headrig kerf width, and sawing thickness variation were recorded during the measurement process. A general linear model (GLM) was used to statistically analyze the relationship between lumber recovery and characteristics of logs and sawing practices. Results indicated that factors such as log grade, log diameter, species, log sweep, log length, and interactions among these factors significantly affected lumber value and volume recovery.

2.1 Introduction

The hardwood industry is an important component of West Virginia's economy, contributing approximately 4 billion dollars annually (Childs 2005). More than 500 primary and secondary processors are located in the state and employ approximately 29,000 workers. The scales and production capability of hardwood sawmills in the state vary from less than 100,000 board feet to more than 50 million board feet (MMBF) per year (Luppold 1995, Luppold et al. 2000). Approximately 68.52 percent of the hardwood lumber sawmills produce less than 4 million board feet (MMBF) of green hardwood lumber per year (West Virginia Division of Forestry 2004). Luppold et al. (2000) also reported that a third of the eastern hardwood lumber production is provided by mills that produce less than 3 MMBF annually. Those small sawmills are key contributors to the industry as they represent a significant share of the market.

Currently, hardwood sawmills are facing many challenges, including: declining log size and quality, limited resource availability, reduced profit margin between log costs and lumber prices, and pressures from foreign competition (Milauskas et al. 2005). In addition, the weak global economy and the housing market slowdown have impacted the hardwood products industry. All of these factors are pressuring hardwood sawmills to adopt more efficient processing methods that can increase the value or volume of lumber produced from logs. Many large-scale sawmills have adopted the latest sawing and optimization technologies to increase the value and yield of lumber. However, small-scale sawmills are less able to employ advanced technologies due to high initial costs, long payback periods, and modifications to current operations (Occeña et al. 2001). Therefore, traditional sawing practices are still being used in small sawmills in the Appalachian region. Traditional sawing practices result in lower conversion efficiency, which makes it more difficult for small sawmills to survive in the highly competitive marketplace.

Maximizing the volume and value recovery of lumber from logs is one of the most common ways of improving the conversion efficiency and competitiveness in lumber production (Rappold et al. 2007). Over the past two decades, several studies have been conducted to analyze the relationships between lumber volume or value recovery and log characteristics or log sawing practices (Shi et al. 1990, Harless et al. 1991, Wade et al. 1992, Steele 1984, Steele et al. 1994, Maness and Lin 1995, Christensen et al. 2002, Young et al. 2007). For example, Steele (1984) reported that factors influencing lumber recovery during sawmilling process include log diameter, length, taper and quality, kerf width, sawing variation, rough green-lumber size, size of dry-dressed lumber, product mix, decision-making, condition and maintenance of mill equipment, and sawing method. Wade et al. (1992) used sawing equipment characteristics and log resource information to develop a multiple-linear regression model to estimate the lumber recovery factor (LRF) for hardwood sawmills. The data were obtained from the Sawmill Improvement Program (SIP) studies of 35 hardwood sawmills that were located in 15 states and had a LRF between 5.0 and 7.5. Their results indicated that the variables such as headrig kerf, log diameter, and log length significantly influenced LRF.

Given the current turbulent economic conditions, a complete analysis of sawing practices and lumber recovery would be beneficial for small-scale hardwood sawmills in West Virginia. Specifically, it was necessary to conduct a study that analyzed the impacts of sawing practices, log characteristics, and sawing equipment on lumber volume and value recovery for small-scale hardwood sawmills. The objectives of this study were to: (1) investigate the current status of log sawing practices for small hardwood sawmills in West Virginia, (2) analyze lumber recovery produced from current sawing practices, and (3) identify the factors that significantly affect lumber volume/value recovery.

2.2 Materials and Methods

The log sawing practices of five small hardwood sawmills (Figure 2.1) in North Central West Virginia were studied between October 2009 and August 2010. These mills were typical small-scale hardwood sawmills, with an annual production less than 4 MMBF. All the sawmills used the grade sawing method to produce lumber (Table 2.1).

Figure 2.1. Sawmill locations.

Table 2.1. Summary of basic information for the selected sawmills.

Site	Annual production (MMBF)	Log debarking	Sawing type	Sawyer's experience (years)	Grader's experience (years)
1	3	Ring Debarker	Circular headrig	20	18
2	4	Ring Debarker	Circular headrig	15	12
3	3	Ring Debarker	Band headrig	18	10
4	2	Ring Debarker	Band headrig	10	5
5	1	-	Band headrig	3	1

2.2.1 Sample selection

The sample logs of two hardwood species, red oak (*Quercus rubra*) and yellow-poplar (*Liriodendron tulipifera*), were selected from five sawmills with a total sample size of 230 logs. Of these 230 logs, 180 sawlogs of both species were measured in three sawmills, while 50 red oak logs were sampled from the other two sawmills. All the sample logs were selected to represent the range of size and quality for each species in West Virginia. The small-end diameters of the sample logs varied from 10 to 15 inches and log length was between 8 and 16 feet (Table 2.2).

Table 2.2. Distribution of the sample logs.

Species	Diameter class (in)	Log length (ft)				
		8	10	12	14	16
Red oak	10	18	3	2	0	0
	11	9	4	1	2	0
	12	9	16	5	0	0
	13	13	7	6	0	0
	14	9	12	3	1	2
	15	10	8	6	3	1
Yellow-poplar	10	3	1	2	1	0
	11	2	4	3	0	0
	12	9	5	2	3	1
	13	6	6	1	4	1
	14	3	5	3	1	0
	15	4	2	1	1	6
Total	-	95	73	35	16	11

2.2.2 Log measurement

In order to track lumber produced from a log, both ends of the sample log were divided into four quadrants and labeled by using consecutive numbers. These four quadrants were determined based on the major and minor axes at both log ends. The zero degree orientation of a log was pre-determined along the log length. Log taper was calculated as the difference between large-end diameter and small-end diameter divided by log length. Log sweep was measured as the maximum deviation from straightness divided by log length. Log ellipticality was calculated based on both lengths of major and minor axes at small-end of a log (Steward 1999). Defects were measured along the entire log length, and included defect type, location, and size. Defect type could be adventitious knot (AK), sound knot (SK), unsound knot (UK), overgrown knot (OK), light distortion (LD), medium distortion (MD), and heavy distortion (HD). Defect location was determined by measuring the distance away from the small-end of the log. The defect angle

(0-360 degrees) was measured and recorded relative to the zero degree orientation. Defect size was measured by length and width along the log's length and cross section, respectively.

2.2.3 Log scaling, grading, and sawing

Currently, three major log scaling rules are used in the eastern United States: Doyle log rule, Scribner rule, and International ¼ inch rule (Cassens 2001). Most sawmills in West Virginia still use the Doyle scale, even though it is less accurate than the others (West Virginia Forestry Association 2001). The use of the Doyle scale may be attributed to the long history of it being used as the standard hardwood log scaling rule that attributes log volume to value (Bond 2006). However, when log shape and size change dramatically, the Doyle scaling rules cannot correctly estimate the volume of logs. A cubic log rule which is based on the actual geometric volume can be used to reduce the effects of log profile. In this study, the Smalians formula was adopted as the cubic scale rule to calculate the log volume (Cassens 2001).

The USDA Forest Service developed standard hardwood saw log grading rules based on log shape and external log defects indicators (Rast et al. 1973). In this study, these log grading rules were adopted to predict high-grade lumber from a log. Log value was determined based on the prices at the time of the assessment which were gathered from mills across the state by log grade, species, and dimension.

The sawing process for each sample log was videotaped to observe how sawyers cut logs using current grade sawing procedures. We recorded the first cutting line location relative to the major and minor axes, the time required for determining the opening face and sawing pattern, and the number of log turnings. The time for locating the opening face of log started when the log was loaded to the carriage and ended before the sawblade cut the log. Log sawing time started from the sawblade cutting the log until a square cant or the last piece of lumber was ejected from the headrig, and the carriage returned and stopped in front of the log deck that was ready for next log.

2.2.4 Log products measurements

A series of consecutive numbers were marked on each piece of sawn boards in order to track its source. For example, "1-1" indicates the first board produced from log 1. After edging and trimming, the length, width, and thickness of each board were measured and its volume was computed in both board feet (bd.ft) and cubic feet (cu.ft). Both edges of each board were measured 4-5 times to determine the mean thickness that was then rounded to 1/32 inches. The lumber grade and surface measure were determined by a National Hardwood Lumber Association (NHLA) certified grader and the lumber value was accordingly calculated based on lumber price matrix. If a cant was produced, its length, width, and thickness were measured; and its volume and value were determined based on species and size of the cant. Sawdust volume was computed by multiplying one-half the saw kerf by the surface area of the board (Ernst and Pong 1985). Chip volume was determined by subtracting the total lumber, cant, and sawdust volumes from the gross cubic log volume.

2.2.5 Lumber recovery analysis

Lumber volume, value, and grade yield for the two dominant species, red oak and yellow-poplar, saw logs was analyzed, respectively. Lumber volume recovery was analyzed using overrun, lumber recovery factor (LRF), and cubic recovery percent (CRP). Overrun refers to the difference between the actual volume of lumber produced by mill and the volume estimated. LRF is expressed as nominal lumber volume in board feet divided by log volume in cubic feet (Wade et al. 1984). CRP is the cubic volume of rough green lumber expressed as a percentage of cubic log scale volume. CPR is a more accurate measure of lumber volume recovery than either overrun or LRF (Ernst et al. 1985). The production of more lumber volume does not always lead to more lumber value. Therefore, most mill managers are interested in lumber value recovery rather than lumber volume recovery. In this study, lumber value recovery was expressed as dollars per thousand board feet of lumber tally ($/MBF), dollars per hundred cubic feet of log volume ($/HCF), and dollars per thousand board feet of net Doyle log scale ($/MBFLS) (Willits et al. 1988). The $/MBF represents the average value of the lumber produced from the log, while the $/HCF and $/MBFLS represent the value of the log which are determined by lumber value and lumber recovery factor (Parry et al. 1996). A value ratio, which is expressed as lumber value divided by log and sawing costs, was used to evaluate log processing profitability. If a value ratio is less than 1.00, it indicates that the resulting lumber value cannot cover the log and operational costs. Lumber grade yield is also an important indicator which can provide information that relates log grade to the grade of lumber produced. Lumber grade yield can be expressed as board feet volume yield or percentage of board feet volume of lumber grade recovered in each log grade. Log grades used were F1, F2, and F3, and lumber grades included FAS, F1F, No.1COM, No.2COM, and No.3COM.

Lumber recovery can be affected by many factors, including raw material, equipment, machining, and processing (Steele 1984). A general linear model was used to analyze the relationships among lumber recovery, characteristics of logs, and sawing equipment for small hardwood sawmills. Only two-factor interactions were considered since it becomes extremely difficult to explain when more interactions were involved in the model. The general linear model for analyzing lumber volume or value recovery can be expressed as:

$$LR_{ijklmnopq} = \mu + SP_i + LG_j + LEN_k + DIA_l + LT_m + LE_n + LS_o + SM_p$$
$$SP_i * LG_j + SP_i * LEN_k + SP_i * DIA_l + LEN_k * LT_m + \varepsilon_{ijklmnopq}$$

$i = 1, 2$

$j = 1, 2$

$k = 1, 2, \ldots 5$

$l = 1, 2, \ldots 6$

$m = 1, 2, \ldots 4$

$n = 1, 2, \ldots 4$

$o = 1, 2, \ldots 4$

$p = 1, 2, \ldots 5$

where, $LR_{ijklmnopq}$ = the qth observation of lumber volume or lumber value recovery,

μ = the mean of each response variable,

SP_i = the effect of the ith species,

LG_j = the effect of the jth log grade,

LEN_k = the effect of the kth log length,

DIA_l = the effect of the lth log small end diameter,

LT_m = the effect of the mth log taper,

LE_n = the effect of the nth log ellipticality,

LS_o = the effect of the oth log sweep,

SM_p = the effect of the pth mill requirements including sawyer's experience and grader experience in respect to each mill,

$\varepsilon_{ijklmnopq}$ = an error component that represents uncontrolled variability, and

q = the number of observations within each treatment.

2.3 Results and Discussion

2.3.1 Statistics of sample logs and sawn lumber

The average small-end diameter of the sampled logs ranged from 10.96 to 13.68 inches with an average of 12.94 inches (Table 2.3). Log length averaged 10.52 feet, ranging from 9.23 to 12.67 feet. Sweep ranged from 0 to 0.625 with an average of 0.03 while log taper varied from 0.01 to 0.55 with an average of 0.16. Fifty-four percent of the sampled logs exceeded 0.50 inches for the difference between the major and minor axes. The average ellipticality of the measured sawlogs was 0.29. The total number of defects per log was between 0 and 18 with an average of 5. The most frequently occurred defects were: AK (8.6%), UK (10.6%), OK (29.6%), SK (26.6%), LD (5.6%), MD (14.8%), and HD (10.3%). Defect size varied greatly with an average length of 5.2 inches and width of 4.3 inches. The average log volume was 54.75, board feet (Doyle scale) or 11.05 cubic feet. A total of 230 logs were sawn which yielded 2,160 boards and 147 cants of two sizes (3.5×6 inches and 3×8 inches). The total lumber and cant tally were 13,745 board feet and 2,628 board feet, respectively. The average number of pieces of lumber produced from each log was 9 with the average lumber length, width, and thickness of 9.49 feet, 6.35 inches, and 1.13 inches, respectively (Table 2.3).

Table 2.3. Statistics of the sawlogs measured and sawn lumber.[a]

	N	Mean	SD	Minimum	Maximum
Log					
SED (in.)	230	13.57	1.7	9.82	15.57
LED (in.)	230	14.39	2.31	10.03	19.79
Length (ft)	230	10.52	2.22	8	16
Sweep	230	0.03	0.10	0	0.625
Taper	230	0.16	0.11	0.01	0.55
Ellipticality	230	0.29	0.13	0	0.59
Log defects					
Number of defects	230	5	2.3	0	18
Defect length (in.)	230	5.2	2.1	1.5	15
Defect width (in.)	230	4.3	2.5	1.5	16
Log volume					
Doyle log rule (bd.ft)	230	54.75	26.21	16.76	138.06
Scribner rule (bd.ft)	230	69.01	29.01	25.9	160.47
International ¼ inch rule (bd.ft)	230	60.34	27.17	20.15	145.78
Cubic log rule (cu.ft)	230	11.05	4.59	4.57	26.17
Lumber					
Length (ft)	2160	9.49	3.04	8	16
Width (in.)	2160	6.35	1.34	3	10.5
Thickness (in.)	2160	1.13	0.04	1.0	1.25
Lumber tally (bd.ft)	2160	58.17	28.5	29.25	149.625
Cant					
Cant tally (bd.ft)	147	23.5	7.65	14	37.33

[a] SED=small-end diameter; LED=large-end diameter; SD=standard deviation.

2.3.2 Log products distribution

The distribution of lumber & cant, chips, and sawdust by sawmill are shown in Figure 2.2. More lumber and cants were produced from the band sawmills compared to the circular sawmills. The circular sawmills converted about 51.2 percent of logs into lumber and cants with about 4.68 percent yield loss compared to the band mills. The distribution of log products slightly changed as the log diameter increased (Figure 2.3). The lumber and cant volume increased 5.8 percent and the chip volume decreased 9.4 percent when the diameter increased from 11 to 15 inches. The proportion of lumber and cants for 10 inch logs was relatively higher than for other diameter classes except for 15 inch logs. It should be noted that all 10 inch logs were sawn at one sawmill (No. 5) that utilized a band saw, and where the sawyer was more concerned about the improvement of lumber recovery rather than productivity.

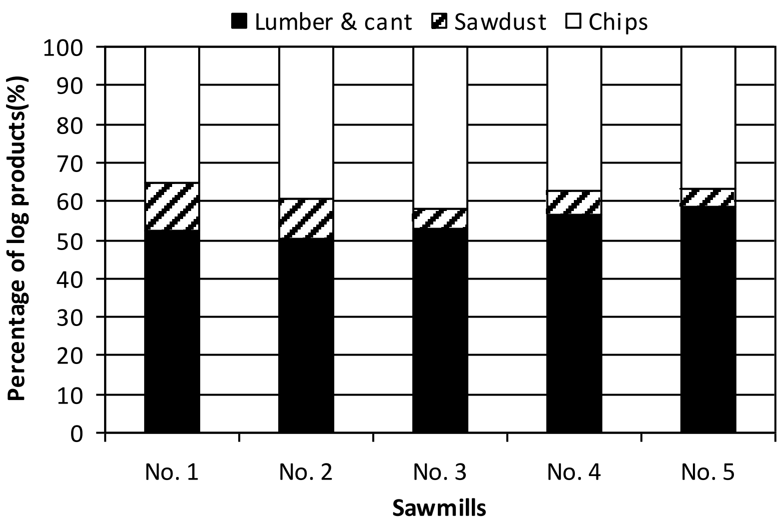


Figure 2.2. Distribution of log products by sawmills.

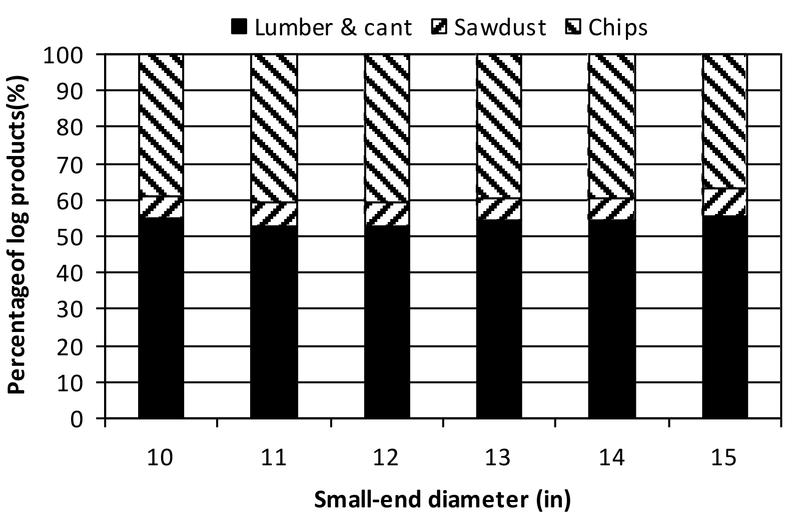


Figure 2.3. Distribution of log products by log diameter class.

2.3.3 Log processing

Primary breakdown was the focus of log processing in this study. All the logs were cut from large-end to small-end in all sawmills. The location of the slabbing or opening face is the key to maximizing lumber recovery. After a log is loaded onto a carriage, the sawyer will determine the appropriate log face by rotating the log. In order to achieve more lumber value, the log should be positioned so that the defects are located on the edges of potential sawing faces so that they can be easily removed during the edging process. However, we found that many defects were not positioned at the edges of the sawing faces. Since all sawmills used no taper sawing, the poor log face should be the first opening face in order to obtain more lumber recovery (Malcolm 1961, 1965). The poor log sawing face can be determined by identifying the external defects. However, the first opening face was not always from the poor log face as we observed in these sawmills. In our study, only 35 percent of first opening faces were observed on poor faces. There might two major reasons why the sawyers could not select the first opening face correctly: debarked logs and short decision times. It is difficult to identify all the defects on the debarked logs. In addition, there is very limited time for the sawyers to consider how to saw a log at the headrig. Therefore, it is recommended that log graders should mark the first opening face on the debarked logs before sawing in order to improve the lumber recovery and quality. A cost effective computer-aided program would also likely help operators make optimum decisions to improve lumber recovery.

The average width of the first board was 5.6 inches, slightly less than the commonly used 6 inches. The widths of lumber were divided into four classes: 4, 6, 8, and 10 inches. The distribution of the average width by log diameter class is shown in Figure 2.4. The proportions of wider lumber (8 inch, 10 inch) increased as the log diameter increased. It was noted that due to the size of logs selected, a majority of the lumber produced were 6-inch wide. As expected, a small percentage of 8 inch wide boards were produced from 12 inch diameter of logs or smaller. The lumber width from 10 inch logs was less than 8 inches.

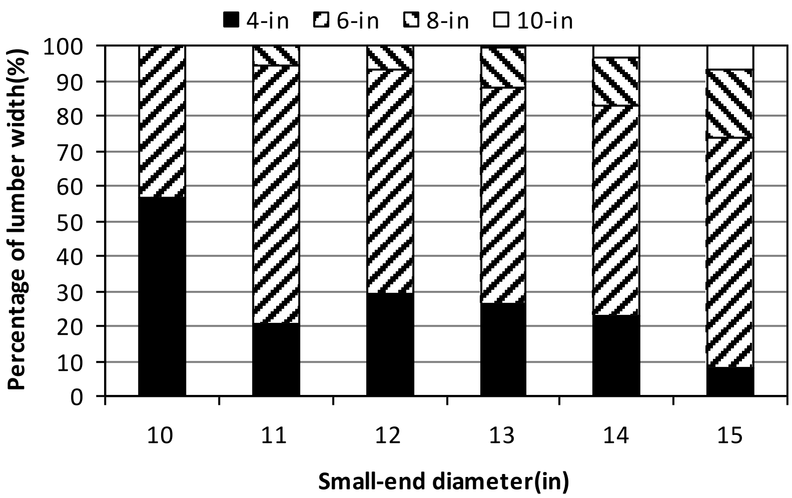


Figure 2.4. Distribution of lumber width by log diameter class.

During log processing, lumber is intentionally oversized to allow for sawing variation, shrinkage from drying, and final surfacing. In this study, 4/4 thickness was the normal thickness of the finished lumber for four sawmills, while one sawmill used 5/4 thickness. The targeted thickness for 4/4 and 5/4 lumber were 1-1/8 inches and 1-3/8 inches, respectively. Therefore, there was 1/8 inch oversizing, which can result in an average of 9.3 percent yield loss depending on log diameter (Steele 1984). The average lumber thickness variation was 0.055 inches with a range of 0 to 0.125 inches. If the variation was more than 0.03 inches, it could be associated with machine alignment, maintenance, or operation (Kilborn 2002). The sawing variation for two sawmills was greater than 0.03 inches, therefore machine adjustment is recommended to minimize the variation of lumber thickness in these two sawmills.

The sawing efficiency was analyzed by computing the average log-sawing time and the number of times that the log was turned during the sawing process. The average sawing time per log was 130 seconds, and the average sawing time per thousand board feet (MBF) was 565 seconds. The logs with higher sweep and an elliptical shape required more processing time than those straight and round logs due to additional log rotating and elapsed times at the headrig. The time needed to determine the opening face averaged 6.5 seconds while the average number of times that the log turned was 4.1. All the sawyers rotated logs by 180 degrees after the opening cut except for larger logs or bad-shape logs (such as the heavy sweep, crooked, or twisted logs). The reason for the 180 degree rotation was that the logs could be easily rotated to produce boards that were wider and required less edging. We noted that at most, one or two flitches were produced from the opening face before the logs were rotated for logs with small-end diameters less than 13 inches. Two or three pieces of lumber were cut from the first opening face for larger logs.

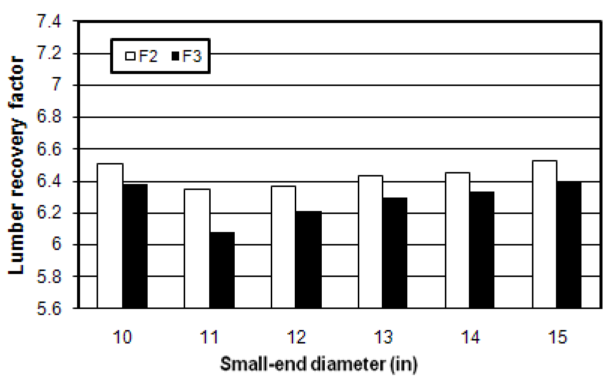
2.3.4 Lumber recovery

The volume recovery differed by log diameter and log scaling rules (Table 2.4). When the Doyle log scale was used, an average overrun for red oak and yellow-poplar was 40.71 percent and 47.33 percent, respectively. If the Scribner log scale was used, an average overrun for red oak and yellow-poplar was 4.61 percent and 7.09 percent, respectively. When using International ¼ log scale, an average overrun for red oak and yellow-poplar was 16.91 percent and 27.67 percent, respectively. The average LRF for red oak and yellow-poplar was 6.37 and 6.87, respectively, while the average CRP for was 53.15 percent and 57.54 percent, respectively. The results indicated that more volume could be recovered for yellow-poplar than red oak. This is due to the fact that the quality of sampled yellow-poplar logs was better than red oak logs and all yellow-poplar logs were sawn by band sawmill. We also found that logs of lower grade presented lower lumber volume recovery since defects or poor-shapes must be removed from boards to improve the grade (Figure 2.5).

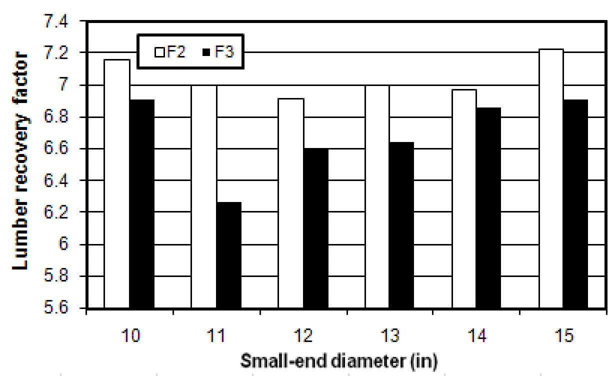
Table 2.4. Statistics of lumber volume recovery.

Species	SED[a] (in.)	No. of logs	Overrun (%)			Lumber recovery factor	Cubic recovery percent (%)
			Doyle	Scribner	International 1/4		
Red oak	10	22	80.39	11.6	45.76	6.45	55.33
	11	16	47.04	4.25	17.60	6.21	51.52
	12	30	46.21	5.53	16.97	6.30	52.51
	13	26	28.88	2.66	6.68	6.37	53.12
	14	27	23.89	3.73	10.00	6.39	53.59
	15	29	17.87	-0.10	4.45	6.48	52.81
Yellow-poplar	10	7	75.95	15.60	49.82	7.03	59.24
	11	9	60.57	6.56	31.62	6.63	55.14
	12	20	46.56	6.65	23.81	6.76	56.71
	13	18	41.88	6.71	20.83	6.82	57.13
	14	12	30.03	3.65	24.45	6.91	57.59
	15	14	29.01	3.39	15.53	7.07	59.41

[a] SED-small end diameter.



(a) red oak



(b) yellow-poplar

Figure 2.5. Lumber recovery factors by diameter class and log grade.

Saw kerf had a significant impact on lumber volume recovery. The average saw kerf for circular sawmill and band sawmill was 0.305 inches and 0.125 inches, respectively. Therefore, more wood would be required to produce a board using a circular headrig compared to a band headrig. The average LRF and CRP for circular sawmills were 6.08 and 51.21 percent, respectively. The average LRF and CRP for band sawmills were 6.63 and 55.54 percent, respectively. Although a thin kerf increases lumber volume recovery and reduces waste, it does not mean that band sawmills would always be more profitable than circular sawmills due to the cost such as operation, equipment and labor cost. In addition, some sawmills use circular headrigs to process low-value logs or make relatively few headrig cutting lines on each log.

The lumber value recovery ($/MBF) was $449.44/MBF for red oak and $327.25/MBF for yellow-poplar. The average $/HCF for red oak and yellow-poplar were $288.72/HCF and $226.52/HCF, respectively. The average $/MBFLS was $631.53/MBFLS and $462.26/MBFLS for red oak and yellow-poplar, respectively (Table 2.5). There were significant differences in lumber value recovery between the two species due to the difference in lumber price and log quality. Similar to lumber volume recovery, we noted that more lumber value recovery can be achieved from high-quality sawlogs. For example, the average lumber value recovery was $495.88/MBF for F2 red oak logs, while it was $403 /MBF for F3 red oak logs. For yellow-poplar, the average lumber value recovery was $365.87 /MBF for F2 logs, and $288.63/MBF for F3 logs.

Table 2.5. Statistics of lumber value recovery.

Species	SED[a] (in.)	No. of logs	Dollars per thousand board feet of lumber tally ($/MBF)	Dollars per hundred cubic feet of net log scale ($/HCF)	Dollars per thousand board feet of net log scale ($/MBFLS)
Red oak	10	22	484.93	320.28	781.94
	11	16	422.41	264.09	638.74
	12	30	420.31	266.99	620.22
	13	26	445.87	285.53	583.96
	14	27	454.33	291.47	607.09
	15	29	468.77	303.94	557.23
Yellow-poplar	10	7	341.02	240.38	518.08
	11	9	304.13	205.74	451.69
	12	20	300.70	205.41	441.69
	13	18	333.99	228.19	474.39
	14	12	326.20	225.47	420.89
	15	14	357.45	253.92	466.81

[a] SED-small end diameter.

Profit is a major incentive for mill managers to continue production, and is directly related to production costs. Assuming, the prices paid for F2 and F3 yellow-poplar logs were $150/MBF and $140/MBF in Doyle log scale, the purchased prices for red oak logs were $300/MBF for F2 grade and $280/MBF for F3 grade, and the average operating cost ranged from $160/MBF for circular sawmills to $200/MBF for band sawmills, a value ratio was computed based on species, diameter classes, and sawmills (Figures 2.6 and Figure 2.7). The average value ratios for red oak and yellow-poplar were 1.13 and 1.10, respectively (Figure 2.6). The value ratio for logs with grades F2 and F3 was 1.21 and 0.98, respectively. It should be noted that utilizing lower-grade logs did not always result in profits. Although sawmills purchased the low-grade logs at minimum price, the value of lumber recovered may be not sufficient to cover the purchasing and processing costs. Although the average lumber value ratio was greater than 1 (Figure 2.7), some processed logs still resulted in a loss.

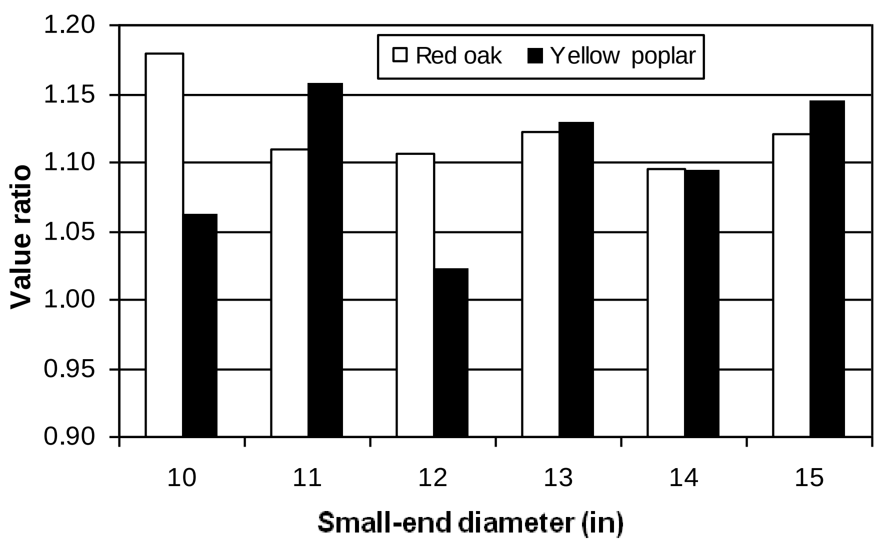


Figure 2.6. Value ratio by diameter class and species.

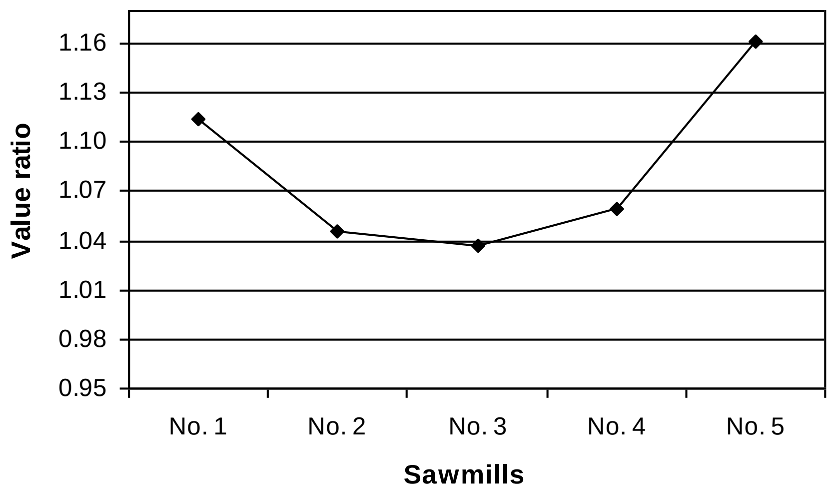


Figure 2.7. Value ratio by sawmills.

Table 2.6 shows the percentage of lumber grade yield in terms of species, log grade, and diameter class. The percentage of higher grade lumber increased as the quality of logs increased (Table 2.6). Among the F2-grade sampled logs, approximately 57.11 percent and 58.48 percent of No. 1 Common or better lumber were produced from red oak and yellow-poplar logs, respectively. Approximately 27.52 percent and 22.44 percent of the lumber were No. 2 Common or lower for red oak and yellow-poplar, respectively. For the F3-grade logs, 24.1 percent and 15.68 percent of No. 1 Common or better lumber were produced from red oak and yellow-poplar, respectively. About 57.58 percent and 64.21 percent was No. 2 Common or lower lumber for red oak and yellow-poplar, respectively. Overall, a majority of lumber produced in the studied sawmills were No.1 and No.2 Common.

Table 2.6. Statistics of lumber grade yield.[a]

Species	Log grade	SED (in.)	Percentage of lumber grade volume (%)					
			FAS	F1F	1C	2C	3C	P
Red oak	F2	10	4.69	9.40	45.00	39.03	1.88	0.00
		11	6.73	9.32	35.42	20.94	6.67	20.92
		12	9.66	12.50	26.08	25.37	5.65	20.74
		13	12.75	9.57	33.42	21.31	1.57	21.37
		14	11.49	10.65	32.20	22.78	5.74	17.14
		15	16.05	14.53	34.64	20.95	4.19	9.64
	F3	10	0.00	0.00	20.69	39.93	39.37	0.00
		11	1.10	1.10	28.32	41.08	12.00	16.40
		12	2.04	2.70	21.08	35.94	20.78	17.47
		13	2.33	0.78	16.59	40.12	18.70	21.48
		14	4.65	0.00	25.63	30.30	16.63	22.79
		15	3.00	0.56	16.76	31.56	25.01	23.11
Yellow-poplar	F2	10	14.21	0.00	33.00	52.79	0.00	0.00
		11	8.49	17.48	50.76	15.51	0.00	7.77
		12	0.81	8.57	33.50	24.38	4.55	28.18
		13	7.48	11.51	30.99	25.13	3.02	21.87
		14	18.25	14.59	30.83	12.33	5.04	18.95
		15	5.95	20.43	38.62	17.40	1.43	16.17
	F3	10	0.00	0.00	9.31	25.93	64.76	0.00
		11	0.00	0.00	10.30	35.26	27.75	26.70
		12	0.00	0.86	12.33	25.79	37.03	24.00
		13	0.00	2.11	23.99	25.87	26.26	21.78
		14	0.00	0.00	9.41	38.24	23.49	28.86
		15	0.00	0.00	35.49	27.50	28.94	8.07

[a] SED-small end diameter. 1C-No.1 Common. 2C-No.2 Common. 3C-No.3 Common. P-Pallet.

2.3.5 Factors affecting lumber recovery

The results showed that log grade (F=52.47; df=1, 194; $p < 0.0001$), log diameter (F=8.87; df=5, 194; $p < 0.0001$), log species (F=54.59; df=1, 194; $p < 0.0001$), sawmills (F=127.48; df=4, 194; $p < 0.0001$), log sweep (F=2.7; df=3, 194; $p = 0.0472$), log length (F=2.98; df=4, 194; p=0.0204) interaction between log species and grade (F=7.85; df=1, 194; p = 0.0056), and interaction between log species and log length (F=3.57; df=4, 194; $p = 0.0078$) had statistically significant effects on lumber volume recovery. For lumber value recovery, log grade (F=84.39; df=1, 194; $p < 0.0001$), log species (F=98.28; df=1, 194; $p < 0.0001$) and different sawmills (F=14.11; df=4, 194; $p < 0.0001$) were statistically significant variables. The adjusted multiple R^2 was 0.79 and 0.68 for lumber volume and value recovery, respectively, which indicated that the goodness of fit for the lumber volume recovery model was better than lumber value recovery.

Logs with a lower grade resulted in lower lumber volume and value recovery because defects or poor shapes must be removed from boards to improve the grade. When logs have significant sweep, traditional straight sawing methods could result in a significant volume loss. Therefore, curve sawing may be appropriate for logs with severe sweep in order to improve lumber recovery. For small diameter logs, there is a higher percentage of chips or hog fuel produced during log processing. Usually, the larger of the log diameter, the higher of the volume recovery percentage that can be achieved. However, exceptions may occur under some circumstances. For example, when processing some large diameter and old logs, lower volume recovery could occur due to internal decay or holes. Species had impact on lumber volume and value recovery. Red oak sawlogs were less straight and contained more defects than yellow-poplar sawlogs, which resulted in lower lumber volume recovery. However, since red oak lumber was more expensive than yellow-poplar, more lumber value could be recovered for red oak species. Lumber volume and value recovery were different among sawmills due to different mill equipment, and operators' experience.

2.4 Conclusions

This study investigated the current status of log sawing practices at five typical small Appalachian hardwood sawmills in West Virginia. Our findings indicated that small sawmills inefficiency in converting hardwood logs into lumber was mainly due to inappropriate selection of opening face, dimensional oversize, and sawing variations. Mill managers can improve these aspects to increase lumber recovery and business profitability. Lumber volume/value recovery and grade yield were significantly different among sawmills. However, due to the limited production data collected, it is difficult to consider how the differences of log characteristics, sawing equipment, and sawyer's skills affect the lumber recovery in each individual mill. Log grade, diameter, sweep, length, species, sawmill specifications, and the interactions between log species and grade and between log species and log length had statistically significant effects on the lumber volume recovery. Furthermore, log grade, species and sawmill specifications had statistically significant effects on the lumber value recovery. Lumber value recovery was affected somewhat differently by those factors that affect lumber volume recovery.

Further assessments with a larger sample of logs and sawmills across West Virginia may be needed to produce more robust statistic results. More factors should be considered for lumber recovery, such as board edging and trimming. In addition, an affordable, cost-effective log sawing optimization system should be developed and implemented to assist small sawmill operators in hardwood log processing in the region.

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CHAPTER 3: DEVELOPMENT OF A 3D LOG SAWING OPTIMIZATION SYSTEM FOR SMALL SAWMILLS IN CENTRAL APPALACHIA[†]

[†] Submitted to Wood and Fiber Science.

Abstract

A 3D log sawing optimization system was developed to perform 3D log generation, opening face determination, sawing simulation, and lumber grading using 3D modeling techniques. Heuristic and dynamic programming algorithms were employed to determine the opening face and grade sawing optimization. The positions and shapes of internal log defects were predicted using a model developed by the USDA Forest Service. Lumber grading procedures were based on the National Hardwood Lumber Association (NHLA) rules. The system was validated through comparisons with the total lumber values generated by the sawmills. External characteristics of logs including length, large-end and small-end diameters, diameters at each foot, and external defects were collected from five local sawmills in central Appalachia. Results have shown that hardwood sawmills have the potential to increase lumber value by determining the optimal opening face and sawing pattern optimization. The average lumber value recovery could be increased by 10.01% using the heuristic algorithm or 14.21% using the dynamic programming algorithm. The lumber grade was also improved significantly by using the optimal algorithms. For example, recovery of select or higher grade lumber could be increased from 16 to 30%. This optimization system would help small sawmill operators improve their processing performance, understand the impacts of defects on lumber grade, and improve industry competitiveness.

3.1 Introduction

Maximizing the profits gained from the conversion of hardwood logs into lumber is a primary concern for both large and small forest products companies. Recently there has been an increase in the competition for hardwood logs, and the increased log costs and limited availability are forcing wood processors to become more efficient in their operations. Conventional log sawing practices rely heavily on the manual inspection of the external log defects, and are based on either maximizing volume or grade (Zhu et al. 1996, Lee et al. 2001). This process is limited by the decision-making ability of the operators. Since most log defects are at unknown internal locations within the log, it is more difficult to give an optimal decision (Sarigul et al. 2001). Problems that arise from manual log defect detection and conventional log sawing practices include low lumber yields, less than adequate lumber quality in respect to grade, slow production, and result in inefficient utilization of forest resources (Thomas 2002).

Log scanning and optimization systems can be used to aid in the sawing of logs into lumber (Thomas et al. 2004). Preliminary studies have shown that the implementation of an automated log scanning inspection system has the potential to improve the productivity and quality, or grade of the hardwood lumber being produced (Zhu et al. 1996). The value of hardwood lumber can be increased by 11 to 21% by using optimal sawing strategies gained through the ability to detect internal log defects (Sarigul et al. 2001). While internal defects are difficult to detect, any improvements in defect detection can lead towards the recovery of higher quality lumber, increased profits, and better utilization of the forest resources (Thomas 2002). Currently, most available scanning systems are based on external models that use a laser-line scanner to collect rough log profile information. These systems were typically developed for softwood (pine, spruce, fir) log processing and for gathering information about external log characteristics (Samson 1993). There are also several internal log scanning technologies being developed (x-ray, computed tomography, MRI, etc.), however, none of them are efficient and cost-effective for small-scale hardwood sawmills. Recently, three dimensional log shape scanners originally developed for softwood sawmills are becoming more common in hardwood mills. The USDA Forest Service in cooperation with Concord University and Virginia Tech has developed a full shape 3D log scanner to detect severe log surface defects using relatively low-cost equipment ($30,000 plus integration labor cost) (Thomas 2002, 2006). In addition, internal log defect prediction models were also developed based on the measurements of external defects (Thomas 2006, Thomas 2008). A recent study has shown that the models can accurately predict about 81% of internal knot defects for red oak (Thomas 2010).

Since the 1960s, there has been ongoing efforts to improve lumber value or volume recovery through either computer simulation or mathematical programming (Tsolakides 1969, Hallock and Galiger 1971, Hallock et al. 1976, Richards 1973, Richard et al. 1979, 1980, Lewis 1985, Harless et al. 1991, Steele et al. 1993, 1994, Guddanti and Change 1998, Occeña and Tanchoco 1988, Occeña et al. 1997, 2001, Chang et al. 2005). For example, Tsolakides (1969) reconstructed a log as a cylinder and developed a digital computer analytical technique to study the effects of alternative sawing methods. Hallock and Galiger (1971), Hallock et al. (1976), and Lewis (1985) developed Best Opening Face (BOF) system to maximize the volume of lumber produced from small-diameter softwood logs. The program was widely adopted during the 1980s, and many softwood sawmills still use it today to produce lumber, however, the application of BOF in hardwood sawmills was very limited. Richards et al. (1979, 1980) designed a computer simulation program for hardwood log sawing. In this program, a log was represented by a truncated cone and each knot was simulated as a cone with its apex of 24° at the pith. Occeña and Tanchoco (1988) used graphic log sawing simulator as an analytical tool for automated hardwood log breakdown. The log sawing optimization can be defined as a dynamic programming problem, and recursive equations were established to find the optimum total lumber value or volume recovery (Faaland and Briggs 1984, Geerts 1984, Funk et al. 1993, Todoroki and Rönnqvist 1997, 1999, Bhandarkar et al. 2002, 2008) while Occeña et al. (1997) and Thawornwong et al. (2003) used heuristics algorithms to optimize log sawing patterns. Although several optimal log sawing programs had been developed, they were either not suitable for hardwood log grade sawing practices or economically feasible for small central Appalachian sawmills.

Small hardwood producers are key contributors to the hardwood industry in the central Appalachian region. In West Virginia, 68.52% of the hardwood sawmills produce less than 4 million board feet (MMBF) of green hardwood lumber per year (West Virginia Division of Forestry 2004). In Pennsylvania, 50% of respondents in a hardwood sawmill profile survey produced less than 2 MMBF of lumber per year (Smith et al. 2004). Currently, most large softwood mills and many large hardwood mills have implemented the latest sawing and optimization technologies to increase lumber yield and value. However, small hardwood sawmills are less able to employ the advanced technologies due to the high initial cost, long payback period, and modifications to current operations (Occeña et al. 2001). In order to survive in the highly competitive marketplace under current turbulent economic conditions, the development of appropriate cost-effective milling technology for these smaller mills is essential for them to improve their profitability and competitiveness. Therefore, the objectives of this study are to (1) design optimization algorithms to determine the opening face and log sawing patterns to improve the lumber value recovery, (2) develop a 3D visualization computer-aided log sawing simulation system for small hardwood sawmills to implement the optimal computer algorithms, and (3) validate the optimal sawing system through comparisons of computer generated results and the existing sawmills.

3.2 Optimal sawing system design

3.2.1. System structure and design

The optimal sawing system consists of four major components: data input/storage, 3D modeling, sawing optimization, and lumber grading (Figure 3.1). The data input/storage component includes data acquisition, data standardization, and data storage while 3D modeling component handles 3D image display and 3D image transformation. The sawing optimization component determines the opening face, log sawing, and cant resawing optimization while the lumber grading component processes lumber grades during the optimization process. A component object model (COM) was used to integrate the system and was designed using the principles of object-oriented programming (OOP). The system was programmed using the Microsoft Foundation Classes (MFC) and Open Graphics Library (OpenGL) using MS Visual C++. ActiveX Data Object (ADO) was employed to retrieve data from and save sawing results to a Microsoft Access database. The sawing results were saved to a table called a lumber table. The entity-relationship (ER) model for the optimal sawing system was implemented via Microsoft Access, including four entity types: (1) logs for storing tree species, position (butt and upper), small-end and large-end diameters; (2) log shapes for storing sweep and diameter at one foot interval; (3) log defects for storing defects associated with each log; and (4) grades for storing lumber grading rules and lumber price (Figure 3.2). The relationships among the entity types were defined in the ER model (Figure 3.2).

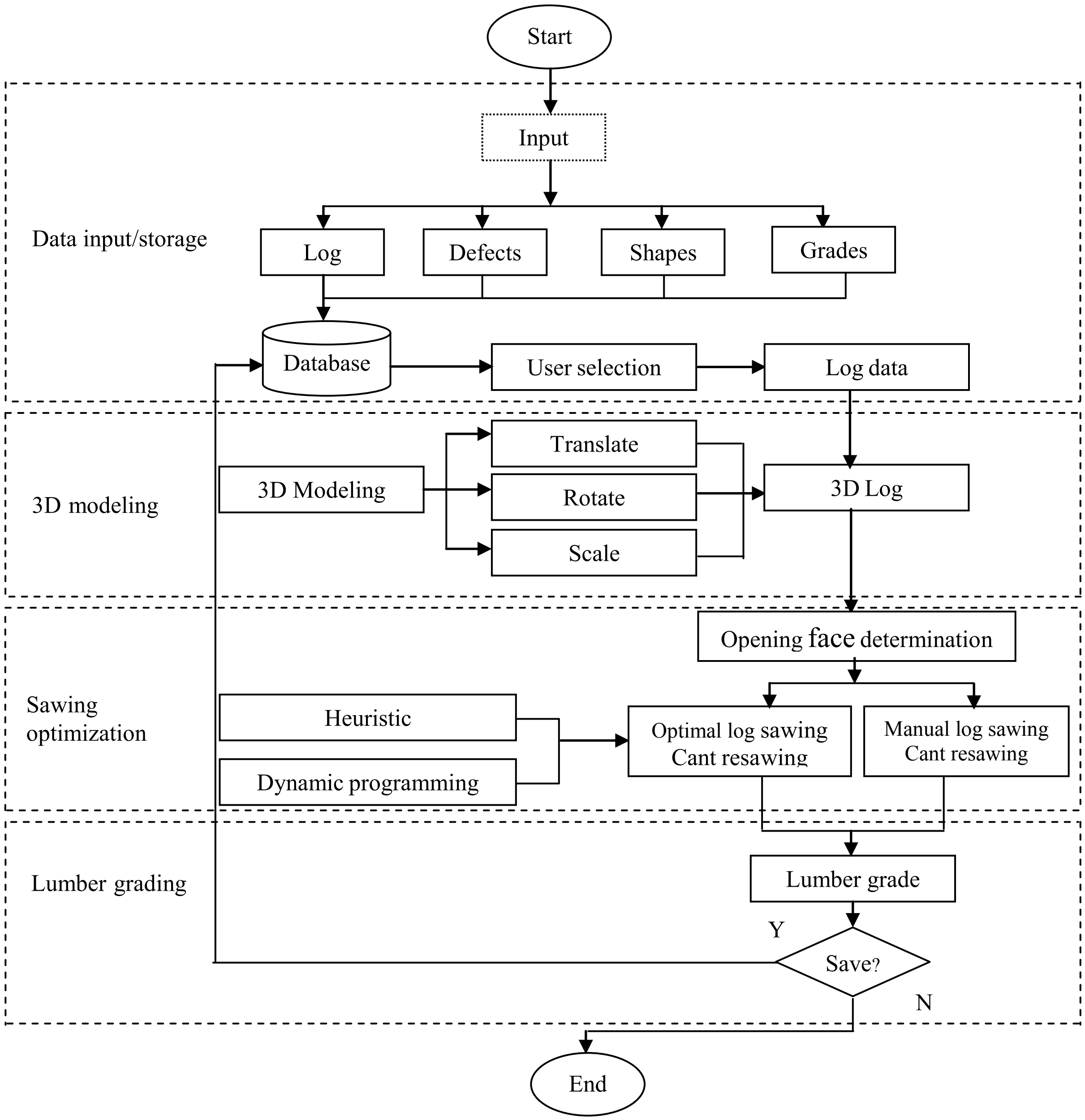

Figure 3.1. Flowchart of the optimal log sawing system.

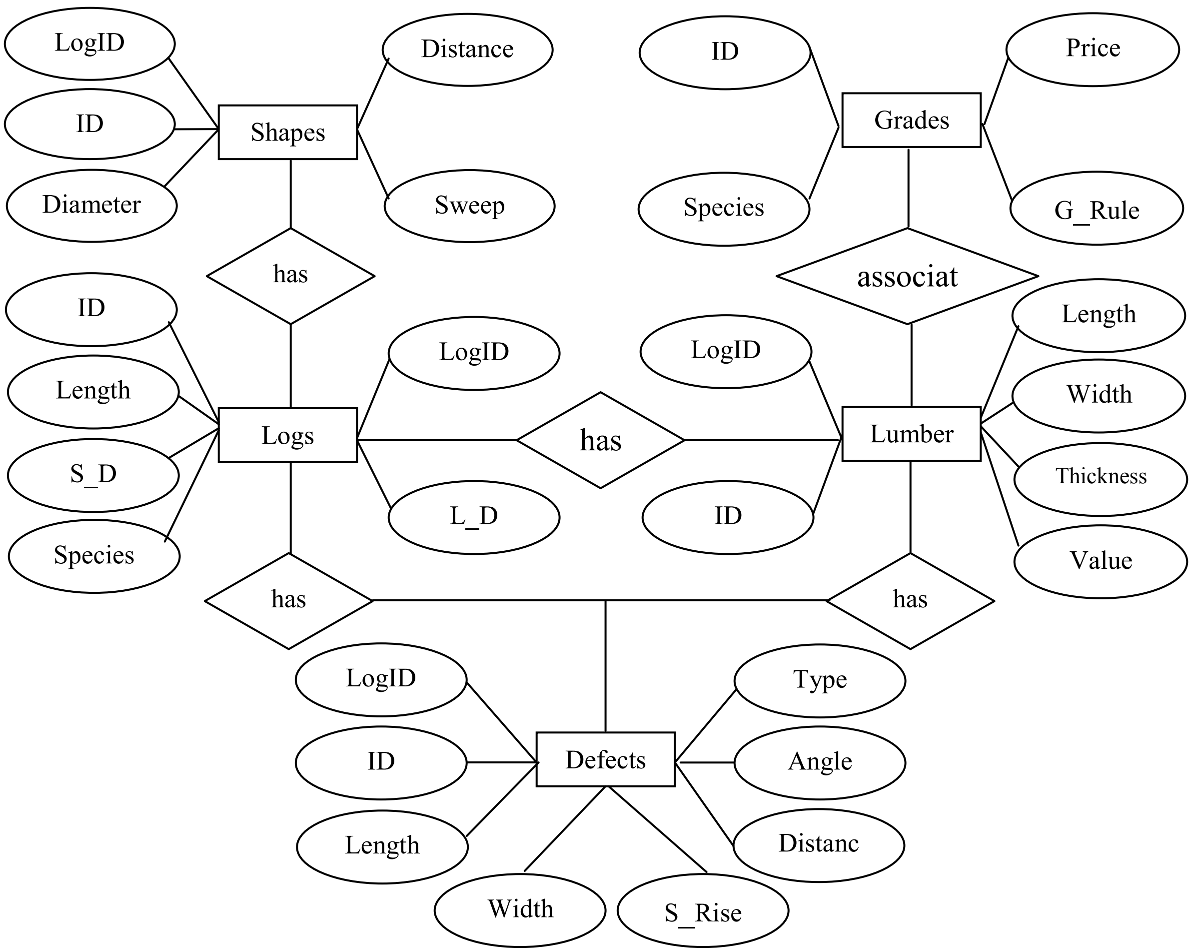

Figure 3.2. ER model of the optimal sawing system.
S_D: small-end diameter; L_D: large-end diameter; S_Rise: defect surface rise; G_Rule: Lumber grading rule.

3.2.2 3D log modeling

3D modeling techniques together with OpenGL primitive drawing functions were used to generate the three-dimensional log visualization (Wang et al. 2009). OpenGL is the most widely adopted 3D graphics Application Programming Interface (API), which consists of about 150 distinct commands that can be used to specify the objects and operations needed to produce interactive applications (Shreiner 2009). A log is reconstructed as a circular cross-section model (Zeng 1995). The cross-section model uses a series of cross sections at a fixed interval along the log length. This model is closer to a real log shape since log sweep and crook are considered at each cross section. A cone model was used to represent an internal defect (knot only), and its apex was assumed at the pith (central axis) of the log. The geometry of the internal defects was described by a mathematical model developed by Thomas (2008). When a sawing plane passed through the internal defect, a two-dimensional rectangle defect area was exposed on the lumber surface. The location and size of the defect area were determined using the development of the mathematical procedures. The OpenGL functions such as translation, rotation, and scaling were used to facilitate the visualization of the log. For example, rotation is performed by calling glRotatef(α, x, y, z) which generates the rotation matrix by defining the degrees to be rotated (α) and the axis to be rotated about (x-axis, y-axis, or z-axis). The generic matrix of rotation α angle around the three axes can be derived and expressed as (Woo et al. 2000):

$$R_x(\alpha)=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\alpha & -\sin\alpha & 0\\ 0 & \sin\alpha & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix} R_y(\alpha)=\begin{bmatrix}\cos\alpha & 0 & \sin\alpha & 0\\ 0 & 1 & 0 & 0\\ -\sin\alpha & 0 & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix} R_z(\alpha)=\begin{bmatrix}\cos\alpha & -\sin\alpha & 0 & 0\\ \sin\alpha & \cos\alpha & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (3.1)$$

To render a 3D log efficiently, simple triangle strips were used. Let the coordinates of the vertices of a triangle be (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), respectively, and the coordinate matrix for this triangle (the following transformation procedures can be applied to all of the triangle strips) after rotating by α degrees around the x-axis can be expressed as (Wang et al. 2009):

$$\begin{bmatrix}x_1' & x_2' & x_3'\\ y_1' & y_2' & y_3'\\ z_1' & z_2' & z_3'\end{bmatrix}=R_x(\alpha)\times\begin{bmatrix}x_1 & x_2 & x_3\\ y_1 & y_2 & y_3\\ z_1 & z_2 & z_3\end{bmatrix} \quad (3.2)$$

$$TS' = R_x(\alpha)\times TS$$

Where, *TS* is the coordinate matrix for one triangle strip on the surface of a log before transformation and *TS′* is the coordinate matrix after transformation. Similarly, the coordinate matrices for the triangle strip can be rotated around the y- and x-axes.

3.2.3 Sawing algorithms

Opening face

There are three steps to determine the best opening face: (1) identifying four sawing faces by log rotation - If the external defects are scattered over the entire log surface, the log should be positioned so that the defects are located on the edges of the sawing faces and can be easily removed by edging. When defects are concentrated in one portion of the log, they should be placed on one log face as much as possible. A mathematical procedure was developed to identify four log faces after placing the majority of the defects at the edge of the cutting planes or on one face; (2) determining the best face - It is assumed that the opening face is cut from the best sawing face (Thawornwong et al. 2003). The procedures for determining the best face are based on the USDA Forest Service hardwood log grading rules (Figure 3.3) (Rast et al. 1973). It is noted that the same grade will occur in more than one log face since there are only 3 grades (F1, F2, and F3). If a log has only one highest grade face, it will be selected as the best face; otherwise the face with the maximum clear area (curved clear surface area) will be selected as the best face; (3) determining the dimension of the opening face - The width of the opening face is determined as follows (Malcolm 1965): if the grade of the best face is F1, the slab width should be 6.25 inches (6-inch is the minimum width for the highest lumber grade board and 0.25-inch is the width of log sawing kerf) for logs greater than or equal to 13 inches in small-end diameter, otherwise the log would be slabbed to a width of 4.25 inches. For all logs that have a best face with grade of F2 or F3, the slab width is 3.25 inches.

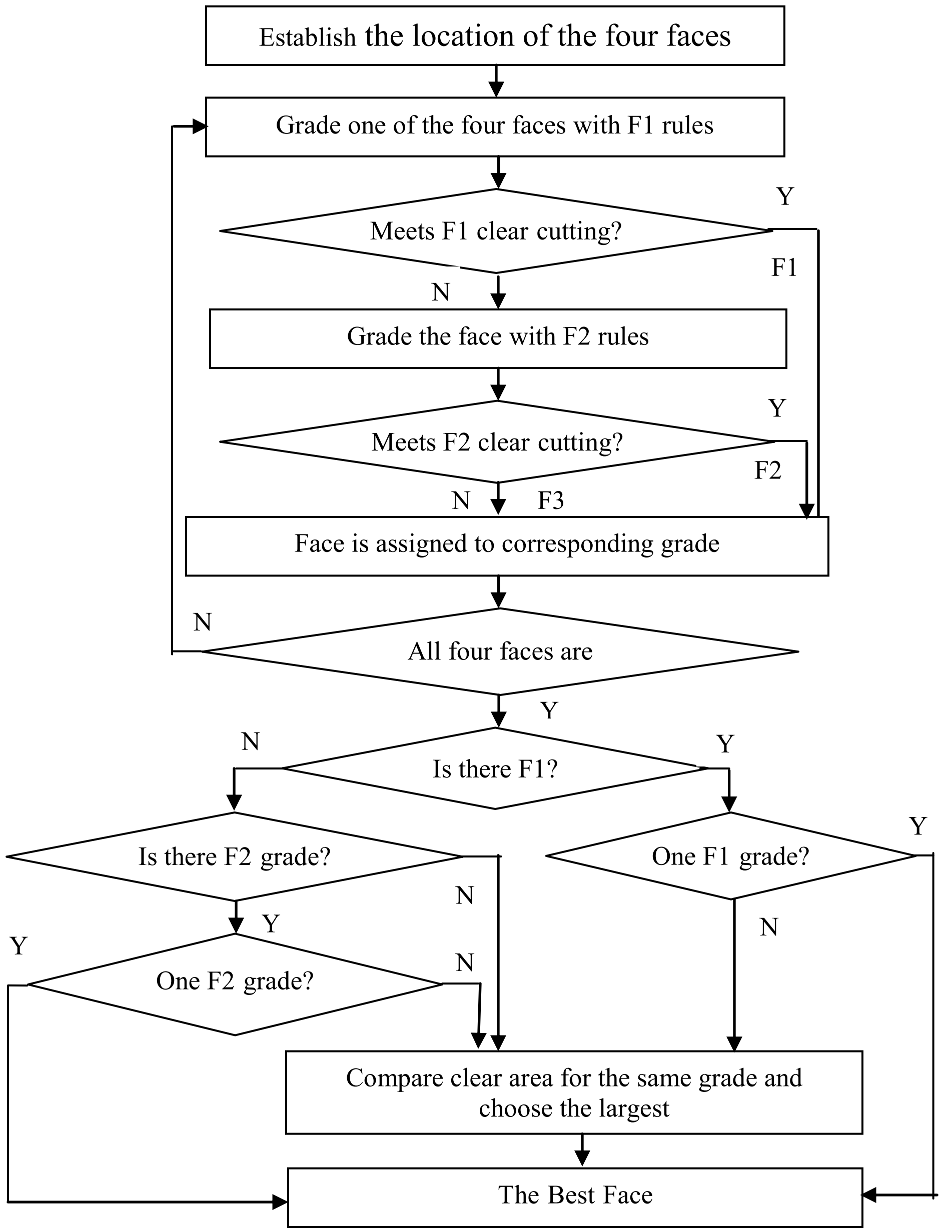

Figure 3.3. Procedures for determing the best face.

Heuristic algorithm for log grade sawing

A computer-based heuristic algorithm was developed based on Malcolm's (1965) simplified procedures for hardwood log grade sawing. Cutting from the small-end, the opening face is set out full taper by using the small-end of the log as the pivot, and the unopened faces are parallel to the sawing lines. The log would not be rotated unless one of the other log faces could yield a higher-grade board than the current sawing face or the current cutting face reaches the central cant. Once a log face is sawn completely, the grade of the last board will be recorded and this face will not be chosen again, and the algorithm will consider the next face. This sawing process is repeated until a specified size cant is produced, indicating that the log sawing process is complete.

Mathematically-based algorithm for log grade sawing

A log is broken into four portions at the small end in log grade sawing (Figure 3.4a). Once the first opening face is determined, the four log sawing faces are fixed. A sequence of parallel sawing planes is first performed on portions 1 and 3 of the log. Then the parallel sawing planes with orthogonal orientation are conducted on portions 2 and 4. A mathematical model for maximizing lumber recovery value through grade sawing can be expressed by the following function:

$$\begin{aligned} F = (&L_1^*, L_2^*(L_1^*), L_3^*(L_1^*, L_2^*), L_4^*(L_1^*, L_2^*, L_3^*), V^*(L_1^*, L_2^*, L_3^*, L_4^*), \\ &S_1^*(L_1^*), S_2^*(L_1^*, L_2^*), S_3^*(L_1^*, L_2^*, L_3^*), S_4^*(L_1^*, L_2^*, L_3^*, L_4^*)) \end{aligned} \tag{3.3}$$

Where, L_1, L_2, L_3, L_4 and S_1, S_2, S_3, S_4 are the sawing planes and sawing patterns at each portion, respectively; V is the lumber value, and * indicates an optimal value. This proposed model is based on the optimal log grade sawing procedure described by Bhandarkar et al. (2008). The objective of function (3) is to find the locations of L_1, L_2, L_3, and L_4 to maximize the total lumber value. To generate the candidate flitches, each portion of the log is divided into n equidistant sawing planes with resolution c, and a sawing plane is denoted by l_1 at the first portion (Fig 3.4a). For computational convenience, all the symbols in the mathematical algorithm are set as integers in millimeter. Let $C = \{1, 2, \cdots, n\}$ be a finite set of all the potential sawing planes, and $S = \{s_0, s_1, \cdots, s_n\}$ be a subset of C that satisfies the following constraints:

$$(s_i - s_{i-1} - \left\lceil \frac{k}{c} \right\rceil) \cdot c \in T, \textit{ for } 1 \le i \le n \tag{3.4}$$

$$s_0 = 1, s_n = n \tag{3.5}$$

Where, $T = (T_1, T_2, \cdots, T_m)$ is a set of lumber thickness values (mm); m is the total number of lumber thicknesses considered.

c is the sawing plane resolution (mm).

k is the kerf thickness (mm).

$n = CR / c$ is the total number of sawing planes within the cutting range, so the possible sawing planes are enumerated as 1,2,…,*n*, while CR is the cutting range between the opening face and central cant (mm).

A sawing pattern which satisfies the functions (3.4) and (3.5) will be considered as a feasible solution for log grade sawing (Figure 3.4b). The optimal sawing patterns can be determined using a dynamic programming algorithm. Let $v^*(i)$ represents the optimal lumber value for each portion of the log between cutting planes 1 and i, $g(i, j)$ be the lumber value from the cutting planes i through j, a recursive mathematical equation for the dynamic programming can be formulated as follows (Bhandarkar et al 2008):

$$v^*(i+1) = \max_{j \in [1,m]} (v^*(i + 1 - \frac{T_j}{c} - \left\lceil \frac{k}{c} \right\rceil) + g(i + 1 - \frac{T_j}{c}, i + 1)) \tag{3.6}$$

The following algorithm is used to optimize the objective function F in Equation (3.3):

(I) Determine the initial cutting range CR_1 and set $N_1 = \lfloor CR_1 / c \rfloor$.

(II) For each $l_1 \in (0, N_1]$:

(A) Run the dynamic programming algorithm on portion 1 of the log and get the output $V_1^*(l_1)$ and $S_1^*(l_1)$.

(B) Determine the cutting range CR_2 for portion 2 of the log, and set $N_2 = \lfloor CR_2 / c \rfloor$.

(C) For each $l_2 \in (0, N_2]$:

(a) Run the dynamic programming algorithm on portion 2 and get the output $V_2^*(l_1, l_2)$ and $S_2^*(l_1, l_2)$.

(b) Determine the cutting range CR_3 for portion 3 of the log, and set $N_3 = \lfloor CR_3 / c \rfloor$.

(1) For each $l_3 \in (0, N_3]$:

1) Run the dynamic programming algorithm on portion 3 of the log and get the output $V_3^*(l_1, l_2, l_3)$ and $S_3^*(l_1, l_2, l_3)$.

2) Determine the cutting range CR_4 for portion 4 of the log, and set $N_4 = \lfloor CR_4 / c \rfloor$.

For each $l_4 \le N_4$, run the dynamic programming algorithm on portion 4 of the log and get the output $V_4^*(l_1, l_2, l_3, l_4^*)$ and $S_4^*(l_1, l_2, l_3, l_4^*)$.

(2) Decide the optimal l_3^* such that $V_3^*(l_1, l_2, l_3^*) + V_4^*(l_1, l_2, l_3^*, l_4^*)$ is maximized, then output $V_3^*(l_1, l_2, l_3^*)$, $S_3^*(l_1, l_2, l_3^*)$, $V_4^*(l_1, l_2, l_3^*, l_4^*)$, and $S_4^*(l_1, l_2, l_3^*, l_4^*)$.

(D) Decide the optimal l_2^* such that $V_2^*(l_1, l_2^*) + V_3^*(l_1, l_2^*, l_3^*) + V_4^*(l_1, l_2^*, l_3^*, l_4^*)$ is maximized, then output $V_2^*(l_1, l_2^*)$, $S_2^*(l_1, l_2^*)$, $V_3^*(l_1, l_2^*, l_3^*)$, $S_3^*(l_1, l_2^*, l_3^*)$, $V_4^*(l_1, l_2^*, l_3^*, l_4^*)$, and $S_4^*(l_1, l_2^*, l_3^*, l_4^*)$.

(III) Decide the optimal l_1^* such that $V_1^*(l_1^*)+V_2^*(l_1^*,l_2^*)+V_3^*(l_1^*,l_2^*,l_3^*)+V_4^*(l_1^*,l_2^*,l_3^*,l_4^*)$ is maximized. Output $V_1^*(l_1^*)$, $S_1^*(l_1^*)$, $V_2^*(l_1^*,l_2^*)$, $S_2^*(l_1^*,l_2^*)$, $V_3^*(l_1^*,l_2^*,l_3^*)$, $S_3^*(l_1^*,l_2^*,l_3^*)$, $V_4^*(l_1^*,l_2^*,l_3^*,l_4^*)$, and $S_4^*(l_1^*,l_2^*,l_3^*,l_4^*)$.

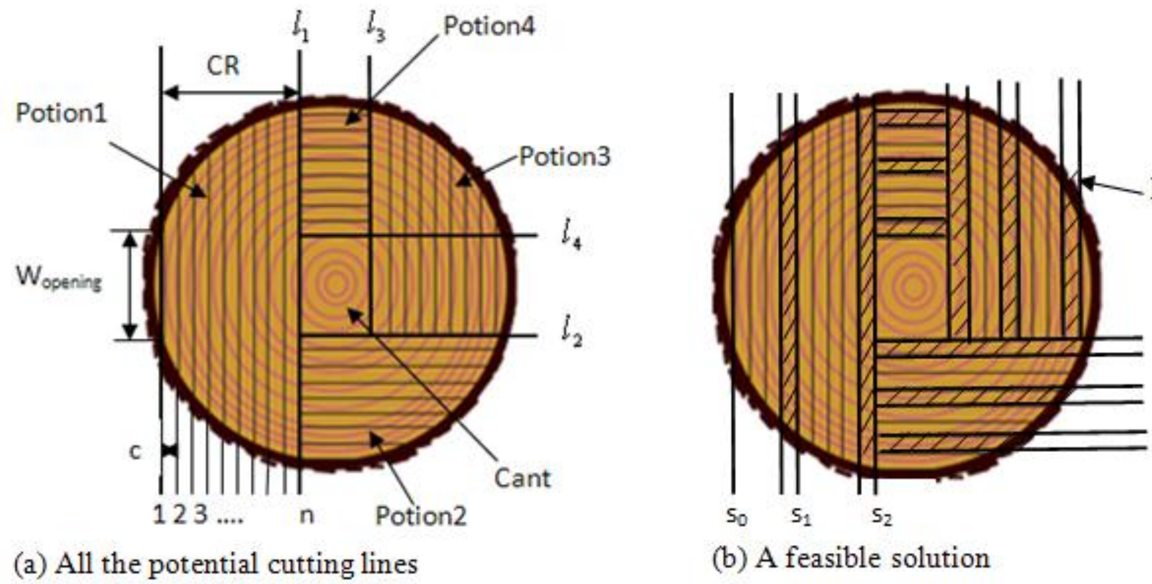

Figure 3.4. Dynamic programming for log grade sawing.

3.2.4 Cant resawing

The value of the central cant is essential when comparing the total lumber value derived from different sawing methods for each log. The 3D optimization system allows the user to make a decision whether to keep the cant or resaw it. If the central cant is sawn, a usable sawing region for the cant should be defined prior to sawing. Since the taper sawing method is used in the sawing process, the cant will not be square. Thus, the taper must be removed from the cant first. It is assumed that the size of the final cant is the same as the small end of the unfinished cant. Given the lumber thickness and sawing kerf, the best cutting solution can be determined by comparing the total lumber value obtained from two sawing directions (horizontal and vertical sawing) using the live sawing method. The problem of central cant resawing can still be solved by the dynamic programming algorithm. The parameters used for cant resawing are the same as log grade sawing with the exception for log sawing orientation and cutting range.

3.2.5 Lumber grading

Prior to lumber grading, the sawn flitch must be re-sawn into lumber. All the flitches were edged to remove the wanes. To generate this lumber pattern, the width of the lumber was assumed as the narrowest clear area width along the flitch. The edged lumber was graded by a computer algorithm based on the NHLA grading rules and a hardwood lumber grading program (Klinkhachorn et al. 1988) (Figure 3.5). To determine the possible grade for a lumber, the width, length and surface measure (SM) of the lumber must be computed, and a potential grade assigned to the poor face. After these steps, the potential number of clear cuttings and cutting units (CUs) can be calculated. By comparing the number of cuttings and CUs obtained from the lumber and the requirements in the NHLA grading rules, a final grade can be obtained (NHLA 2007). In this study, the lumber grades include First and Seconds (FAS), FAS-One-Face (F1F), Select, 1Common (1COM), 2Common (2COM), and 3Common (3COM).

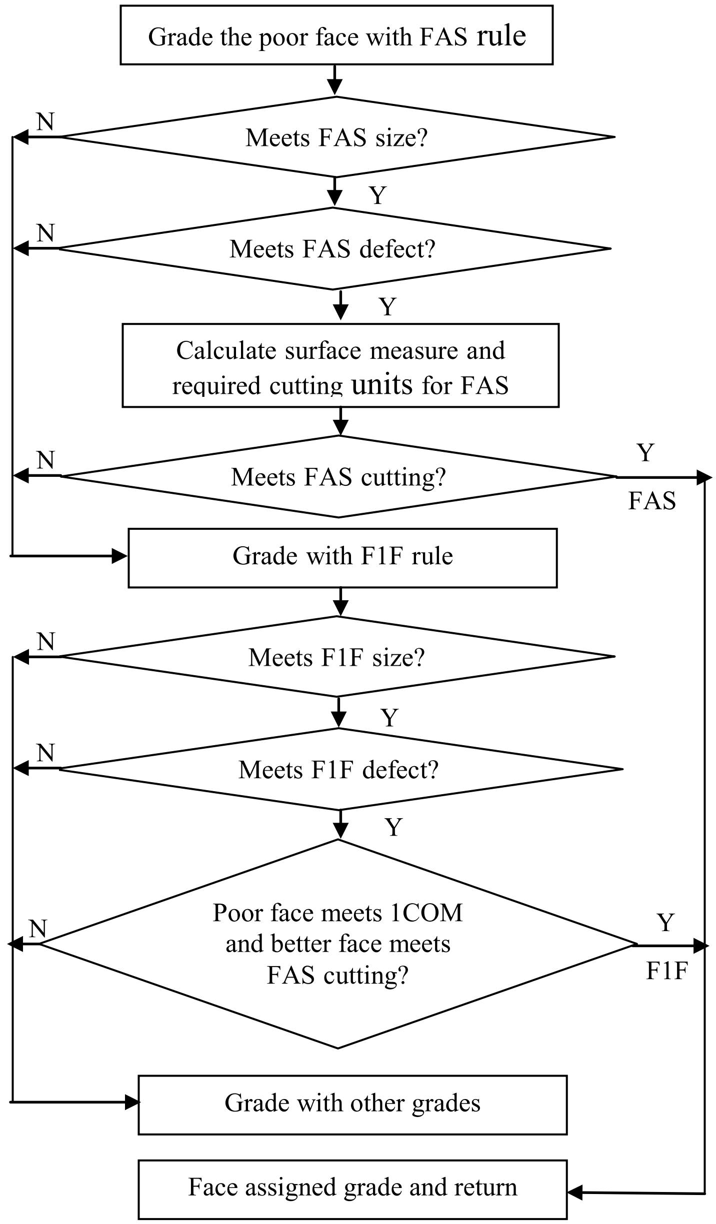

Figure 3.5. Flowchart of lumber grading process.

3.3 Optimal Sawing System Implementation

3.3.1 Running the system

The system can be implemented on either a desktop or a laptop and run on Windows platform. In this study, all the log sawing simulations were performed on a desktop PC equipped with 3.16 GHz CPU, 3.25 GB RAM, 300 GB hard drive. After starting the program, the user needs to click Run -> 3D Log in the menu bar, then a dialog with a list of logs will pop up for selection (See appendix I). There are four tab controls labeled “Logs”, “Shapes”, “Defects”, and “Grades” in the dialog. The “Logs” tab is used to display all the log data saved in the Access database. By clicking one of the other three tabs, the defects, shapes, and grades associated with the selected log can be displayed. A structured query language (SQL) query was employed to retrieve the related data from the database.

3.3.2 3D log visualization

Once a log is selected, the user can click the “Next” button at the lower right corner of the dialog box to access to the main interface, which is composed of four major sections: display area (top area), sawing results area (bottom middle area), information area (bottom left area), and command area (bottom right area) (Figure 3.6a). The selected log in three dimensions is shown in the display area. There are several menus on the top of the interface including “File”, “Edit”, “View”, “Help”, and “Run”. By clicking the “view” menu, the user can opt to move, rotate, and zoom out/in the log.

3.3.3 Opening face determination

The opening face is determined by clicking the “Best Open Face” button. When the user clicks the “Best Face” radio button, the results of the log rotation angle, best face, and the number of defects on each log face appear on the top of the display area. For the example log, it is rotated 10 degrees counterclockwise, face 4 is the best face, and the numbers of defects at faces 1 to 4 are 1, 2, 2, and 0, respectively (Figure 3.6b). If the user clicks the “Log Cut Face” radio button, the opening face will be generated from face 4 and displayed in the display area. The user can also click the “Log Grade” radio button to determine the log grade.

3.3.4 Log sawing simulation

Once the opening face is determined, the user can choose either the heuristic or dynamic programming algorithm to saw the log. Prior to the interactive simulation process, the user needs to specify some sawing variables (i.e., kerf width, lumber thickness, cant size, and sawing interval) at the bottom left area and choose appropriate commands at each group box. In our example, the sawing kerf width and lumber thickness were 1/8 inch and 1-1/8 inch, respectively, and the cant size was 4×6 inches, all of the sawing parameters used were the same as the sawmills surveyed. When using the dynamic programming algorithm to optimize log grade sawing, a sawing interval must be selected. The interval between stages is an important factor in the dynamic programming formulation, which should be a common denominator of all sizes handled (e.g., a common denominator of all thicknesses and saw kerf). Here, the interval was set as 0.16 inch (4mm), therefore the sawing kerf and lumber thickness became 4mm and 28 mm, respectively. The lumber thickness 1 3/8 inch (36mm) was also used when multiple lumber thicknesses was considered in the system.

The log grade sawing process using heuristic algorithm can be conducted after the sawing kerf, lumber thickness, cant size, and sawing interval were specified. Then the log was sawn except for the central cant. The user can opt to saw the central cant or keep it. If the cant is left, its value will be computed based on its volume and price. Similarly, the log grade sawing process can be simulated using the dynamic programming algorithm. The final sawing patterns and sawing results with cant resawing based on the two algorithms were presented in Figure 3.6c and Figure 3.6d. A total of 10 pieces of lumber were generated and the total lumber value is $20.62 using the heuristic algorithm and $25.32 using dynamic programming, respectively.

"Enumerative for log sawing" and "Simulation for log sawing" can be performed to simulate log sawing without using optimal algorithms. "Enumerative for log sawing" enables the selected log to rotate from 0 to 85 degrees at 5 degree increment and the opening face width is 3.25, 4.25, and 6.25 inches, respectively. The opening face needs to be determined before log sawing if "Simulation for log sawing" is used. If the first opening face is face 1 and the user chooses "GradeSawing90", the log is cut clock-wisely from face 1, face 2, face 3, to face 4. If the user chooses "GradeSawing180", the log is cut from face 1, face 3, face 2, to face 4.

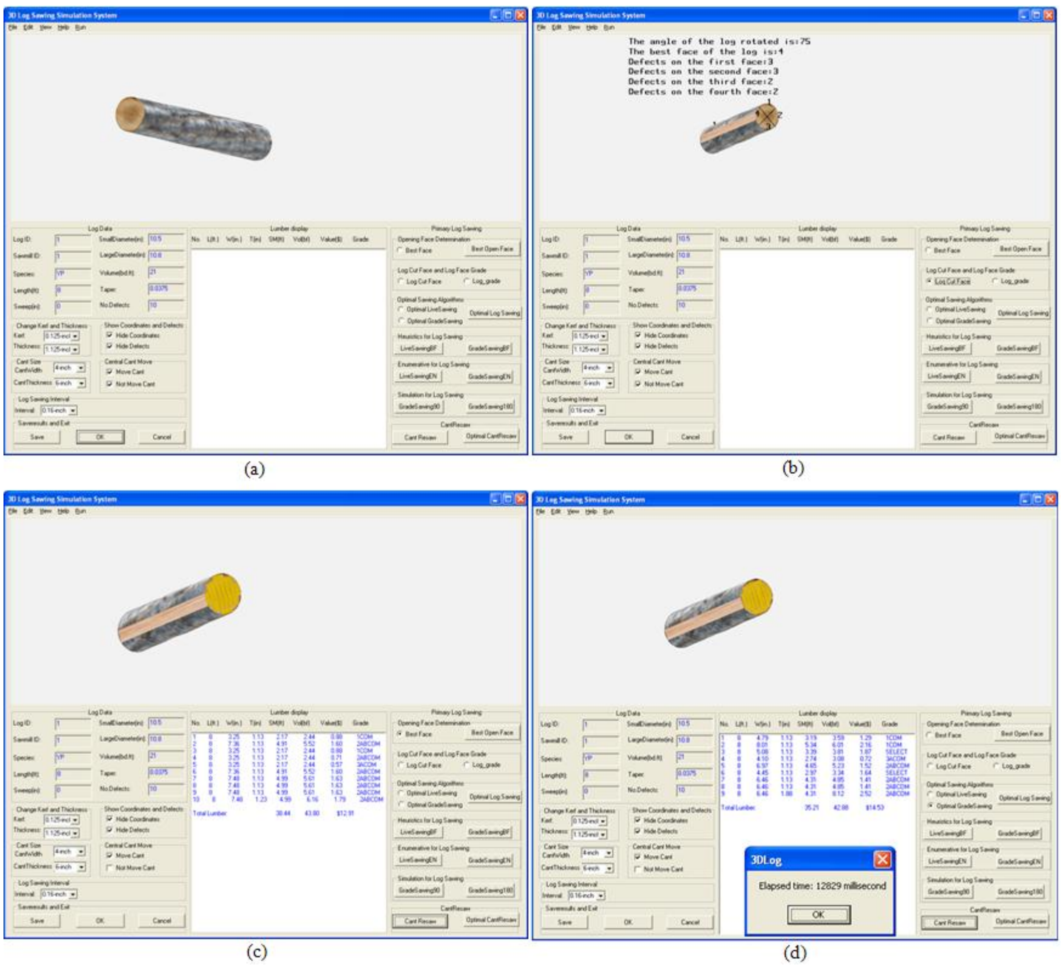

Figure 3.6. Log sawing results.
(a) Main interface. (b) Determining the opening face. (c) Heuristic optimal sawing. (d) Dynamic optimal sawing.

3.4 System Application and Verification

3.4.1 Data collection

Log sawing practices for five small hardwood sawmills in North Central West Virginia were studied between October 2009 and August 2010 (Lin et al. 2010). These mills were typical small-scale hardwood sawmills across the state in terms of equipment and sawing methods. A total of 230 logs in two species, red oak (*Quercus rubra)* and yellow-poplar (*Liriodendron tulipifera*), were measured on site, of which 50 logs (25 in each species) were selected to test the program. The selected logs were 8-14 feet in length and 10-13 inches in scaling diameter (Table 3.1). Log taper was calculated as the difference between large-end diameter and small-end diameter divided by log length. Log profile data include log length, large and small end diameters, and diameters at every foot from the small end. External log defect data collected include defect types (such as adventitious knot (AK), heavy distortion (HD), medium distortion (MD), light distortion (LD), overgrown knot (OK), sound knot (SK), and unsound knot (UK)), distance of defects away from the small end of a log, defect angle with respect to the predetermined initial zero degree, defect size, and defect surface rise. The external log defect data format is the same as those obtained by using the 3D log laser scanner developed by the USDA Forest Service, which allows the future integration of the laser scanning data process with the developed sawing system. Internal log defect locations were predicted using the models by Thomas (2008). The recorded log and predicted data were stored in a MS Access database.

All the logs were marked with unique numbers and the corresponding boards sawn from the each log were labeled in order to track the source of the lumber after completing the sawing process for the sample log. Lumber length (ft), width and thickness (inches), and volume (bd. ft) were measured (Table 3.2). The grade and surface measure of the lumber were determined by a certified NHLA grader at each sawmills. The lumber value was based on the green rough lumber price at the time of assessment. The collected lumber data were compared with the optimal log sawing system simulation results.

Table 3.1. Characteristics of the sample logs.

Statistic categories	Length (foot)	Small-end diameter(inch)	Large-end diameter(inch)	Taper (inch/foot)
Min	8	10.00	10.22	0.01
Max	14	13.19	14.84	0.31
Mean	9	11.38	12.20	0.08
Stdv*	1.62	1.14	1.43	0.07

* Standard deviation.

Table 3.2. Characteristics of lumber from the sample logs.

Statistic categories	Length (feet)	Width (inch)	Thickness (inch)	SM**	Volume (bd.ft)	Value ($)
Min	6	3.50	1.00	2	2.75	0.86
Max	14	8.44	2.13	7	10.69	6.93
Mean	9	6.10	1.42	4	5.58	2.27
Stdv*	1.52	1.12	0.16	0.9	1.44	0.88

* Standard deviation. ** Surface measure.

3.4.2 Opening face

To determine if the optimal opening face is better than any faces chosen randomly, we simulated log sawing based on the optimal opening face and other assumed opening faces with log rotation angle from 0 to 85 degrees with a 5 degree-increment and the opening face width of 3.25, 4.25, and 6.25 inches, respectively (Table 3.3). A sequence of parallel cuts was performed for each log face until a central cant remain, which is sawn later by parallel cuts. The results showed that the total lumber value using the optimal opening face cut was higher than the average total value derived from any other opening faces by an average of 4.31%. The log rotation angle and the width of the opening face had impacts on the total lumber value recovered.

Table 3.3. Lumber value from the optimal opening face cut vs. the average lumber value from the other opening face cut.

Log No.	Lumber Value*	Average Lumber Value**	Log No.	Lumber Value*	Average Lumber Value**
1	12.91	10.59	26	34.72	30.79
2	16.06	15.25	27	40.04	38.6
3	17.01	15.95	28	43.02	45.05
4	14.57	12.97	29	55.23	54.34
5	20.52	19.83	30	43.06	40.70
6	12.48	12.66	31	32.02	28.91
7	27.12	25.39	32	21.05	20.96
8	20.40	19.71	33	32.02	32.51
9	18.93	17.39	34	17.22	15.05
10	20.13	19.80	35	23.00	22.46
11	30.02	28.58	36	23.35	21.68
12	25.17	24.92	37	35.64	33.83
13	17.50	15.66	38	21.15	18.73
14	16.84	14.70	39	27.69	27.36
15	28.26	26.28	40	26.18	24.04
16	32.76	31.63	41	47.25	45.85
17	35.04	34.29	42	22.15	20.49
18	28.29	26.08	43	24.14	23.47
19	40.38	39.78	44	34.28	33.80
20	18.92	17.91	45	29.67	28.08
21	23.27	22.50	46	29.50	28.62
22	30.56	28.39	47	21.15	20.97
23	37.24	37.24	48	19.82	18.75
24	31.17	30.74	49	33.18	31.83
25	39.09	38.29	50	22.76	21.32

* Lumber value from the optimal opening face cut

** Average lumber value from other opening faces cut.

3.4.3 Log sawing comparisons

<u>*Lumber value and volume improvement*</u>

If heuristic and dynamic programming optimization are used, sawmills have the potential to improve their lumber recovery value by 10.01% and 14.21% (Figure 3.7 and Figure 3.8), respectively. High volume recovery tends to result in high lumber value recovery. For example, when using heuristic and dynamic programming algorithms to optimize log sawing, the average volume of lumber was 55.56 bd.ft and 56.40 bd.ft, respectively, and the average lumber value was $28.18 and $29.42, respectively. The average lumber volume was improved 2.5% and 4.1%, respectively. However, it is noted that high volume recovery does not always mean high lumber value recovery for some logs. It is also noted that lumber value recovery could be improved significantly for logs with more defects. For instance, for logs with 6 or more defects, the average of lumber value recovery could be improved by 11.08% and 16.28%, respectively. However, the average lumber value recovery was improved by 9.01% and 12.56% for logs with 5 or less defects. The average lumber value obtained by the dynamic programming algorithm was not always greater than the value generated by the heuristic algorithm as the precision of the dynamic programming optimization depends on the selected stage interval. The smaller the state interval is, the more precise the solution will be. However, the more precise solution comes with the expense of longer computing time.

Lumber grade improvement

We found that the distribution of lumber grades differed among different sawing methods. About 16%, 30%, and 36% of lumber grade were Select or higher in actual sawmilling operation, or using heuristic, or dynamic programming optimization (Figure 3.9), respectively. In the actual sawmilling operation, 44%, 32%, and 9% of lumber was graded as 1COM, 2COM, and 3COM, respectively. When using the heuristic algorithm to optimize those logs, 48%, 19%, and 3% of lumber was graded as 1COM, 2COM, and 3COM, respectively. When using the dynamic programming algorithm, 44%, 18%, and 2% of lumber yielded the grade of 1COM, 2COM, and 3COM, respectively. Therefore, lumber grades can be improved using optimization algorithms, resulting in the increase of the final lumber value recovery.

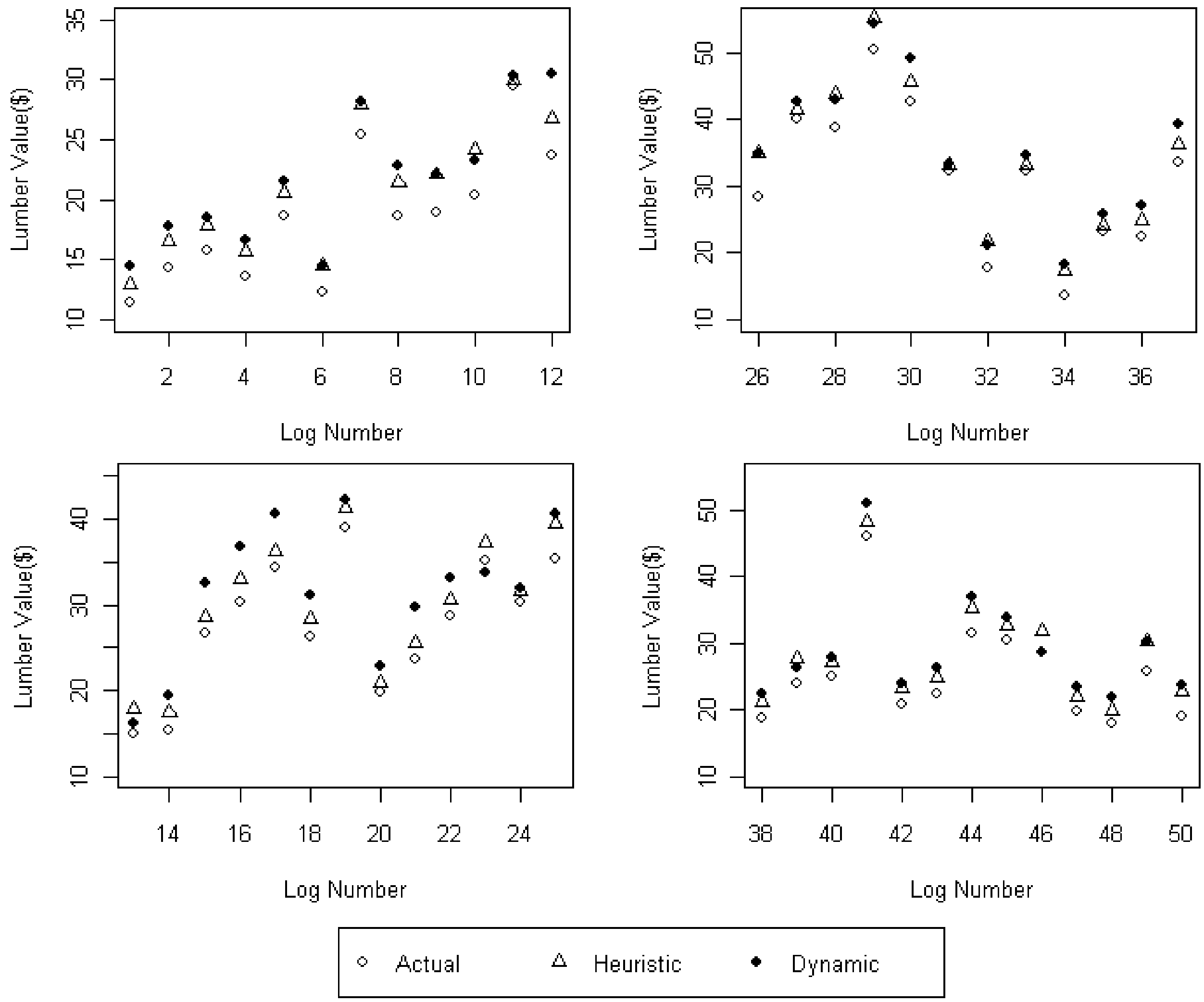

Figure 3.7. Average lumber value from actual sawmills, heuristic and dynamic programming algorithms.

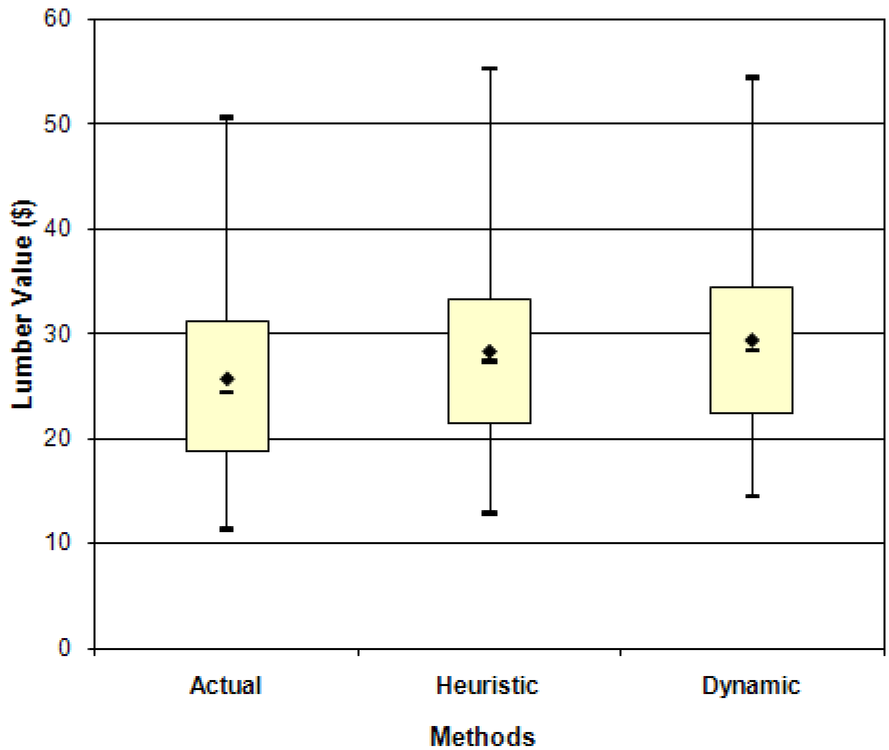

Figure 3.8. The distribution of lumber value by methods.

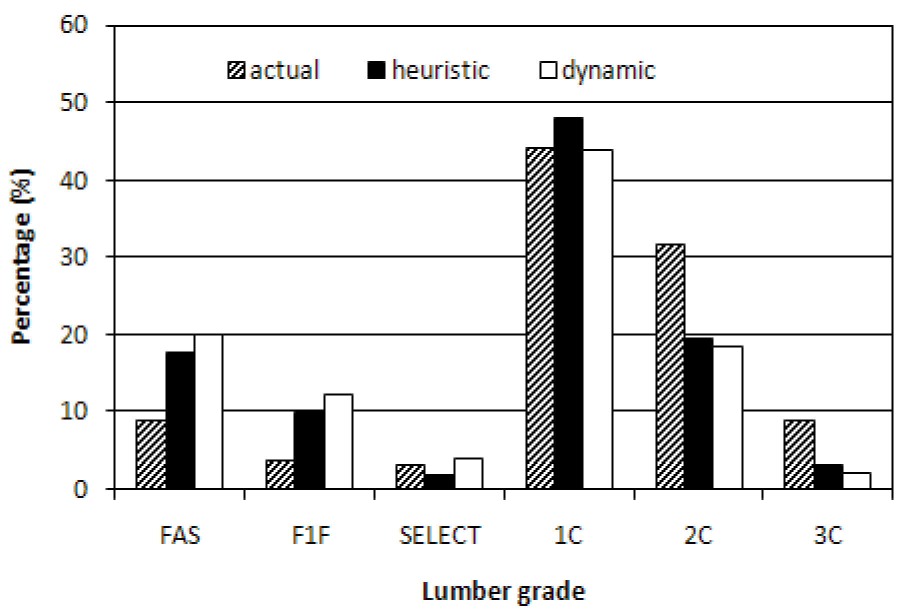

Figure 3.9. Lumber grade distribution.

3.4.4 Lumber value recovery by species

The average lumber value recovery was compared between two species, red oak and yellow-poplar. In the sawmill, yellow-poplar and red oak lumber value averaged $20.71 and $29.28, respectively. If using the heuristic algorithm to optimize log sawing, the average lumber value could be $23.01 and $31.89, respectively. If using the dynamic programming, the average lumber value could be up to $23.81 and $33.17, respectively. The lumber value using the heuristic algorithm could improve 11.11% for yellow-poplar or 8.94% for red oak when compared to the sawmill's results. On the other hand, the lumber value using the dynamic programming algorithm improved 14.95% for yellow-poplar and 13.29% for red oak. Lumber value recovery depends on log diameter, length, taper, quality, and other factors (Steele 1984). Among 50 selected sample logs, the log dimension is not significantly different between yellow-poplar and red oak. However, the number of external defects averaged 7.45 for yellow-poplar and 5.47 for red oak, which might explain why more improvement was achieved for yellow-poplar than red oak logs using the sawing optimization system. The results also showed that the lumber value recovery was different by species, which indicated that mill operators should pay more attention to valuable species when sawing.

3.4.5 Effects of multiple lumber thicknesses

Approximately 70% of the hardwood sawmills only saw 4/4'' inch thickness lumber in the U.S. (Chang et al. 2005). In this study, we analyzed whether high lumber value could be improved if multiple thicknesses were considered in the system using dynamic programming algorithm and various lumber thicknesses (Figure 3.10). The results showed that using multiple lumber thicknesses can improve lumber value recovery. For example, when lumber thickness of 28mm and 36mm were used in log sawing optimization, the average lumber value could increase

4.9% from $29.42 to $30.87. Therefore, if sawmills can efficiently handle different thicknesses of marketable lumber during lumber processing, multiple lumber thicknesses should help gain more lumber value recovery. However, optimization time could be doubled compared to a single lumber thickness.

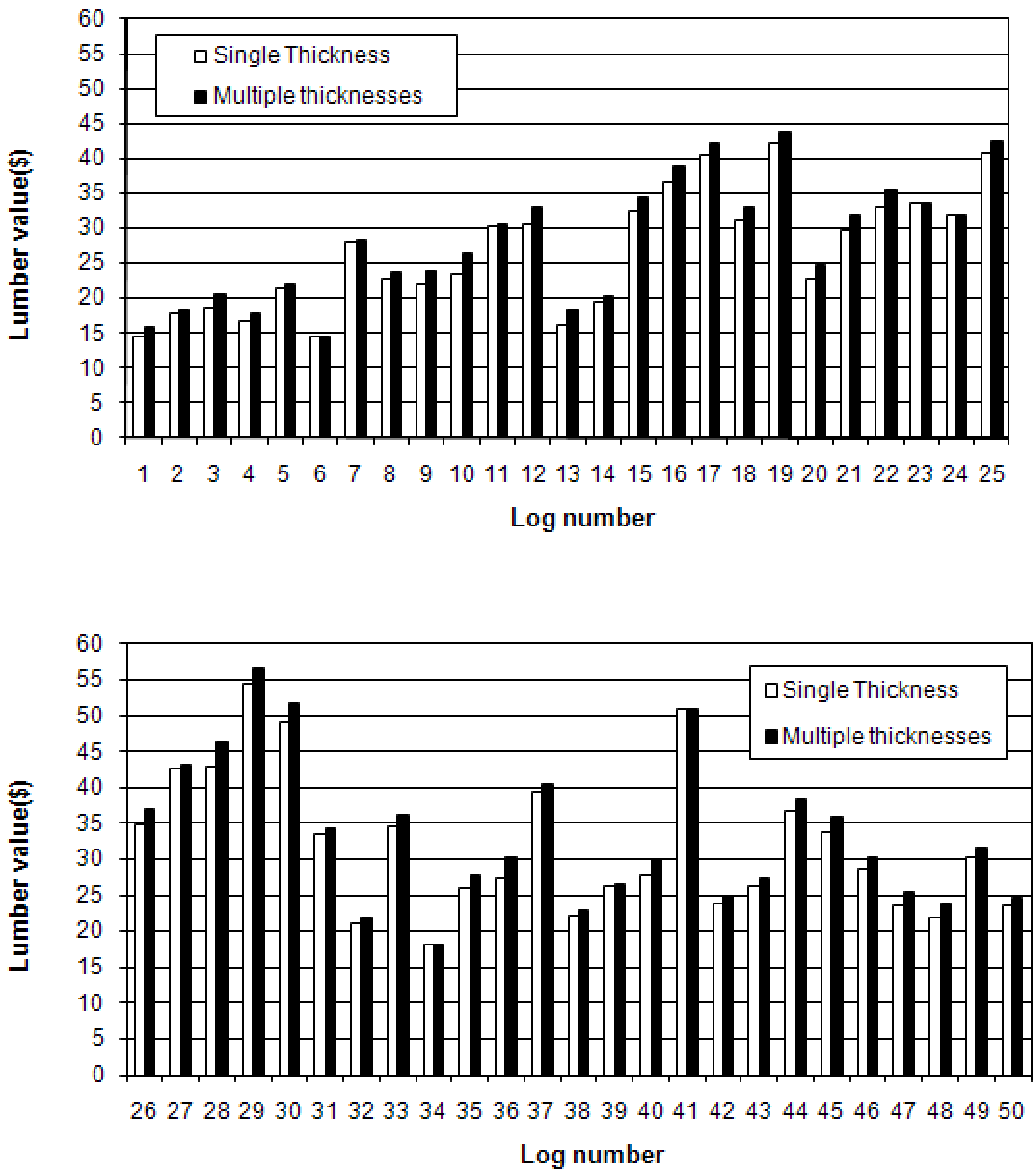

Figure 3.10. Average lumber value produced using single and multiple lumber thickness.

3.5 Discussion and Conclusions

Currently, the hardwood industry in the central Appalachian region is facing a set of challenges including: decreased log size and quality, limited resource availability, tightened environment restrictions on timber harvesting, reduced profit margins, and pressure from foreign competition (Milauskas et al 2005). Remaining viable and competitive, given the current market, has become a major concern for hardwood industry (Wang et al 2010). In response to these issues, hardwood sawmills in the region need to take action and aggressively search for new markets and while adopting more efficient processing methods to utilize the limited forest resources. Application of appropriate computer-aided sawing and grading systems will be one of the strategies to improve processing performance and enhance their competitiveness, specifically for small sawmills.

In this study, a low cost and user friendly 3D log sawing optimization system was developed to perform 3D log generation, opening face determination, sawing simulation, and lumber grading. Lumber value could be increased 4.31% when using the optimal opening face cutting, compared to the average lumber value by any random opening face cuts. The lumber value recovery could be improved 10.01% using heuristic or 14.21% using the dynamic programming optimization. The lumber grade could be improved significantly using the sawing optimization system. While, approximately 16% of lumber sawn in the sawmill graded Select or higher, this percentage could be increased to 30% by using the heuristic algorithm. Using multiple lumber thicknesses could improve further lumber value recovery compared to using a single lumber thickness. In this study using multiple lumber thicknesses showed that the average lumber value could be increased 4.9% from $29.42 to $30.87.

In this study, the optimal opening face was determined by heuristics, and it also can be determined by exhaustive search. However, this process would be time-consuming since every degree of log rotation and opening face width need to be considered simultaneously. We noted that the lumber value produced from the optimal opening face was not maximal in some cases. The reason may be that the defect types and sizes were not fully considered in the opening face algorithm. For example, defect penetration depth and clear area between bark and pith of a log will vary among defect types. In addition, severe and large defects have more significant effects on lumber value than slight defects, thus severe defects must be given top priority and should be rotated to the edge of the log sawing planes. Future research is needed to combine the internal defect information with the external defect information to determine the optimal opening face.

A significant improvement of lumber value and grade existed between the actual sawmilling production and the optimization simulation. Some measurement errors also existed in data collection process due to equipment, operators' experience, and other factors. For example, there were only 7 external defects found for one log, but 10, 14, and 16 defects appeared in three pieces of lumber after sawing it and most of them were tiny and small defects. Areas of some logs had lost bark due to operation or longtime storage, which affected external defect identifications. Logs were debarked in these five sawmills prior to sawing process. The sawyers had difficulty in identifying external defects, which could affect their decisions on sawing. In addition, the accuracy of the defect prediction model also contributed to the difference between real production and simulations. Factors including experience and error of operators, and mill equipment also have impacts on decision making at the headrig.

While the log sawing optimization system has the potential to improve lumber value recovery, some limitations exist in the system. The accuracy of the log sawing simulation is limited due to using a circular cross-section model to represent real logs. The stage interval for the dynamic programming algorithm was chosen as 4mm rather than 1mm in order to increase the system efficiency, and the precision of the sawing results was affected accordingly. More sample logs of various species, shape and defect should be tested to verify the system. All flitches produced from logs were edged to remove the wanes. The maximum lumber value was not guaranteed since flitch edging and trimming also has effects on the final lumber value. The optimum algorithm should be used to deal with flitch edging and trimming in order to increase the total lumber value recovery.

Future improvements of the log sawing optimization system include: (1) considering elliptical cross sections in the 3D log model to improve the accuracy of the model, (2) involving more variables including external defects type and size as well as internal defects to determine the opening face, (3) improving the log sawing algorithm to increase the efficiency and accuracy of the system, and (4) integrating log sawing with flitch edging and trimming optimization.

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CHAPTER 4: DEVELOPMENT OF AN OPTIMAL 3D VISUALIZATION SYSTEM FOR ROUGH LUMBER EDGING AND TRIMMING IN CENTRAL APPALACHIA*

* Submitted to International Journal of Forest Engineering.

Abstract

An optimal 3D visualization system was developed for edging and trimming of rough lumber in central Appalachian. ActiveX Data Objects were implemented via MS Visual C++/OpenGL to manipulate board data at the backend supported by a relational data model with four data entity types of board, shape, defect, and defect type. Exhaustive search procedures and a dynamic programming algorithm were employed to achieve the optimal edging and trimming solution, respectively. A lumber grading module was also developed to grade hardwood lumber based on the National Hardwood Lumber Association (NHLA) grading rules. The system was validated through comparisons of the total lumber values generated by the system and by six local sawmills. A total of 360 boards were measured including board dimensions, defects, shape, wane and the results of edging and trimming for each board. Results indicated that the lumber value and surface measure gained in these six sawmills could be increased on average by 19.97 percent and 6.2 percent respectively using the optimal edging and trimming system. The optimal edging and trimming system can not only be used as a training tool but also be installed on a field PC to aid the edging and trimming process.

4.1 Introduction

During primary log breakdown, a log is sawn into flitches at the headrig. These flitches are then edged or trimmed into lumber during the secondary breakdown process. Approximately 20 percent of the flitches produced must be edged and nearly all the flitches must be trimmed into lumber (Kline et al. 1990). In most hardwood sawmills, edger and trimmer operators visually examine the board surfaces, and then make quick judgments about the placement of cuts based on their knowledge of lumber grades and current lumber prices (Lee et al. 2003a). Many factors can impact the edging and trimming process, including visual estimates of board surface measure, fluctuating prices, numerous edging and trimming solutions, operators experience, and others (Abbott et al. 2000). Therefore, even for experienced operators it is difficult to obtain the optimal edging and trimming solution. Previous studies found that substantial losses could occur in the edging and trimming process (Flann and Lamb 1966, Bousquet 1989, Regalado et al. 1992a, Wang et al. 2009a). For example, Bousquet (1989) indicated that most sawmill edger operators removed an excessive amount of wood, which can result in value losses up to 30 percent. Regalado et al. (1992a) concluded that the edging and trimming operations resulted in lumber values that were only 65 percent of the optimum. Wang et al. (2009a) found that an average loss per board could be nearly half of a foot of surface measure and the average value loss ranged from 0.5 to 24.1 percent. Therefore, it is necessary to optimize the edging and trimming operations in order to increase sawmill profits and to ensure continued operations of hardwood mills (Abbott et al. 2000).

Several studies have been conducted to solve the optimization of hardwood lumber edging and trimming. Steele and Wengert (1987) studied the effects of edging and trimming practices on hardwood lumber yield using the best opening face method. Regalado et al. (1992a) developed a computer-based procedure to estimate the optimum edging and trimming solution. They evaluated the lumber value obtained from the optimization using different levels of defect information (Regalado et al. 1992b). Todoroki and Rönnqvist (1997) indicated that the problem of edging and trimming operations could be formulated as a packing problem with the objective of maximizing the total lumber value, and be solved using dynamic programming (Bhandarkar et al. 2008). Schmoldt et al. (2001) used branch and bound (B&B) search to obtain the optimal edging/trimming solution. In addition, several edging and trimming computer software systems have been developed (Kline et al. 1990, 1992, 2001, Abbott et al. 2000, Schmoldt et al. 2001, Lee et al. 2003a, 2003b). For example, Kline et al. (1992) designed a computerized hardwood lumber edger and trimming training system which could be used both as training and testing tool. Abbott et al. (2000) and Schmoldt et al. (2001) developed a prototype scanning system to scan rough hardwood lumber and process the data using a branch and bound (B&B) algorithm to derive the optimal edging and trimming solution. Lee et al. (2003a, 2003b) described a system that can scan rough, green lumber and automatically provide an optimal edging and trimming solution along with lumber grade. The wane boundaries in the system can be detected and a modular artificial neural network (MANN) used to locate clear wood, knots, and decay.

Although the automated edging and trimming systems have the potential to increase lumber yield, the applications of such systems are very limited, especially in small sawmills (Kline et al. 1990, Bowe et al. 2001). Small-scale sawmills are important components of the hardwood industry in central Appalachia. In West Virginia, approximately 68.52 percent of green hardwood producers produce less than 4 million board feet (MMBF) of lumber per year (WVDOF 2004). The small sawmills are less able to apply the advanced systems due to initial cost, payback period, and modifications to operations. According to a survey conducted on the small hardwood sawmills in the central Appalachian region (Hassler 2000), the lumber grading and edging/trimming were two of the top five priorities in terms of the importance and educational needs. In these sawmills, the lumber trimming/edging and grading procedures are still the processes that do not utilize any type of decision-making assistance. Wang et al. (2009a) evaluated lumber edging, trimming, and grading practices of small sawmills in West Virginia and indicated that most of the investigated sawmills were losing money to some extent because of their edging, trimming, and grading practices. With increased training on edging, trimming, and grading practices, these losses could be reduced significantly and profits improved for small sawmills. Therefore, it is necessary to develop a cost-effective and user-friendly computer aided processing system for small sawmills to assist their edging and trimming operations.

The objectives of this study were to: (1) develop algorithms to determine the optimum edging and trimming solution to maximize lumber value from rough lumber, (2) develop a user-friendly software system to implement the optimum algorithms within 3D visual simulation environment, and (3) evaluate the difference of lumber volume, lumber grade, and lumber value obtained from the optimum edging and trimming and those recovered relative to the actual sawmilling operations.

4.2 Optimal Edging and Trimming System Design

4.2.1 System structure

The optimal edging and trimming system consists of four major components: data manipulation/storage, 3D modeling, lumber grading, and edging and trimming optimization (Figure 4.1). A component object model (COM) was used to integrate the system that was designed using the principles of object-oriented programming (OOP). The system was programmed with Microsoft Foundation Classes (MFC) and Open Graphics Library (OpenGL). MFC provides a user friendly interface and can be easily connected to the database and transplanted to any other Windows applications, while OpenGL provides color images of 3D objects and offers the 3D virtual simulation environment (Wang et al. 2009b). The software system can be implemented either on a desktop or laptop and run on Windows platform.

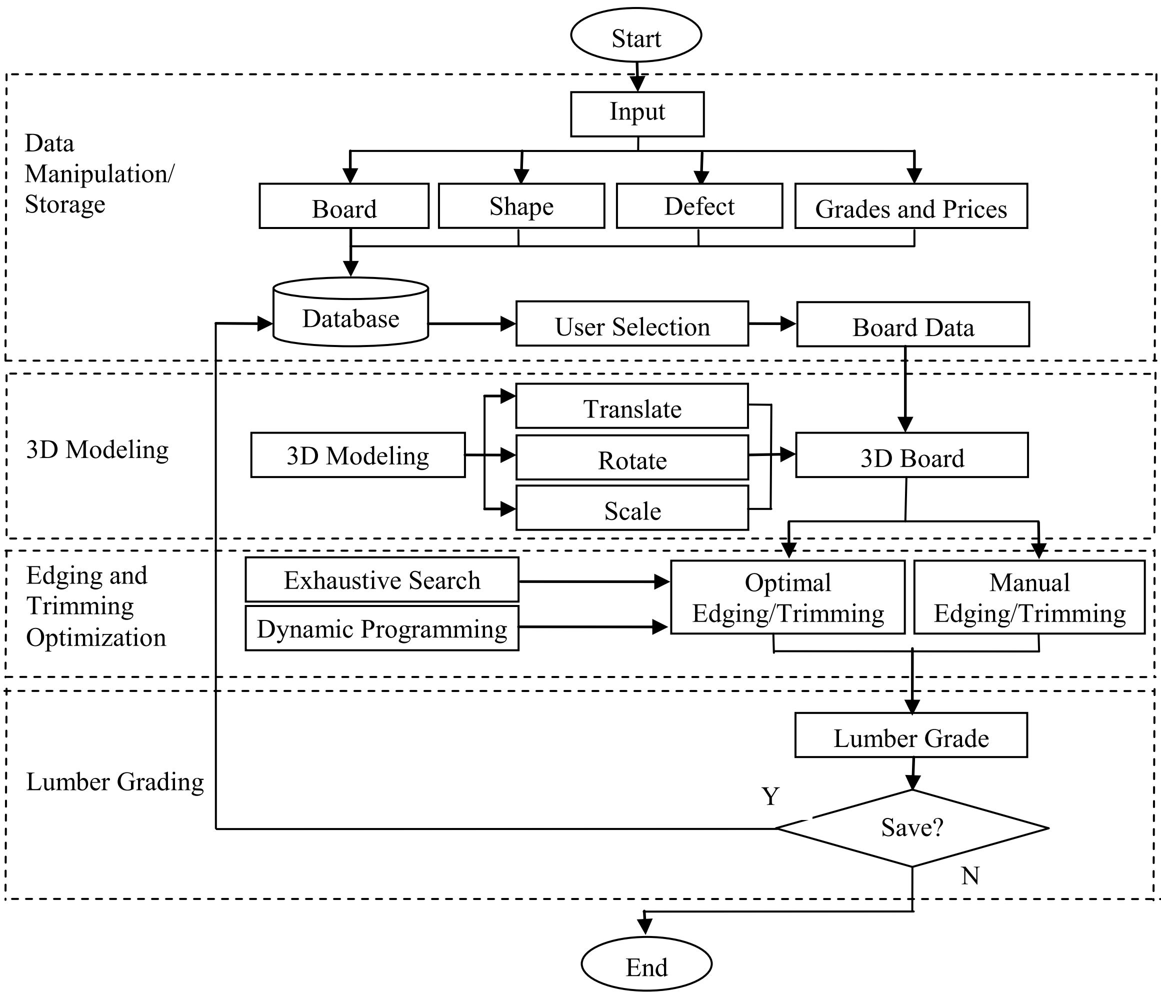


Figure 4.1. Architecture of optimal lumber edging and trimming system.

4.2.2 Data manipulation and storage

Microsoft ActiveX Data Objects (ADO) enables client applications to access and manipulate data from a variety of sources through an Object Linking and Embedding Database

(OLEDB) provider (MSDN 2010). The primary benefits of ADO are ease of use, high speed, low memory overhead, and a small disk footprint. In this study, ADO was applied to retrieve data from and save edging and trimming results to a Microsoft Access database. The simple way to incorporate ADO into programming is through the use of ActiveX controls, and it is very convenient to link the system database with MFC and ActiveX controls. The entity-relationship (ER) model for the optimal edging and trimming system was implemented via Microsoft Access, including four entity types: Board, Shape, Defect, and Defect Type. Once a board was edged and trimmed, the results including surface measure, lumber grade, and lumber value can be stored in a summary table within the database.

4.2.3 3D lumber modeling

3D modeling techniques together with OpenGL primitive drawing functions were used to generate three-dimensional lumber visualizations. OpenGL is a powerful yet flexible and standard tool to create high quality multidimensional graphics (Woo et al. 2000). Two OpenGL libraries, OpenGL Utility Library (GLU) and OpenGL Utility Toolkit (GLUT), were used to make visual representation of lumber and edging/trimming process. A board is visualized using simple triangle strips filled with a digital image of an actual board. The user can rotate, zoom in/out, and/or move the board around to facilitate visualization of the board to better understand the superficial characteristics at different scales. Three basic transformations of rotate, scale, and translate were modeled by using three functions: glRotatef(), glScalef(), and glTranslatef(), respectively. For example, rotation is performed by calling glRotatef(α, x, y, z) which generates the rotation matrix by defining the degrees to be rotated (α) and the axis to be rotated about (x-axis, y-axis, or z-axis). The generic matrix of rotation α angle around the x-axis can be derived and expressed as (Woo et al. 2000):

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.1}$$

Let the coordinates of a board originally drawn on screen be (x_1, y_1, z_1), (x_2, y_2, z_2),…, (x_n, y_n, z_n), respectively. If that piece of lumber is rotated by α around the x-axis and coordinates are transformed to $(x_1^{'}, y_1^{'}, z_1^{'})$, $(x_2^{'}, y_2^{'}, z_2^{'})$, …, $(x_n^{'}, y_n^{'}, z_n^{'})$, then the coordinate matrix after rotating by α degrees around the x-axis can be expressed:

$$\begin{bmatrix} x_1^{'} & x_2^{'} & \dots & x_{n-1}^{'} & x_n^{'} \\ y_1^{'} & y_2^{'} & \dots & y_{n-1}^{'} & y_n^{'} \\ z_1^{'} & z_2^{'} & \dots & z_{n-1}^{'} & z_n^{'} \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} = R_x(\alpha) \times \begin{bmatrix} x_1 & x_2 & \dots & x_{n-1} & x_n \\ y_1 & y_2 & \dots & y_{n-1} & y_n \\ z_1 & z_2 & \dots & z_{n-1} & z_n \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} \tag{4.2}$$

$$TS^{'} = R_x(\alpha) \times TS$$

Where, TS is the matrix containing locations of different coordinates for shape, defects, and other visual controls before transformation and TS´ is the matrix of coordinates of after transformation. Similarly, the coordinate matrices for the triangle strip can be rotated around the y- and x-axes.

The scale and translation are performed by calling glScalef(Sx, Sy, Sz) and glTranslatef(dx,dy,dz) functions which generate the scale and translation matrices. Sx, Sy, and Sz are the scales to the x, y, and z coordinates of each point of measurements for board while dx, dy, dz are the values needed to be translated along the x-axis, y-axis, and z-axis, respectively.

4.2.4 Lumber grading

The lumber grading component is based on Klinkhachorn's hardwood lumber grading routine (Klinkhachorn et al. 1988) and the NHLA lumber grading rules. To determine a possible grade for a lumber, the width, length and surface measure (SM) of the lumber should be computed, and a potential grade from the highest to the lowest is assigned to the poor face, then the potential number of clear cuttings and cutting units (CUs) can be calculated (Lin et al. 2010). By comparing the number of cuttings and CUs obtained from a piece of lumber, a final grade can be determined based on the requirements of the NHLA grading rules (NHLA 2007). Potential grades used in the current version include First and Seconds (FAS), SELECT, 1Common (1COM), 2Common (2COM), and 3Common (3COM). After a board was edged and trimmed, the processed board data including dimension, shape, and defect were recalled by the lumber grading routine, and a lumber grade was assigned to this board. Using stored lumber price data by grade and specie, the lumber value can be determined.

4.2.5 Optimal edging and trimming algorithm

Since there are numerous ways of edging and trimming a flitch, an optimal computer procedure was developed to aid in this searching process including exhaustive search and dynamic programming. The exhaustive search algorithm explores all possible combinations of edging and trimming lines within the original size of the board, which is guaranteed to find the maximal solution. The shape of the board is determined by different combinations of edging and trimming lines. Information regarding board length, width, surface measure, and defects is then recalled by the lumber grading component, and a lumber grade for that board can be assigned. The board’s value is determined based on the grade, surface measure, species, and the lumber price. A cutting pattern that yields the maximum value is the optimum edging and trimming solution. This exhaustive searching process can be very time consuming.

Dynamic programming is a more efficient search procedure which can be used to achieve the optimum edging and trimming solution. All potential edging and trimming line positions are pre-defined by dividing a board into equidistant levels in both horizontal and vertical directions.

This allows the lumber edging and trimming problem to be formulated as a set packing problem and the objective is to maximize the total lumber value. The key to solving the edging and trimming problem by dynamic programming is to recognize the recursive relationship (Bhandarkar et al. 2008). An original board can be divided into $N_e = ER/c_1$ horizontal edging lines and $N_t = TR/c_2$ vertical trimming lines, where ER and TR are edging range and trimming range, respectively, c_1 and c_2 are the edging and trimming intervals, respectively. Let $s^*(i, j)$ be the optimal edging and trimming patterns for the horizontal edging lines from 1 to i and vertical trimming lines from 1 to j, and $v^*(i, j)$ be the corresponding lumber value. Based on Bhandarkar et al. (2008) studied, if $v^*(k,l)$ and $s^*(k,l)$ for all $k \le i$ are known, then the combined edging and trimming flitch problem can be formulated as a recursive function:

$$\begin{aligned} v^*(i+1, j+1) = \max_{k\in[1,m]}(\max_{l\in[1,n]}((v^*(i+1-\left|\frac{W_k}{c_1}\right|-\left|\frac{K}{c_1}\right|, j+1-\left|\frac{L_l}{c_2}\right|-\left|\frac{K}{c_2}\right|)+ \\ g(i+1-\left\lceil\frac{W_k}{c_1}\right\rceil, i+1, j+1-\left\lceil\frac{L_l}{c_2}\right\rceil, j+1)))) \end{aligned} \tag{4.3}$$

Where $W_k = \{W_1, W_2, \cdots, W_m\}$ is the allowed set of lumber width, $L_l = \{L_1, L_2, \cdots, L_n\}$ is the allowed set of lumber length, K is the sawkerf, and $g(i, j, k, l)$ is the lumber value between edging lines i and j, and trimming lines k and l. The requirements for the lumber are: the lumber width ≥ 3 inches, and the lumber length ≥ 4 feet.

4.3 Optimal Edging and Trimming System Implementation

All the computer simulations were performed on a regular desktop PC equipped with 3.16 GHz CPU, 3.25 GB RAM, 300 GB hard drive under Microsoft Windows platform. The edging and trimming process was implemented by a 3D-based Windows dialog box with four tab controls labeled as “Board”, “Shape”, “Defect”, and “Defect Type”. The “Board” tab is used to display all the board data saved in the database. To view the shapes and defects information associated with a selected board, the user can click the corresponding tab controls. A defect on a board is measured by two lengths (left and right) and two widths (low and up). For each cut, there are 9 possible sections. These sections are named from 1 to 9 from starting from top left corner all the way through bottom right corner. The section determination for each cutting board is illustrated in Figure 4.2 and the measurements of shape and defect information are illustrated in Figure 4.3.

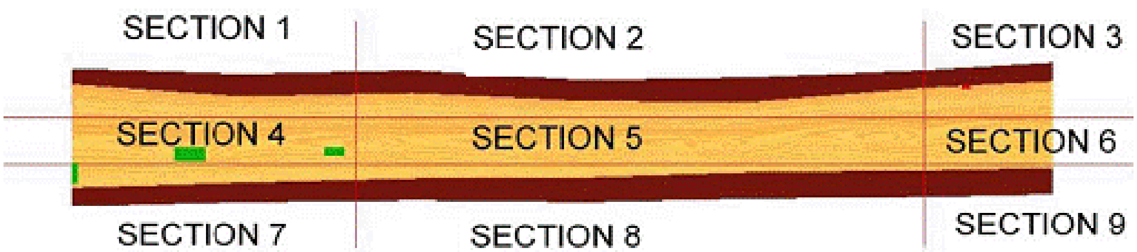
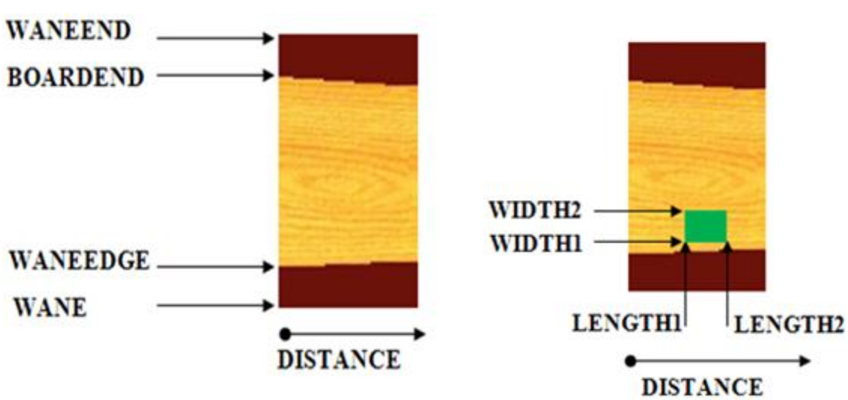


Figure 4.2. Section determination for a cutting board.



(a) *Measuring shape information* (b) *Measuring defect information*

Figure 4.3. Illustration of meaning shape and defect information.

Once a board is selected, its 3D image can then be generated (Figure 4.4a). The interface consists of three major sections: display area (right top area), results area (right bottom area), and control and command area (left area). The display area is to display the 3D board image and the edging and trimming results of a selected board. Information provided by a NHLA grader is displayed in the upper of the display area including lumber length, width, thickness, grade, surface measure, and value, which was used to compare the edging and trimming results produced by the optimal system. On the top of the control and command area, there are two control checkboxes (View Grid and View Defect). By default both checkboxes appear unchecked. The first one is used to display the grid along X, Y and Z axis, respectively, to show the length, width, and thickness of the lumber in inches, and the second one displays the defect with legend in different colors. There are two control combo boxes which are used to change the intervals for edging lines and trimming lines. By default, the interval is 0.5 inches for edging lines and 6 inches for trimming lines. The user can also manually change the interval values. For the edging line interval, 0.25, 0.5, and 1 inch are available for use, while 2, 6, and 12 inches are available for trimming intervals.

Edging and trimming simulations can be performed by two approaches: optimal cutting and manual cutting. For optimal cutting, exhaustive search or dynamic programming algorithm is available to optimize the edging and trimming process for the selected board (Figure 4.4b and 4.4c). During the optimal simulation, the program will show the searching progress, and finally the total running time will be given. For example, for board 1, SM and total lumber value were 4.25 and $2.25, respectively when using exhaustive search, while the SM and lumber value were 3.77 and $2.06, respectively for dynamic programming algorithm (Figure 4.4b and 4.4c). The controls and commands in the manual cutting group (Figure 4.4d) can be used to training edger and trimmer operators. When the user clicks “View Cut Frame” checkbox, the edging and trimming function will be activated and the “CUT” button is enabled. At this stage, the board is bounded by four red frames which are edging and trimming lines, with the horizontal lines representing the edging lines and the vertical lines representing the trimming lines. These frames can be moved by clicking the up and down arrow buttons. The left 2 buttons can be used to move the left trimming lines, and the right 2 buttons can be used to move the right trimming lines. Similarly, the upper and lower buttons can be used to control the moving directions of the edging lines. Every time a frame is moved, the board will be regenerated and the updated lumber length, width, and surface measure will be displayed. Once the frames are set up for desired sections, users can press the “CUT” button to cut the board (Figure 4.4d). If the user is not satisfied with the current operation, he can delete the generated lumber and process the board again.

Figure 4.4. Displaying the board. Displaying the board.
(a) Original board (b) Exhaustive search algorithm solution (c) Dynamic programming algorithm solution (d) Manual solution

4.4 Optimal Edging and Trimming System Applications

4.4.1 Board data collection

A total of 360 boards of five species were assessed in six sawmills across West Virginia between June and September 2006 (Wang et al. 2009a) (Figure 4.5). Flitches were gathered directly after being sawn from logs, which enabled measurements for the pieces before further processing. Flitches were collected randomly, but generally contained wane on two edges. Only flitches that were going to be sent to the edger were examined (Wang et al. 2009a). The flitch profile data measured included the geometric shape, size, and wane. Each defect on the flitch including type, size, and location was recorded. A National Hardwood Lumber Association (NHLA) certified lumber grader was employed to determine the grades of the pre-edged boards on both sides. The boards were then put back into the sawmill production line to be edged, trimmed, and graded by sawmill employees. After processing, the grade and surface measurement of the boards were determined by the same NHLA certified grader and a sawmill grader, respectively. All the collected data was entered into a Microsoft Access database. Lumber prices were based on Hardwood Market Report for Appalachian Hardwoods in April 11, 2009.

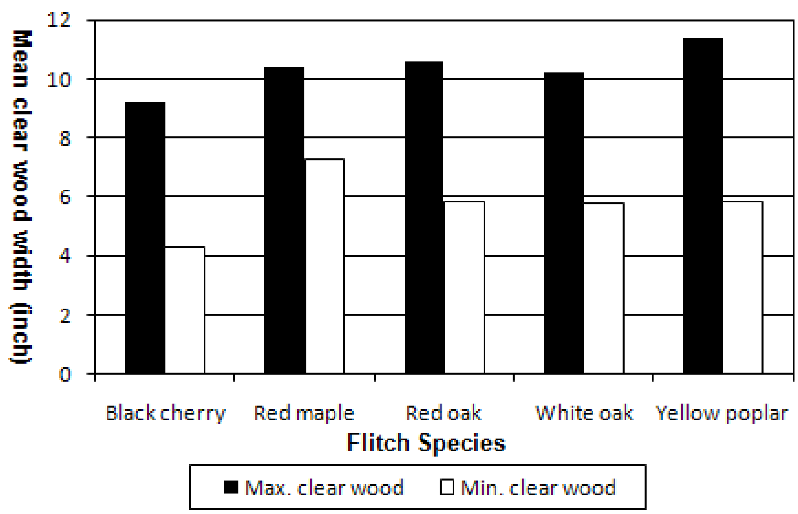


Figure 4.5. Sample characteristics of the 360 flitches-by species.

4.4.2 Lumber edging and trimming simulation for training

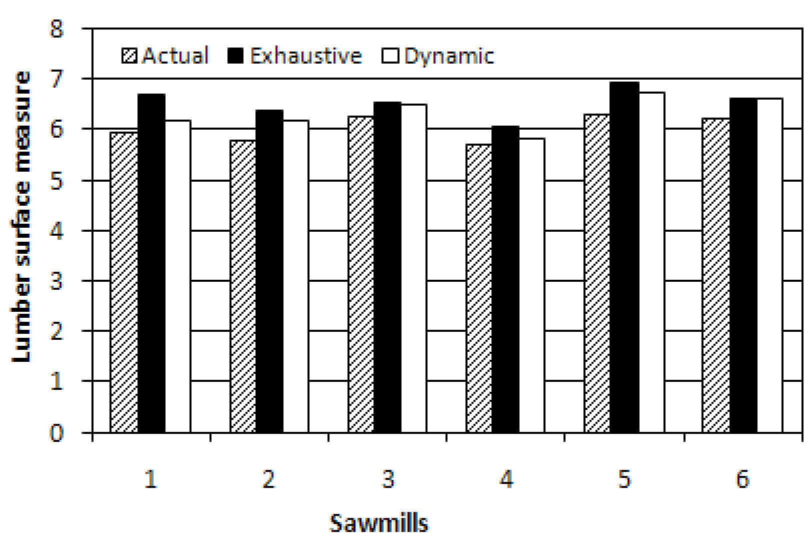
Training is essential for sawmills employees in order to realize the maximum product value since their decisions made at various processing stages have direct impacts on the product value. Computer simulation allows the repeated cutting of the same board with varying cutting patterns without physically destroying the board piece. The developed computer program can be used as a training tool to assist edger and trimmer operators in making good manufacturing decisions. For the 3D virtual board generated by the system, users can move either edging lines or trimming lines, or both to generate desired lumber. Every time the edging or trimming lines are moved, the board display is updated to show where the cutting lines are placed and the resulted lumber length, width, and defects on the lumber. The process is repeated until the user is satisfied with the placement of the edging and trimming lines, then the user can generate a piece of lumber. The lumber grade and value are determined by the system. Under the simulation mode, users can edge or trim the virtual board as many times as they want to sharpen their cutting skills in order to understand the impacts of the placement of edging and trimming lines on final lumber value. At the same time, the user's decisions can also be compared to an optimum edging and trimming solution determined by the system, and the percent recovery in lumber value can be known. The non-destructive simulation of edging and trimming can help users obtain a better understanding of edging, trimming, and grading.

4.4.3 Optimal vs. actual edging and trimming by sawmills

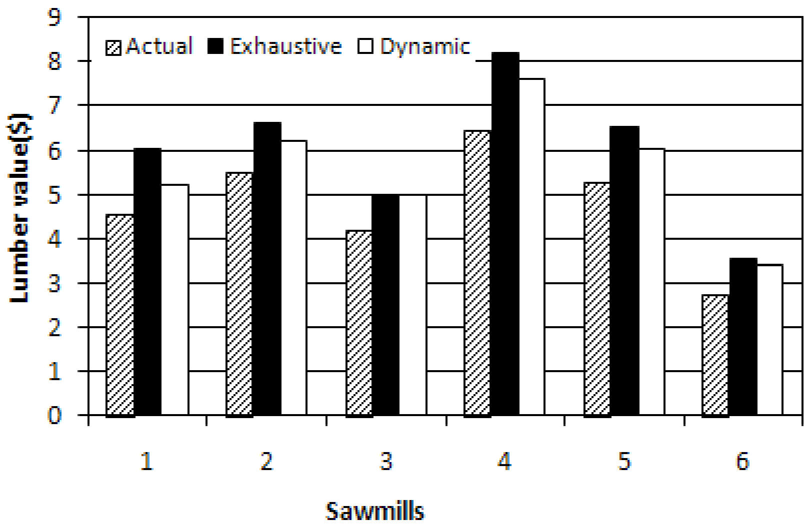
The average of lumber surface measure and lumber value generated by the optimization system were compared to the values by the actual sawmills (Figure 4.6). It was found that the mills had the potential to increase their average surface measure by an average 6.2 percent through optimal edging and trimming. Two of the six sawmills could even improve 10.1 and 12.25 percent (Figure 4.6a). The average surface measure per board was 6.05 units in the actual sawmills, 6.53 using exhaustive search, and 6.33 using dynamic programming algorithm, which indicated that excessive edging or trimming occurred in the operations of the studied sawmills.

The mills also had the potential to increase lumber value on average by 19.97 percent (Figure 4.6b). If the average value of lumber produced is $0.50 per board foot and one million board feet go through both edging and trimming process annually, the potential recovery in lumber value could be as high as $99,850 per year. The lumber value per board averaged $4.8 in the actual sawmills, $5.94 using exhaustive search, and $5.58 using dynamic programming algorithm, respectively. It is noted that even though excessive cutting may lead to a higher-grade lumber, the final value still be lower than the optimal solution due to smaller surface measure.

The edging and trimming of each flitch was dependent on the flitch's shape, size, and clear area. A one-way ANOVA was conducted to test the null hypothesis that the three treatments or groups (sawmill, exhaustive, dynamic programming) have equal mean lumber value. There was a significant difference of mean lumber value among the three groups (P = 0.0002). The Turkey multiple comparison was then conducted and the results further indicated that there were significant differences of lumber values between sawmills and using optimal computer simulations. However, no significant difference existed in mean lumber values between using exhaustive and dynamic programming optimizations (Table 4.1).



(a) *Lumber surface measure on average*



(b) *Lumber value on average*

Figure 4.6. Actual vs. optimal surface measure and lumber value on average by sawmills.

Table 4.1. The Tukey multiple comparison among three groups of actual sawmill production, using exhaustive and dynamic programming algorithms.

Methods Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		Significance[a]
Exhaustive - Dynamic	0.4012	-0.2820	1.0843	
Exhaustive - Sawmill	1.2007	0.5176	1.8838	***
Dynamic - Exhaustive	-0.4012	-1.0843	0.2820	
Dynamic - Sawmill	0.7995	0.1164	1.4827	***
Sawmill - Exhaustive	-1.2007	-1.8838	-0.5176	***
Sawmill - Dynamic	-0.7995	-1.4827	-0.1164	***

[a]*** indicates the comparison significance at 0.05 level.

4.4.4 Optimal vs. actual edging and trimming by species

In the sawmills surveyed, red oak had the largest surface measure, followed by white oak, red maple, yellow-poplar, and black cherry (Table 4.2). Although black cherry lumber had the smallest surface measure, its value was the highest, followed by red maple, red oak, white oak, and yellow-poplar. When using the exhaustive search algorithm for optimizing trimming and edging, the surface measure could improve 10.77 percent for yellow-poplar and 10.17

percent for white oak while the lumber value improved 31.11 percent for black cherry and 27.17 percent for yellow-poplar. If the dynamic programming algorithm was used, the two largest improvements for surface measure were 6.04 percent for red oak and 5.95 percent for white oak, while the two largest improvements for lumber value were 23.12 percent for black cherry and 15.85 percent for red oak. The improvements of lumber surface measure and lumber value were significantly different among species, which indicated that mill operators must carefully edge and trim the valuable species, such as black cherry in this case. Higher surface measure does not always mean more lumber value recovery since lumber value is also affected by other factors, such as grade and price.

Table 4.2. Actual vs. optimal lumber surface measure and value on average by species[a].

Species	Actual		Exhaustive		Dynamic		Exhaustive improvement (%)		Dynamic improvement (%)	
	SM	Value	SM	Value	SM	Value	SM	Value	SM	Value
RO	6.79	4.29	7.37	5.27	7.21	4.97	8.58	22.84	6.04	15.85
YP	5.94	2.65	6.58	3.37	6.21	3.01	10.77	27.17	4.38	13.58
BC	4.96	8.39	5.18	11	5.09	10.33	4.41	31.11	2.42	23.12
RM	6.21	4.42	6.36	4.95	6.41	5.07	2.37	11.99	3.06	14.71
WO	6.39	4.18	7.04	5.23	6.78	4.75	10.17	25.12	5.95	13.64

[a]. RO-Red Oak, YP-Yellow Poplar, BC-Black Cherry, RM-Red Maple, WO-White Oak.

4.4.5 Optimal vs. actual edging and trimming by grades

The comparisons indicated that lumber grade was improved significantly by using optimal edging and trimming algorithms (Table 4.3). In the studied sawmills, 73.61 percent of lumber produced were with No. 1Common or better grades lumber. The percentage of lumber with No. 1Common or better grades lumber were 85.15percent or 83.68 percent when using exhaustive and dynamic programming optimization algorithms, respectively. A higher grade improvement was observed in black cherry species boards than in other species (Table 4.4).

To determine the lumber value distribution, all the boards were grouped based on lumber grade (Table 4.5). The largest difference between the optimum and actual values was observed for the FAS & SELECT boards. The lumber value difference suggested that there could be a value loss occurred when the potential FAS & SELECT boards were dropped to a lower grade in sawmills since the price gaps between successive lumber grades are significant. Therefore, extra lumber value recovery can be achieved by using the edging and trimming optimization. The total lumber value could be improved by 23.15 percent using exhaustive searching or by 16.71 percent using the dynamic programming. Even though the exhaustive search algorithm showed more improvements when compared to dynamic programming, more execution time needed. For example, the average execution time for each board was 498 seconds using exhaustive search, while the optimization time averaged 254 seconds using dynamic programming.

Table 4.3. Actual lumber grade vs. optimal lumber grade distribution.

	Actual		Exhaustive		Dynamic Programming	
Lumber grade	# of boards	Percentage	# of boards	Percentage	# of boards	Percentage
FAS/SELECT	87	24.17	122	31.77	102	26.84
1COM	178	49.44	205	53.39	216	56.84
2COM	65	18.06	43	11.20	42	11.05
3COM	30	8.33	14	3.65	20	5.26
Total	360	100	384*	100	380*	100

*. Extra pieces are permitted through optimal edging and trimming.

Table 4.4. Actual lumber grade vs. optimal lumber grade distribution by lumber species.

Species	Grade	Actual (%)	Exhaustive (%)	Dynamic (%)
Red oak	FAS/SELECT	29.89	38.49	34
	1COM	51.12	49.74	51.13
	2COM	13.76	8.37	11.87
	3COM	5.23	3.4	3
	Total	100	100	100
Yellow-poplar	FAS/SELECT	21.02	28.23	24.15
	1COM	51.3	55.34	62.18
	2COM	21	12.78	8.82
	3COM	6.68	3.65	4.85
	Total	100	100	100
White oak	FAS/SELECT	23.11	28.68	27.05
	1COM	42.12	53.12	50
	2COM	24.88	13.02	15.95
	3COM	9.89	5.18	7
	Total	100	100	100
Black cherry	FAS/SELECT	22.68	33.26	27.65
	1COM	49.32	56.14	58
	2COM	18.05	6.12	10
	3COM	9.95	4.48	4.35
	Total	100	100	100
Red maple	FAS/SELECT	24.13	29.85	26.86
	1COM	52.97	52.17	58.12
	2COM	13.03	14.98	9.14
	3COM	9.87	3	5.88
	Total	100	100	100

Table 4.5. Actual lumber value vs. optimal lumber value distribution by lumber grade.

Lumber grade	Actual value($)	Exhaustive value($)	Dynamic value($)	Difference[a]	Difference[b]
FAS/SELECT	789.31	1025.06	918.27	235.75	128.96
1COM	764.21	948.78	952.73	184.57	188.52
2COM	102.05	92.84	84.37	-9.21	-17.68
3COM	52.89	37.27	38.65	-15.62	-14.24

[a] represents the difference between the total lumber values by exhaustive and actual sawmills.
[b] represents the difference between the total lumber values by dynamic programming and actual sawmills.

4.4.6 Factors affecting lumber surface measure and lumber value

Factors that could affect board surface measure or value include species, mill requirements, board length, board clear width, number of defects, defect size, and others. A generic general linear model (GLM) was employed to determine the impacts of these individual factors and their interactions on board surface measure or value through edging and trimming, which can be expressed as:

$$\begin{aligned} BMV_{ijklmnop} &= \mu + SP_i + M_j + MAXW_k + MINW_l + L_m + ND_n + DTS_o \\ & MAXW_k * MINW_l + MAXW_k * L_m + MINW_l * L_m + SP_i * ND_n + SP_i * L_m + \varepsilon_{ijklmnop} \end{aligned} \quad (4.4)$$

$$\begin{aligned} i &= 1,2,\cdots,5 \\ j &= 1,2,\cdots,6 \\ k &= 1,2,\cdots,5 \\ l &= 1,2,\cdots,5 \\ m &= 1,2,\cdots,5 \\ n &= 1,2,\cdots,5 \\ o &= 1,2,\cdots,5 \end{aligned}$$

Where, $BMV_{ijklmnop}$ is the pth observation of board surface measure or lumber value obtained by sawmills, by using exhaustive search or dynamic programming; μ is the mean of each response variable; SP_i is the effect of the ith species; M_j is the effect of the jth mill requirements, edger experience, and grader experience in respect to each mill; $MAXW_k$ is the effect of the kth maximum clear width of flitch; $MINW_l$ is the effect of the lth minimum clear width of flitch; L_m is the effect of the mth flitch length; ND_n is the effect of the nth number of defects; DTS_o is the effect of the oth total size of defects (aggregate); $\varepsilon_{ijklmnop}$ is an error component that represents uncontrolled variability; p is the number of observations within each treatment (sawmill, exhaustive, dynamic programming).

Based on the ANOVA analysis, the board surface measure collected at sawmills was significantly different among maximum board clear widths (F=6.70; df=4, 277; p<0.0001), minimum board clear widths (F=21.60; df=3, 277; p<0.0001), lengths (F=27.55; df=4, 277; p<0.0001), species (F=2.60; df=4, 277; p<0.0362), interactions between minimum board clear width and length ($F=2.50$; $df=11, 277$; $p<0.0052$), and interactions between species and length ($F=2.78$; $df=11, 277$; $p<0.0019$). There was no significant difference among mills with respect to board surface measure. If the exhaustive search was used in edging and trimming, the board surface measure was significantly different among maximum board clear widths ($F=8.21$; $df=4, 277$; $p<0.0001$), minimum board clear widths ($F=15.49$; $df=3, 277$; $p<0.0001$), lengths ($F=21.74$; $df=4, 277$; $p<0.0001$), total defect size ($F=2.80$; $df=4, 277$; $p=0.0264$), and interactions between maximum board clear width and length ($F=2.19$; $df=15, 277$; $p<0.0068$). If using dynamic programming algorithm, a significant difference also existed in board surface measure among widths ($F=9.84$; $df=4, 277$; $p<0.0001$), minimum board clear widths ($F=8.51$; $df=3, 277$; $p<0.0001$), lengths ($F=18.23$; $df=4, 277$; $p<0.0001$), total defect size ($F=3.94$; $df=4, 277$; $p=0.0039$), and interactions between maximum board clear width and length ($F=2.11$; $df=15, 277$; $p<0.0099$). However, the surface measure was not significantly affected by species but was affected by the total defects size on board using the optimal algorithm.

The board value generated at sawmills was significantly different among sawmills ($F=19.75$; $df=5, 277$; $p<0.0001$), species ($F=31.38$; $df=4, 277$; $p<0.0001$), number of defects ($F=21.68$; $df=3, 277$; $p<0.0001$), minimum clear board widths ($F=7.18$; $df=3, 277$; $p=0.0001$), maximum clear board widths ($F=4.14$; $df=4, 277$; $p=0.0028$), board lengths ($F=5.62$; $df=4, 277$; $p=0.0002$), defects size ($F=3.79$; $df=4, 277$; $p=0.0051$), and the interactions between maximum clear board width and board length ($F=4.16$; $df=15, 277$; $p<0.0001$), between species and number of defects on board ($F=8.34$; $df=8, 277$; $p<0.0001$), and between species and board length ($F=2.23$; $df=11, 277$; $p=0.0134$). A significant difference in board value obtained by exhaustive search existed among sawmills ($F=21.95$; $df=5, 277$; $p<0.0001$), maximum clear widths ($F=3.87$; $df=4, 277$; $p=0.0044$), minimum clear widths ($F=9.51$; $df=3, 277$; $p<0.0001$), length ($F=7.23$;

df=4, 277; $p<0.0001$), number of defects (F=25.38; df=3, 277; $p<0.0001$), total defect size (F=3.44; df=4, 277; $p=0.0091$), species (F=37.76; df=4, 277; $p<0.0001$), interactions between maximum clear board width and board length (F=3.06; df=15, 277; $p=0.0001$), between species and number of defects on board (F=8.40; df=8, 277; $p<0.0001$), and between species and length (F=2.50; df=11, 277; $p=0.0053$). The board value using dynamic programming optimization was significantly different among sawmills (F=18.04; df=5, 277; $p<0.0001$), maximum clear widths (F=6.88; df=4, 277; $p<0.0001$), minimum clear widths (F=6.43; df=3, 277; $p=0.0003$), lengths (F=7.44; df=4, 277; $p<0.0001$), number of defects (F=37.24; df=3, 277; $p<0.0001$), total defect size (F=2.94; df=4, 277; $p=0.0209$), species (F=33.23; df=4, 277; $p<0.0001$), interactions between maximum and minimum clear board width (F=2.04; df=9, 277; $p=0.0347$), between maximum clear board width and board length (F=4.87; df=15, 277; $p<0.0001$), between species and number of defects on board (F=9.83; df=8, 277; $p<0.0001$), and between species and length (F=2.78; df=11, 277; $p=0.0019$). As expected, the board surface measure was mainly determined by board dimensions, while board value mainly depends on species, defects, and board dimensions.

4.5 Discussion and Conclusions

Currently, small mills in the central Appalachian hardwood region still rely on trained workers to make quick decisions on lumber edging, trimming, and grading based on their knowledge and market information. It would be advantageous for lumber trimsaw/edger operators and graders to have an easily accessible tool in understanding of quality control, decision-making, and optimization strategies. This 3D trimming, edging and grading system is a useful tool which can be used to simulate lumber edging, trimming and grading and improve lumber utilization and lumber value recovery. As a training tool, the user can observe how the placement of edging and trimming lines affect the final lumber value. The lumber edging and trimming training would provide hardwood lumber edger and trimmer operators a better understanding of the impacts of lumber grade, surface measure, and prices on lumber value and processing decisions.

The optimal edging and trimming system can effectively increase the lumber value recovery compared to the actual sawmill operations. The results showed that sawmills had the potential to increase their surface measure and lumber value on average by 6.2 percent and 19.97 percent, respectively, through optimal edging and trimming. Lumber grade could be improved significantly by using optimal edging and trimming algorithms. For example, lumber with No. 1Common or better grades could be improved 11.54 percent using exhaustive search and 10.07 percent using dynamic programming algorithms, respectively. Therefore, the value improvement opportunities exist for boards with higher grade potentials through edging and trimming optimization. The total lumber value could be improved by 23.15 percent using exhaustive searching or by 16.71 percent by using dynamic programming for six sawmills. Although the exhaustive search algorithm presented slightly more improvements in lumber value recovery compared to dynamic programming, it took more execution time per optimization run. Additionally, we realized that many factors including experience and error of operators, mill equipment, and others have effects on edging and trimming decision in sawmills. So it should be noted that care must be taken in interpreting potential lumber value gains.

While the optimal lumber edging and trimming system has the potential to improve lumber value recovery, there are still some limitations associated with this system. Getting the required data directly from field measurements could take a considerable amount of time. It will be helpful to collect board profile and defect data using computer-aided vision systems. In addition, the optimal algorithms need improve to increase the system efficiency. Last, lumber specifications were not flexible for the system. More customized lumber specifications should be considered in the future version of the system, making it more applicable in sawmills.

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CHAPTER 5: AN INTEGRATED 3D LOG PROCESSING OPTIMIZATION SYSTEM FOR SMALL SAWMILLS IN CENTRAL APPALACHIA, USA[†]

[†] To be submitted to Computers and Electronics in Agriculture.

Abstract

An integrated 3D log processing optimization system was developed to perform 3D log generation, opening face determination, headrig log sawing simulation, flitch edging and trimming simulation, cant resawing, and lumber grading. A circular cross-section model together with 3D modeling techniques were used to reconstruct 3D virtual logs. Log internal defects (knots) were depicted using a cone model with apex at the central axis of the log. Heuristic and dynamic programming (DP) algorithms were developed to determine the best opening face, primary log sawing, edging and trimming, and cant resawing optimization. The National Hardwood Lumber Association (NHLA) grading rules were computerized and incorporated into the system for lumber grading. Sawing methods considered in the system include live sawing, cant sawing, grade sawing, and multi-thickness sawing. The system was tested using field data collected at two central Appalachian hardwood sawmills. Results showed that lumber value recovery can be significantly improved by using the optimization system. The optimization system can assist mill managers and operators in efficiently utilizing raw materials and increasing their overall competitiveness in the ever-changing forest products market.

5.1 Introduction

Hardwood lumber production consists of a sequence of interrelated operations, including log debarking, primary log breakdown at the headrig, cant resawing, and flitch edging and trimming at the secondary log breakdown phase, as well as lumber grading. These processes are very complicated due to variations in log geometry, log quality, sawing variation, sawing method, edging and trimming method, and product mix. Given this, it is extremely difficult for an operator to make an optimal sawing, edging and trimming decision. Currently, the hardwood industry in the central Appalachian region is facing a set of challenges including decreases in log size and quality, limited resource availability, tightened environmental restrictions on timber harvesting, reductions in profit margin, and pressure from foreign competition (Milauskas et al. 2005). Log primary breakdown practices in this region heavily rely on manual inspection for external log defects, and logs are sawn based on either maximum volume or the highest grade (Zhu et al. 1996, Lee et al. 2001). Similarly, edger and trimmer operators visually examine the board surfaces, and then make quick judgments about the placement of cuts during the secondary log breakdown. These practices have resulted in low lumber yield, inadequate lumber quality in respect to grade, slow production, and an inefficient utilization of forest resources (Regalado et al. 1992a). In response to these issues, there is a growing need for an advanced sawmilling technology that can optimize hardwood lumber recovery and help increase business competitiveness and profitability (Zhu et al. 1996, Sarigul et al. 2001).

Since the 1960s, several computer simulations and mathematical programming models have been developed to improve lumber recovery. For example, the Best Opening Face System (BOF) was developed to maximize the lumber volume produced from small-diameter softwood logs (Hallock et al. 1971, 1976, Lewis 1985). This program was the most widely adopted simulation model during the 1980s and some softwood sawmills still use it today. However, the application of this program was limited in hardwood sawmills. Computer simulation programs were developed for hardwood log sawing (Richards 1973, 1979, and 1980, Adkins et al. 1980), in which a log was represented by a truncated cone and each knot was simulated as a cone with its apex of 24° at the pith. Occeña and Tanchoco (1988) developed a graphic log sawing simulator to automatically perform hardwood log breakdown. Several studies were also conducted to analyze the impacts of sawing methods, internal defects, and log orientations on the potential lumber value recovery (Harless et al. 1991, Steele et al. 1993, 1994, Guddanti et al. 1998, Occeña et al. 2000, 2001, Chang et al. 2005).

Mathematical programming has been extensively used to achieve optimum sawing patterns. The log sawing optimization problem can be defined as a dynamic programming problem, and recursive equations were established to find the optimum total lumber value/volume recovery (Faaland and Briggs 1984, Geerts 1984, Todoroki et al. 1997, 1999, Bhandarkar et al. 2002, 2008). Occeña et al. (1997) and Thawornwong et al. (2003) also designed heuristics algorithm to optimize log sawing patterns. A computer-based exhaustive enumeration procedure was developed to achieve the optimal edging and trimming solution and analyzed the effect of defects on lumber value (Regalado et al. 1992a, 1992b). Todoroki et al. (1997) indicated that the edging and trimming optimization problem could be formulated as a set packing problem, and be solved using dynamic programming. They developed a sawing simulation software to implement the dynamic programming algorithm. Schmoldt et al. (2001) used branch-and-bound (B&B) search to obtain optimal edging/trimming solution. To date, several edging and trimming computer software systems have been developed to aid in milling operations (Kline et al. 1990, 1992, Araman et al. 1996, Abbott et al. 2000, Schmoldt et al. 2001, Lee et al. 2003).

Decisions made in sawing, edging, and trimming operations are interrelated. For example, any decisions made in primary log breakdown can directly impact the piece dimensions and the decisions in secondary log breakdown (Zeng 1991). Therefore, it is necessary to simultaneously optimize the primary and secondary breakdown to achieve a global optimal solution. Faaland and Briggs (1984) combined primary log sawing and tree bucking together using dynamic programming and modeled a log as a cylinder without taper, curvature, and defects. Geerts (1984) used a nested two-dimensional dynamic programming algorithm to determine the optimal log sawing and flitch edging patterns. Log models and defect cores were assumed as perfect cylinders in this algorithm. Funck et al. (1993) developed a computer program called SAW3D to optimize log breakdown, edging, and trimming operations, in which only external profile was used to represent logs. Further refinement was implemented by Zeng (1995) who modified this program by including internal defects and an expert system for softwood lumber grading (Zeng 1995). Todoroki et al. (1999) developed a model that integrated the primary and secondary log breakdown based on dynamic programming principles and the combined model was incorporated into the AUTOSAW sawing simulation system (Todoroki 1997), which is only appropriate for live-sawing practices.

Existing computer simulations or mathematical programming models for log breakdown optimization varied significantly in terms of sawing method (live sawing, grade sawing), log model assumptions (truncated cone, cylinder, cross section), internal defects consideration, local optimization (primary sawing) vs. global optimization (combined sawing and trimming), and hardwood vs. softwood. Some sawing or edging and trimming systems that are currently used in softwood mills are not suitable for small hardwood sawmills due to the inability of considering internal defects or relying on expensive scanners (CT scanners) to detect internal defects. The log models applied were simple (cylinder or truncated cone), which have created significant differences before the computer simulations were conducted. Most previous studies focused on either primary log breakdown or secondary breakdown, rather than simultaneously combining them to optimize lumber recovery. Although a few studies combined primary and secondary breakdown for softwood or hardwood live sawing, application in hardwood sawmills, which typically use grade sawing, was very limited.

Currently, many large softwood mills and hardwood mills have the latest sawing and optimization technology to increase lumber yield and value. Smaller sawmills, however, are less able to adopt new, more efficient technologies because of initial cost, payback period, and modifications to operations (Occeña et al. 2001). For example, only 35% of all Pennsylvania hardwood sawmills use a computer-aided headrig (Smith et al. 2004). In West Virginia, approximately 68.52% of the hardwood lumber sawmills produce less than 4-million board feet (MMBF) of green hardwood lumber per year (West Virginia Division of Forestry 2004). These small hardwood producers are key contributors to the industry as they represent a significant share of the market. Application of an appropriate, user friendly, and high efficient computer-aided sawing, edging and trimming, and grading system could be one of the important strategies to improve processing performance and enhance their competitiveness in the forest products market. Such a system is especially important in the current turbulent economic situations.

Therefore, we aim to develop a cost effective computer-aided log sawing simulation system for lumber manufacturing to improve lumber value recovery. Specifically, the objectives of this study are to: (1) design heuristic procedure to determine the log opening face based on log shape and external defects, (2) develop heuristics and dynamic programming (DP) algorithm for primary log breakdown, (3) formulate exhaustive search and DP algorithm to optimize flitch edging and trimming, (4) integrate the primary and secondary log breakdown optimization simultaneously, (5) develop an integrated 3D log processing system to implement these algorithms, and (6) compare the lumber values generated in sawmills and by the optimization system.

5.2 System Design

5.2.1 System components

The system was developed using the Microsoft Foundation Class (MFC) and Open Graphics Library (OpenGL). MFC provides a user friendly interface and can be easily transferred to any other Windows applications, while OpenGL offers great power to create a 3D virtual simulation environment (Wang et al. 2009). A component object model (COM) was used to integrate the system that was designed using the principle of object-oriented programming (OOP). The system consists of six major components: 3D log generation, opening face determination, headrig log sawing, flitch edging and trimming, cant resawing, and lumber grading (Figure 5.1). Each component accomplishes its own task and is linked to related components by transferring arguments and/or global variables, which will make modifications and maintenance easier.

The 3D log generation component generates a 3D visual real-shape log that can be rotated, scaled, and translated based on log data and performance requirements. The opening face component determines the log position, opening face position, and opening face size. The headrig optimization component saws the log into slabs, flitches, and/or cants, and determines the optimal sawing patterns with maximum log value by applying either heuristic or DP algorithm (Figure 5.2). The optimum value of each flitch or cant cut from the log can be determined as well (Figure 5.3). If cant resawing is performed, the boards generated from the cant also need to be edged and/or trimmed. The edging and/or trimming optimization component calls the headrig optimization or cant resaw component for flitch/board information and defect profiles exposed on the board faces. The optimal edging and/or trimming patterns are then determined by either exhaustive search or DP algorithm. All the generated lumber will be processed by the lumber grading component for grading. Based on lumber dimensions, defects, lumber price, and species, the optimum lumber value will be obtained. Finally, the total lumber value along with the corresponding optimum sawing and edging and/or trimming pattern will be recorded in the system.

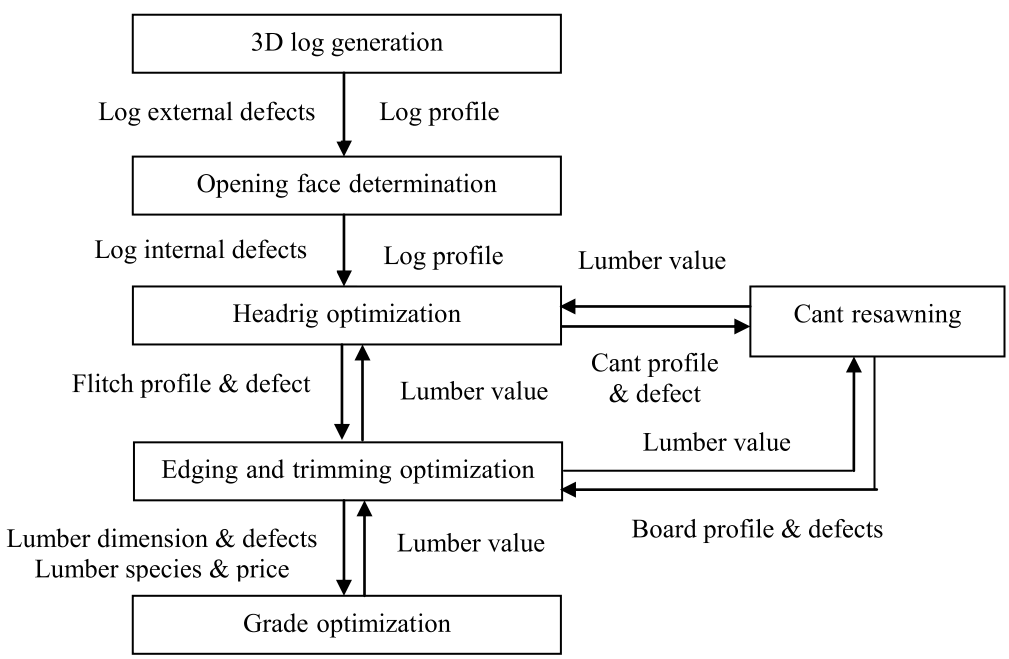


Figure 5.1. System components.

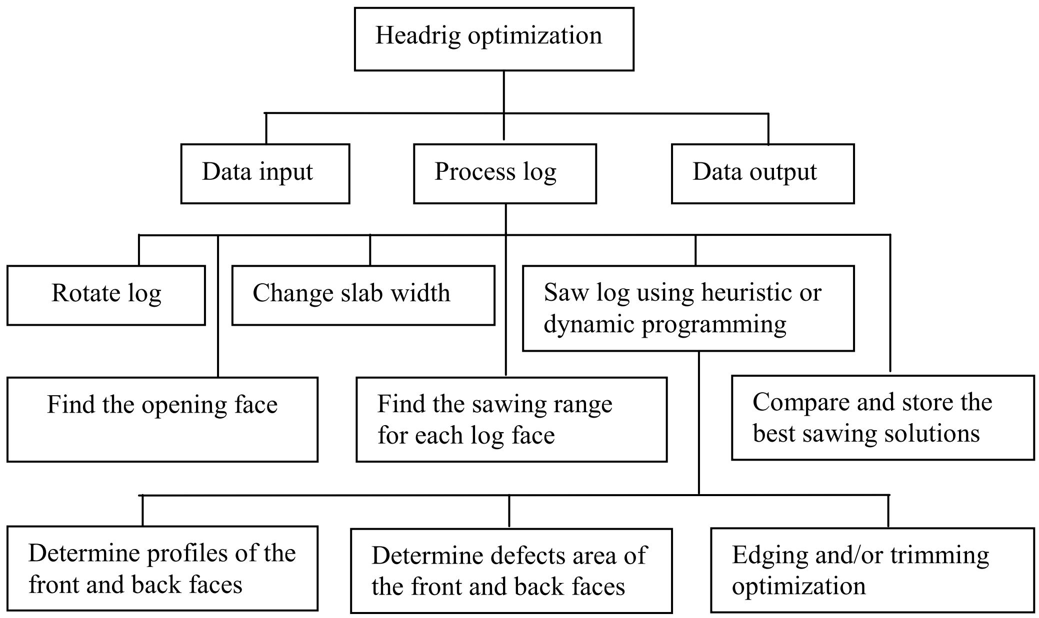


Figure 5.2. Hierarchy of the headrig optimization components.

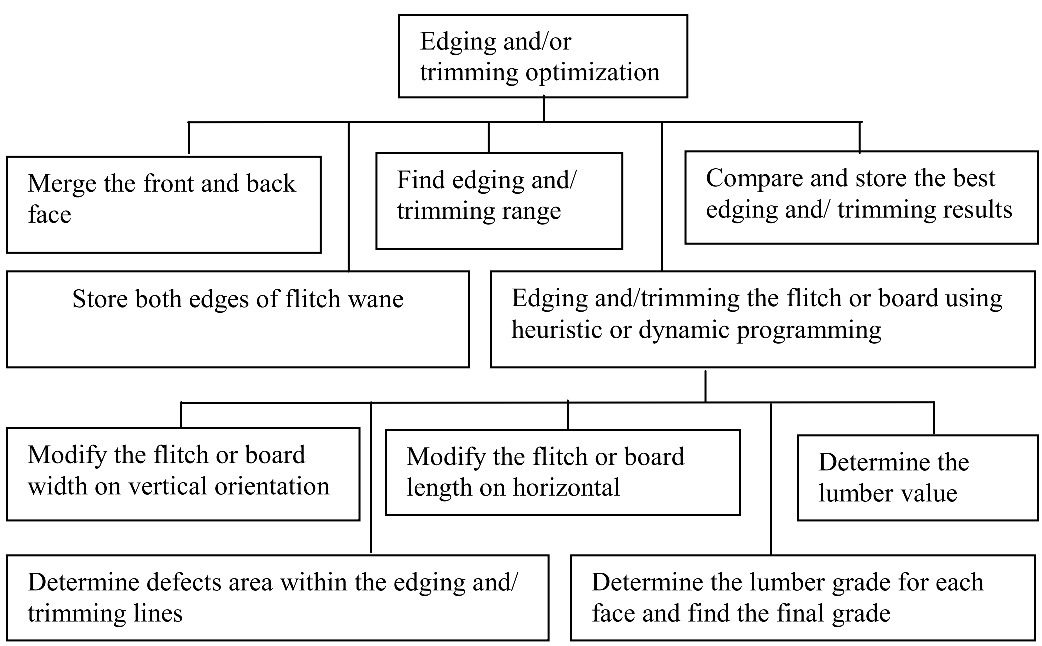


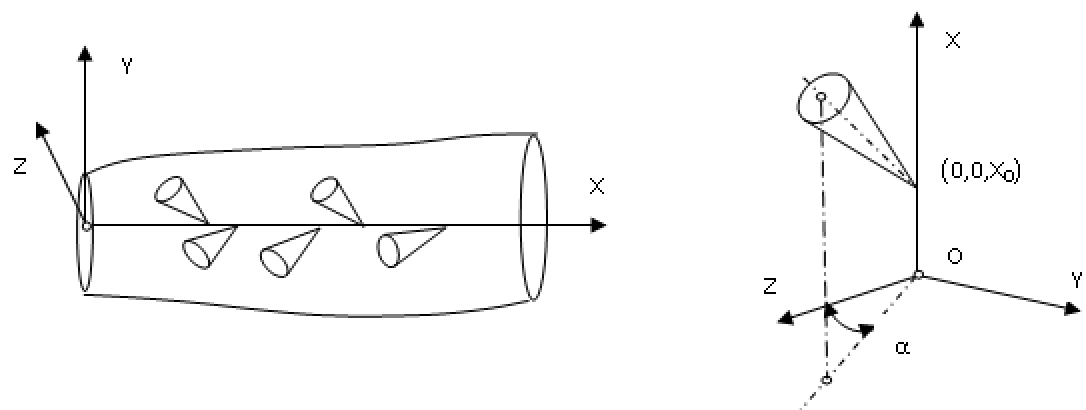
Figure 5.3. Hierarchy of the edging and/ trimming optimization component.

5.2.2 System data management

Microsoft ActiveX Data Objects (ADO) was used to retrieve data from and save sawing results to an MS Access database. ADO enables client applications to access and manipulate data from a variety of sources through an Object Linking and Embedding Database (OLEDB) provider (MSDN 2010). The simple way to incorporate ADO into programming is through the use of ActiveX controls, so the user can link the system database conveniently by MFC and ActiveX controls. The MS Access database, which includes four entity types: logs, shapes, defects, and grades, was created to hold the log and lumber information in the system. The logs entity type stores log number and basic log information, such as species, log position, log length, small end and large end diameters; the shapes entity type stores log sweep and diameter data at one foot intervals; the defects entity type contains defects data associated with each log; and the grades entity type stores lumber grading rules and lumber price. An entity-relationship (ER) model was implemented via the MS database.

5.2.3 3D log and internal defect modeling

Log shape modeling is very important in determining the optimum log breakdown. A circular cross-section model was adopted to represent a log, which uses a series of cross sections at designated intervals along the log length (Figure 5.4a). This model is much closer to real log shape because the data at each cross section were collected and log sweep and log crook were also considered. 3D modeling techniques together with OpenGL primitive drawing functions were used to generate three-dimensional log visualizations. The OpenGL functions such as translation, rotation, and scaling are used to facilitate log visualization and the related mathematical modeling was described by Woo et al. (2000). Studies have shown that there exists strong correlations between surface defect indicators such as overgrown knot, overgrown knot cluster, sound knot, and unsound knot and internal knot defects (Thomas 2008). We only considered knots as internal log defects in this study, because they are the most commonly found on board surfaces and can have significant impacts on log quality and lumber value. A cone model is used to represent an internal log knot with apex assumed at the central axis of the log (Thomas 2008) (Figure 5.4b). The vertex of the cone lies on the X axis at a distance X_0 from the origin of the coordinates, and α is the knot angle between the Z axis and the projection of the knot axis on the YZ plane.



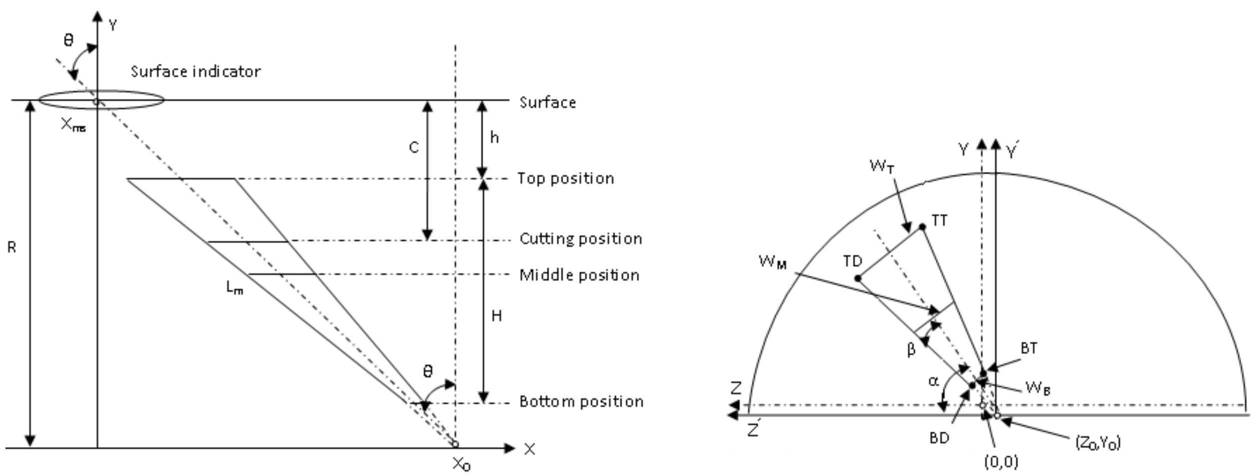
(a) (b)

Figure 5.4. 3D log and defect model.
(a) A 3D log and knots. (b) Knot represented as a cone arbitrarily positioned in the XYZ space.

When a sawing plane passes through an internal knot, a two-dimensional rectangle defect area is assumed to be exposed on the lumber surface. The approximate location and size of the defect area are then determined using mathematical procedures. The projection of a knot on the XY plane is illustrated in Figure 5.5a to help determine the approximate X coordinates on the left and right of the defect area, where θ is the rake angle, h and H are the clear wood depth and the defect depth, respectively, C is the distance from the surface to the cutting line, which can be determined when a cutting position was fixed, R is the log radius at the defect position, L_M is the length at middle point ($(H+h)/2$) of the defect, X_{MS} is the coordinate of the surface defect center. All these parameters except for C can be determined by Thomas's model (2008).

Equation 5.1 is used to determine the approximate X coordinates on the left (X_{LC}) and right (X_{RC}) end of the defect area on a board:

$$\begin{cases} X_{LC} = X_{MS} + |C| \times tg\theta - (R - |C|) \times L_M \\ X_{RC} = X_{MS} + |C| \times tg\theta + (R - |C|) \times L_M \end{cases} \tag{5.1}$$



(a) (b)

Figure 5.5. The projection of a knot.
(a) The projection of a knot on the X and Y plane. (b) The projection of a knot on the $Y'Z'$ and YZ planes. The origin on the $Y'Z'$ plane is corresponding to the coordinate (Z_0, Y_0) on the YZ plane.

When the knot was projected to the $Y'Z'$ plane, the coordinates of the four corners (TT , TD , BT , and BD) of the knot should be determined to assist the determination of the Y and Z coordinates of the defect on a board (Figure 5.5b, Equations 5.2-5.4), where W_T , W_M , and W_B are the top, middle, and bottom width of the knot on the $Y'Z'$ plane, respectively, and β is the semi-angle of the projected cone on the $Y'Z'$ plane.

$$\begin{cases} W_T = \dfrac{2W_M(R-h)}{2R-(H+h)} \\ \beta = \arctan(\dfrac{W_T}{2(R-h)}) \\ W_B = \dfrac{2W_M(R-H-h)}{2R-H-h} \end{cases} \tag{5.2}$$

$$\begin{cases} Y'_{TT} = \sqrt{(\frac{W_T}{2})^2 + (R-h)^2} \times \sin(\alpha+\beta), \quad Y_{TT} = Y'_{TT} + Y_0 \\ Z'_{TT} = \sqrt{(\frac{W_T}{2})^2 + (R-h)^2} \times \cos(\alpha+\beta), \quad Z_{TT} = Z'_{TT} + Z_0 \\ Y'_{TD} = \sqrt{(\frac{W_T}{2})^2 + (R-h)^2} \times \sin(\alpha-\beta), \quad Y_{TD} = Y'_{TD} + Y_0 \\ Z'_{TD} = \sqrt{(\frac{W_T}{2})^2 + (R-h)^2} \times \cos(\alpha-\beta), \quad Z_{TD} = Z'_{TD} + Z_0 \end{cases} \tag{5.3}$$

$$\begin{cases} Y'_{BT} = \sqrt{(R-H-h)^2 + (\frac{W_B}{2})^2} \times \sin(\alpha+\beta), \quad Y_{BT} = Y'_{BT} + Y_0 \\ Z'_{BT} = \sqrt{(R-H-h)^2 + (\frac{W_B}{2})^2} \times \cos(\alpha+\beta), \quad Z_{BT} = Z'_{BT} + Z_0 \\ Y'_{BD} = \sqrt{(R-H-h)^2 + (\frac{W_B}{2})^2} \times \sin(\alpha-\beta), \quad Y_{BD} = Y'_{BD} + Y_0 \\ Z'_{BD} = \sqrt{(R-H-h)^2 + (\frac{W_B}{2})^2} \times \cos(\alpha-\beta), \quad Z_{BD} = Z'_{BD} + Z_0 \end{cases} \tag{5.4}$$

For a specific cutting line passing the knot along the Z' axis, the Z' coordinates are known and the approximate Y' coordinates on the board can be determined with consideration of the defect positions and quadrants (Figure 5.6). For example, in Figure 5.6a, the Y' coordinates are the intersection points between the cutting line and the projected side of the knot, which can be computed based on α, β, and Z' coordinate. However, if one intersection point (Figure 5.6b, 5.6c) or both points (Figure 5.6d) is located on the top/bottom end of the projected knot, the Y' coordinates should be calculated based on α, β, Z' coordinate, and Equations 5.2-5.4. It is noted that all the relative coordinates on the $Y'Z'$ plane will be converted to the absolute coordinates on the YZ plane. Similarly, when a cutting line cuts along the Y' axis, the approximate Z' and Z coordinates of the defect area can also be determined.

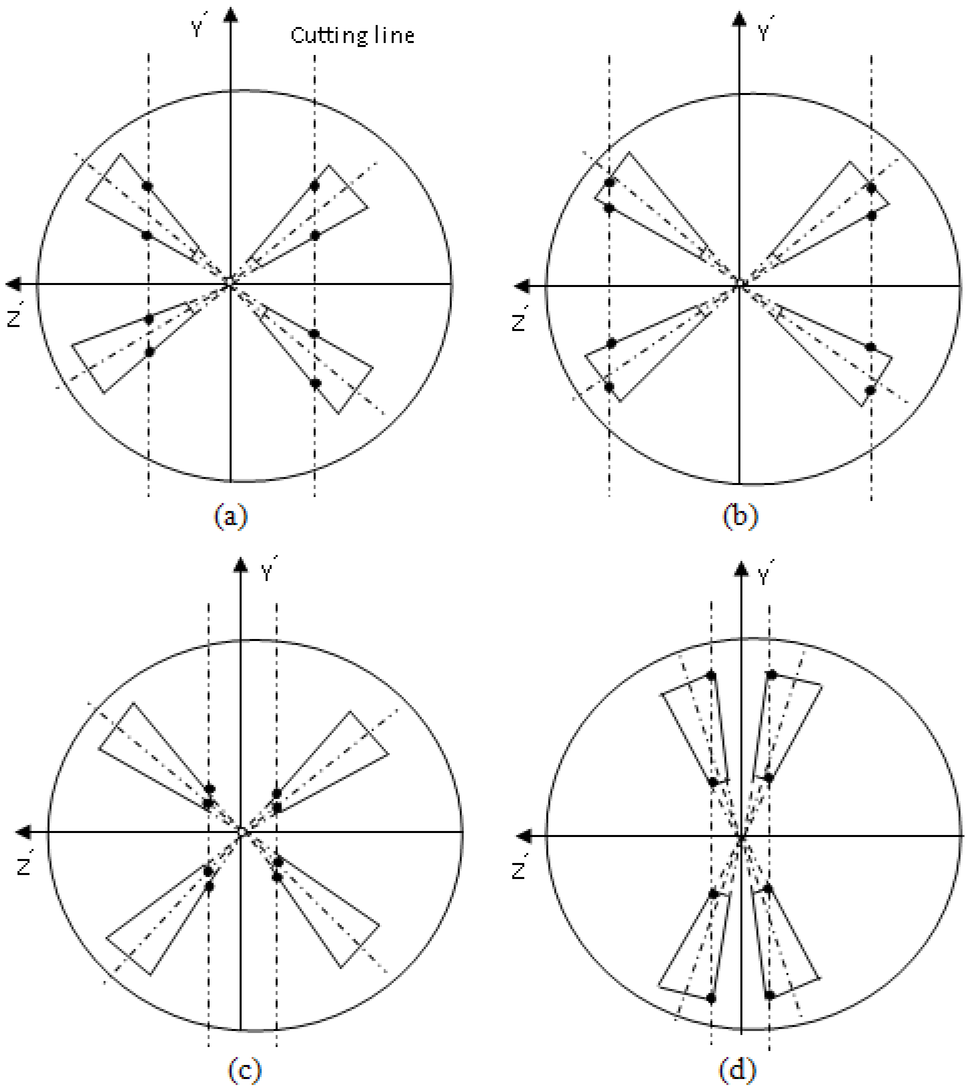


Figure 5.6. Scenarios of a cutting line passing the projected knot.
(a) cutting line intersects with two sides of the projected knot. (b) cutting line intersects with top end and one side of the knot. (c) cutting line intersects with bottom end and one side of the knot. (d) cutting line intersects with top and bottom ends of the knot.

5.2.4 Determining opening face

During lumber production, the first cut determines the remaining cuts which must be either parallel or perpendicular to the first cut. Therefore, the initial saw cut has direct impact on the lumber grade and volume yield (Denig 1993). In this study, the opening face is determined with consideration of log surface defects and log profile. Since no logs are absolutely straight, log sweep is considered to describe the curvature of a log. If a log sweep is less than 3 inches, the log will be treated as a non-sweepy log, otherwise it will be deemed as a sweepy log and log sweep will be considered in the modeling process.

(1) Non-sweepy logs

Three steps are needed to determine the opening face for non-sweepy logs (Lin et al. 2011): log orientation, the best face, and opening face dimension. To maximize lumber value, a log is positioned so that defects are placed at the edge of the sawn flitch face and can easily be cut off. A mathematical procedure has been developed to identify four log faces after placing major defects at edges of the cutting planes or in one log face as in Equation (5.5):

$$Min\,Z_\theta = \sum_{i=1}^{4}\sum_{p=1}^{n_i} d_{ip},\ \ 0 \le \theta \le 90^\circ. \tag{5.5}$$

where Z is the sum of angles from log defects to the nearest edges of log faces, i is log face index, i =1, 2, 3, 4, n_i is the number of defects on log face i, p is defect number, p =1, 2, …, n_i, and d_{ip} is the minimum angle of the p^{th} defect to the edges of log face i.

It is assumed that the best face is the opening face. To determine which log face is the best, the four log faces are graded based on a computerized log grading algorithm using the USFS log grading rules. After identifying the best log face, the opening face dimension is then determined. The size of the opening face has a direct bearing on profitability (Denig 2005). The width is the only consideration since the lumber length is assumed to be the same as the log at primary log sawing. The width of the opening face is determined using a modified version of Malcolm's opening face heuristic (Malcolm 1965). The opening face determination was described in detail by Lin et al. (2011).

(2) Sweepy logs

For logs with sweep of 3 inches or more, the opening face is based on log sweep rather than clear face (Malcolm 1965; Denig et al. 2005). It is assumed that the concave surface of a log towards to the sawyer, and log sawing starts from this face. Only one cut is allowed in this face, and then a flat surface running the full length of the log is produced. We used a no taper sawing method with the initial lumber width at the largest sweep deviation set at 3.25 inches (3 inches is the minimum width for a validated lumber grade board and 0.25 inches is for log sawing kerf width and lumber shrinkage). The opening face widths at the small end and large end of the log are determined as in Equation (5.6):

$$\begin{cases} w_1 = 2 * \sqrt{r^2 - (r - (H - h_1) - (R' - \sqrt{(R')^2 - 1.625^2}))^2} \\ w_2 = 2 * \sqrt{R^2 - (R - (H - h_2) - (R' - \sqrt{(R')^2 - 1.625^2}))^2} \\ w_3 = 2 * \sqrt{r^2 - (r - ((h_4 + R - \sqrt{R^2 - 1.625^2}) - h_3))^2} \\ w_4 = 2 * \sqrt{R^2 - (R - ((h_3 + r - \sqrt{r^2 - 1.625^2}) - h_4))^2} \end{cases} \quad (5.6)$$

where w_1 and w_2 are the opening face width at small and large end of a log, respectively, r and R are the radius of small end and large end of the log, respectively, h_1 and h_2 are the distances from the horizontal line to the small end and large end of the log, respectively, H is the maximum curved height, and R' is the corresponding log radius (Figure 5.7). After the first cut, the log is rotated 180 degrees to saw the opposite side. It is also assumed that currently only one cut is produced from this face with full log length. Similarly, no taper sawing is used and the opening face width at one log end equals to 3.25 inches depending on which end has larger curve. Let w_3 and w_4 be the opening face width at small and large end of the log, respectively, when the log rotates 180 degree from the first opening face, r and R be the radius of small end and large end of log, respectively, and h_3 and h_4 be the lower height at small end and large end of the log to the ground, respectively. If $h_4 > h_3$, the opening width at the large log end will be 3.25 inches and the opening width at small end is computed as w_3 in Equation (5.6), otherwise the opening width at small end will be 3.25 inches and the width at large end is computed as w_4 in Equation (5.6). Once the sweep has been removed from a log, the turning rules and procedures of the log would be the same as for not sweepy logs during grade sawing process.

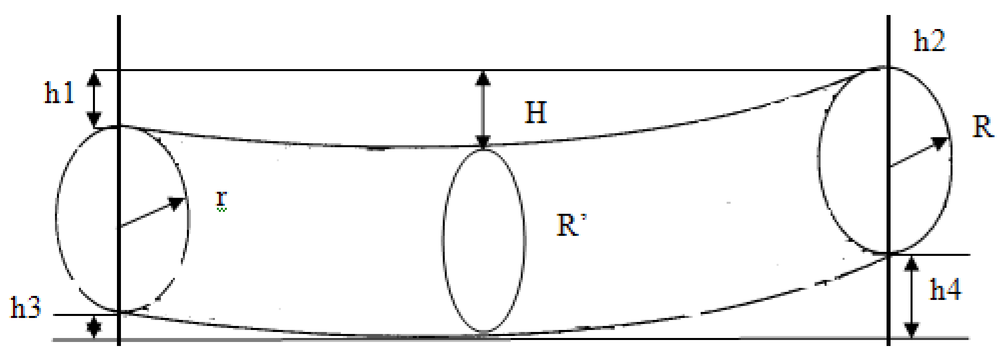


Figure 5.7. Log sweep measurement.

5.2.5 Primary log sawing algorithms

The integrated primary and secondary log breakdown optimization is solved by linking two recursive relationships. The primary log breakdown produces a flitch which is sent to the secondary breakdown to determine the value. An optimal edging and/ trimming solution is then generated for the produced flitch. Specifically, once the log opening face is determined, the system uses either heuristic or DP algorithm to achieve the optimum sawing pattern at the headrig. The generated flitches are then edged and trimmed through the optimal edging and trimming algorithms. The optimum value of a flitch is then returned to the headrig log sawing, and the log sawing pattern is finalized.

(1) Heuristic algorithm

Heuristic refers to experience-based techniques for problem solving. It is more easily adaptable to a complex restriction problem, such as log grade sawing process. In this study, the heuristic for log sawing is developed based on a modified Malcolm's (1965) simplified procedure for lumber grading from hardwood logs. The basic principle is that the log is not rotated unless one of the other log faces could yield a higher-grade of lumber than current sawing face or the current face reaches the central cant. Then the log is rotated to next face with a potential for the highest lumber grade. This sawing process is repeated until a specified size cant is produced (Lin et al. 2011).

Algorithm to determine log grade sawing pattern:

```
begin
    cutting from the opening face
    repeat
    if (the lumber grade from current face <  the remaining face )
        let the log rotate to the face that generates the highest lumber grade
    else if (the current face reaches the central cant)
        assign a flag to current face to prohibit cutting current face and rotate the
        log to the face that generates the highest lumber grade
    until-  all faces are cut and a central cant left
end
```

(2) Dynamic programming algorithm

The primary log breakdown problem can be easily solved using dynamic programming which separates a large problem into a series of tractable smaller problems. The key to the dynamic programming is to find the recursive relationship. In log grade sawing, a log is divided into four log sawing faces. Then an optimal sawing pattern can be found for each face by solving the recursive function:

$$f_n(i) = \max\{ f_{n+1}(j) + v_{ij} \} \tag{5.7}$$

where n is the current stage, n =1, 2, 3. Each stage is corresponding to one log sawing face, i is the current state at stage n, j is the state at stage $n+1$, v_{ij} is the lumber value contributed to the objective function, $f_{n+1}(j)$ is the contribution values at stages $n+1$, .., 4 to the objective function if the log sawing in state *j* at stage $n+1$.

For each stage at Equation 5.7 the optimal lumber value from each sawing face can be obtained using Equation 5.8:

$$v(n) = \max\{ v(m) + g(m,n) \} \tag{5.8}$$

where m and n are possible sawing lines positions at current sawing face ($1 \le m \le n \le N$, m and n are discrete values), N is the total potential sawing lines positions between the opening face and central cant. The $g(m,n)$ is the lumber value generated between the sawing lines m and n, which is determined by the edging and/ trimming optimization. $v(m)$, $v(n)$ are portions of the optimal lumber value at the current face from the opening face to sawing line m and n, respectively.

If lumber thicknesses, sawing kerf width, and sawing resolution were given, Equation 5.8 can also be expressed as Equation 5.9, which is a modified recursive function based on Bhandarkar et al. (2008).

$$v^*(i+1) = \max_{j\in[1,m]}(v^*(i+1-\frac{T_j}{c}-\left\lceil\frac{K}{c}\right\rceil) + g(i+1-\frac{T_j}{c}, i+1)) \quad (5.9)$$

where $T_j = (T_1, T_2, \cdots, T_m)$ is a set of lumber thicknesses values, and m is the total number, c is the sawing plane resolution (mm), K is the kerf thickness (mm), $v^*(i)$ represents the optimal lumber value between cutting planes 1 and i, $g(i, j)$ is the lumber value from the sawing line i through j, depending on flitch edging and trimming optimization.

5.2.6 Flitch edging and trimming

Flitches produced in the primary log breakdown need to be edged and trimmed to remove excessive wane and defects. The edging lines move along the vertical direction and trimming lines move along the horizontal direction of a flitch. In hardwood sawmills, edging and trimming operations occur independently, and each individual process can be optimized using mathematical algorithms. In addition, the combined edging and trimming optimization might be complex and costly, so it also is of interest to optimize edging and trimming independently. For edging only, an optimal strategy is to determine the optimal spacing between the mutually paralleled edging lines so as to maximize the value of the resulted edged flitch. Similarly, for trimming only, the optimal spacing between trimming lines should be determined. Since edging and trimming operations are interrelated and the placement of edging lines has effect on the trimming decision and vice versa. The two operations should be considered simultaneously in order to achieve the global optimal lumber value recovery. In this study, two optimal algorithms, exhaustive search and dynamic programming were embedded into the system as an integrated edging and trimming component to maximize lumber value recovery.

Before edging and/or trimming, the two faces of the flitch are merged together and wane allowances on both edges of the flitch are taken into account. To merge the two faces, several steps are required. First, for a cross section of a flitch (Figure 5.8), find the merged upper and lower points, which are the maximum and minimum Y coordinates or Z coordinates among the four points, depends on which sawing face are cut during the primary log sawing. In Figure 5.8, the merged points for the cross section will be right-upper and right-lower coordinates. Next, record wane using a vector for the left face since there is no wane on the right face. Wane at upper-left corner and lower-left corner includes two dimensions, a vertical dimension and a horizontal dimension. So wane at this cross section will be recorded and they can be used to determine the sizes of wane on the final lumber. The process of merging two faces to one face is similar to the procedure described by Zeng in 1996. The wane included not only the sloping side where bark was removed but also areas where wood was missing entirely. It is assumed that the outermost location of an edging line is in place to make sure that the total length of the wane on either edge equals half of the length of the flitch. This is also the maximum allowable wane for the FAS grade. All other wane left on the flitch are treated as defects and represented with rectangles. If the current flitch satisfies FAS lumber grade, then the edging and trimming optimization will terminate and return the lumber value because no improvement can be achieved by edging and/or trimming operation. Otherwise, the edging and/ trimming algorithms will be recalled to achieve the optimal solution, and multiple pieces of lumber will be generated.

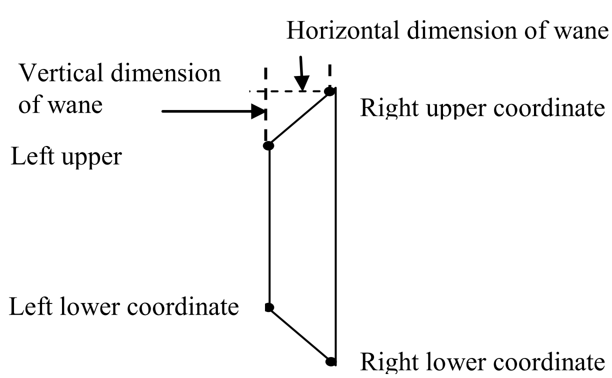


Figure 5.8. A cross section of a flitch.

(1) Exhaustive search algorithm

This edging and/or trimming algorithm will try all possible combinations of edging and/or trimming lines to find the optimal pattern. For the integrated flitch edging and trimming, if there were n_1 and n_2 edging increments for each edge of flitch, and n_3 and n_4 increments at both end, there would be a total of ($n_1 \times n_2 \times n_3 \times n_4$) combinations of cutting lines. Each set of edging and/or trimming lines determines the shape of the edged and/or trimmed flitch. Information regarding length, width, surface measure, and defects of the edged and/or trimmed flitch is then passed to the lumber grading component for grading. The combination of grade and SM determines the board's value based on the lumber price. The solution that yields the maximum lumber value will be the optimal edging and/or trimming solution.

(2) Dynamic programming algorithm

Similar to primary log sawing at each sawing face, the positions of all potential edging and trimming lines are pre-defined by dividing a flitch into equidistant levels in the horizontal (Figure 5.9a) and vertical (Figure 5.9b) directions, respectively.

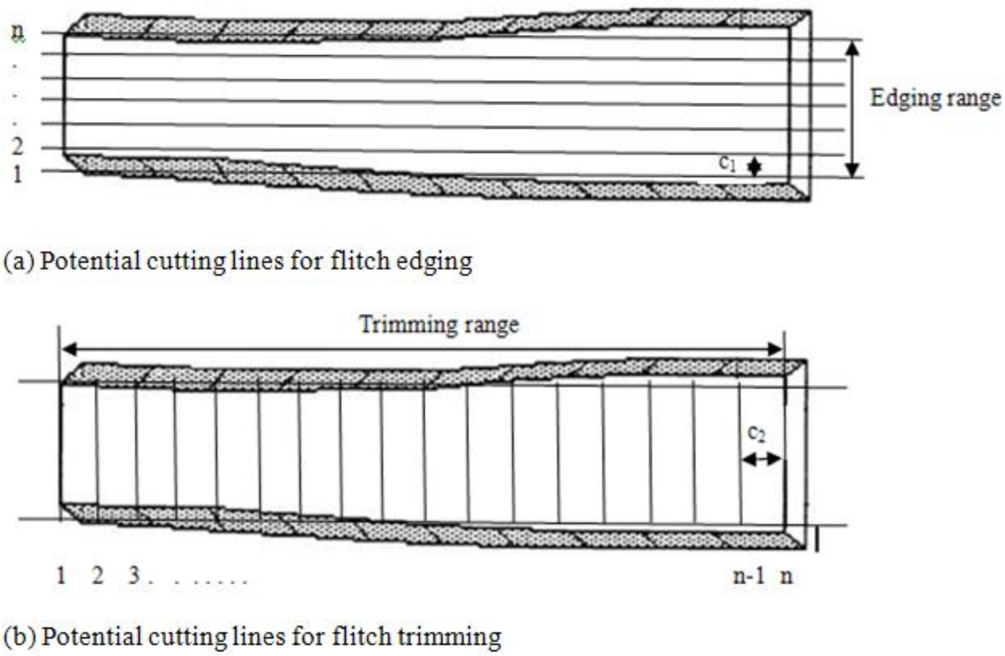


Figure 5.9. Potential cutting lines for flitch edging and trimming.

This allows the lumber edging and/or trimming problem to be formulated as a set packing problem with the objective of maximizing the total lumber value. The recursive relationship for flitch edging or trimming can be expressed as Equation 5.10:

$$\begin{cases} v(j) = \max\{v(i) + g(i, j)\} \\ v(l) = \max\{v(k) + g(k, l)\} \end{cases} \tag{5.10}$$

where i and j are possible edging line positions within the edging range ($1 \le i \le j \le N_e$), N_e is the total potential edging lines between the lower and upper flitch boundaries, k and l are possible trimming line positions within the trimming range ($1 \le k \le l \le N_t$), N_t is the total potential trimming lines between the left and right flitch boundaries, $g(i, j)$ is the value of the edged flitch between the edging lines i and j, $g(k,l)$ is the value of the trimmed flitch between the trimming lines k and l, $v(i)$, $v(j)$ are portions of the optimal edged flitch value from the lower boundary to edging lines i and j, respectively, and $v(k)$, $v(l)$ are portions of the optimal trimmed flitch value from the left boundary to the trimming lines k and l, respectively.

Given the lumber width, length, sawing kerf width, and edging and trimming resolutions, the recursive mathematical equations for flitch edging or trimming can be written as Equation 5.11 based on Bhandarkar et al. (2008).

$$\begin{cases} v^*(i+1) = \max\limits_{k\in[1,m]}\left(v^*\left(i+1-\left\lfloor \frac{W_k}{c_1} \right\rfloor - \left\lfloor \frac{K}{c_1} \right\rfloor\right) + g\left(i+1-\left\lfloor \frac{W_k}{c_1} \right\rfloor, i+1\right)\right), \text{ for edging only} \\ v^*(i+1) = \max\limits_{l\in[1,n]}\left(v^*\left(i+1-\left\lceil \frac{L_l}{c_2} \right\rceil - \left\lceil \frac{K}{c_2} \right\rceil\right) + g\left(i+1-\left\lceil \frac{L_l}{c_2} \right\rceil, i+1\right)\right), \text{ for trimming only} \end{cases} \quad (5.11)$$

To integrate edging and trimming together, let $g(i, j, k, l)$ be the lumber value between edging lines i and j and trimming lines k and l, $v^*(i, j)$ be the optimal value for the horizontal edging lines from 1 to i and vertical trimming lines from 1 to j. Based on Bhandarkar et al. (2008) studied, the integrated edging and trimming flitch problem can be formulated as follows:

$$\begin{aligned} v^*(i+1, j+1) = \max_{k\in[1,m]}\Bigg(\max_{l\in[1,n]}\Bigg(\bigg(v^*\left(i+1-\left\lfloor \frac{W_k}{c_1} \right\rfloor - \left\lfloor \frac{K}{c_1} \right\rfloor, j+1-\left\lfloor \frac{L_l}{c_2} \right\rfloor - \left\lfloor \frac{K}{c_2} \right\rfloor\right) + \\ g\left(i+1-\left\lceil \frac{W_k}{c_1} \right\rceil, i+1, j+1-\left\lceil \frac{L_l}{c_2} \right\rceil, j+1\right)\bigg)\Bigg)\Bigg) \end{aligned} \quad (5.12)$$

where $W_k = \{W_1, W_2, \cdots, W_m\}$ is the allowed set of lumber width, $L_l = \{L_1, L_2, \cdots, L_n\}$ is the allowed set of lumber length, c_1 and c_2 are the edging and trimming intervals, respectively, and K is the sawing kerf. The minimum lumber width and length can be 3 inches and 4 feet, respectively. Any lumber width and length that equals the multiple of respective edging and trimming interval are allowed.

5.2.7 Cant resawing and lumber grading

Whether to make a cant or to saw the cant into lumber is a typical issue that needs to be considered by sawmill personnel. If the user would like to compare the total lumber value derived from different sawing methods for each log, the value of the central cant must be considered. If cant resawing occurs, the boards generated from the cant will be sent to the edging and trimming optimization component to obtain the optimal lumber value. As in the case of primary log sawing for each face, a similar DP algorithm can be used to resaw the central cant. The final cant will be divided into equidistant potential sawing lines in horizontal or vertical direction, and the final sawing pattern will be the one that yields the highest total lumber value.

The lumber grading component is modified based on a hardwood lumber grading routine (Klinkhachorn et al. 1988). A heuristic algorithm is designed to assign the NHLA lumber grade to a piece of lumber (Lin et al. 2011). The basic principle is that the potential lumber grades are tested sequentially, starting from the highest lumber grade and working downwards until the satisfied lumber grade is found. After edging and/or trimming, the processed flitch information including dimension, shape, and defect is called by the lumber grading component to determine the lumber grade. Based on lumber prices of different grades, the lumber value can be derived. The lumber prices can be updated whenever necessary. As a module, this grading algorithm can be easily combined with other modules within the system.

5.3 System Application

5.3.1 Data collection

A total of 30 hardwood logs in two species, yellow-poplar (*Liriodendron tulipifera*) and red oak (*Quercus rubra*), were collected at two local small sawmills in central Appalachia. These sawmills were typical mills across the region in terms of equipment and sawing methods. Log information such as log length, small-end and large-end diameters, log diameter at each foot interval, and log sweep were measured. To get log sweep, two stadia rods were put against both ends of the log and a string was horizontally stretched between the rods at the height of the upper end of the log (Figure 5.7). We measured the distances between the string and the log surface at each 1-foot interval using a folding ruler. The largest distance and the corresponding log diameter at this position were also measured. The distances from the opposite log surface to the ground at the large and small end were computed based on the measurements. External log defects data were also collected including defect type, defect distance from one end of log, and defect size. Based on the collected external defects, internal log defects were predicted by using the models developed by USDA Forest Service (Thomas 2008). The small-end diameters of the sample logs varied from 10 to 13 inches with log length between 8 and 14 feet (Figure 5.10). Log tapers range from 0.01-0.026 inch/foot and log sweep varied from 0-3.25 inches. Lumber length (ft), width and thickness (inches), and volume (bd. ft) were measured (Table 5.1). The grade and surface measurement of the lumber were determined by a certified NHLA grader at each sawmills. Lumber prices were based on Hardwood Market Report for Appalachian Hardwoods in April 11, 2009 (Table 5.2).

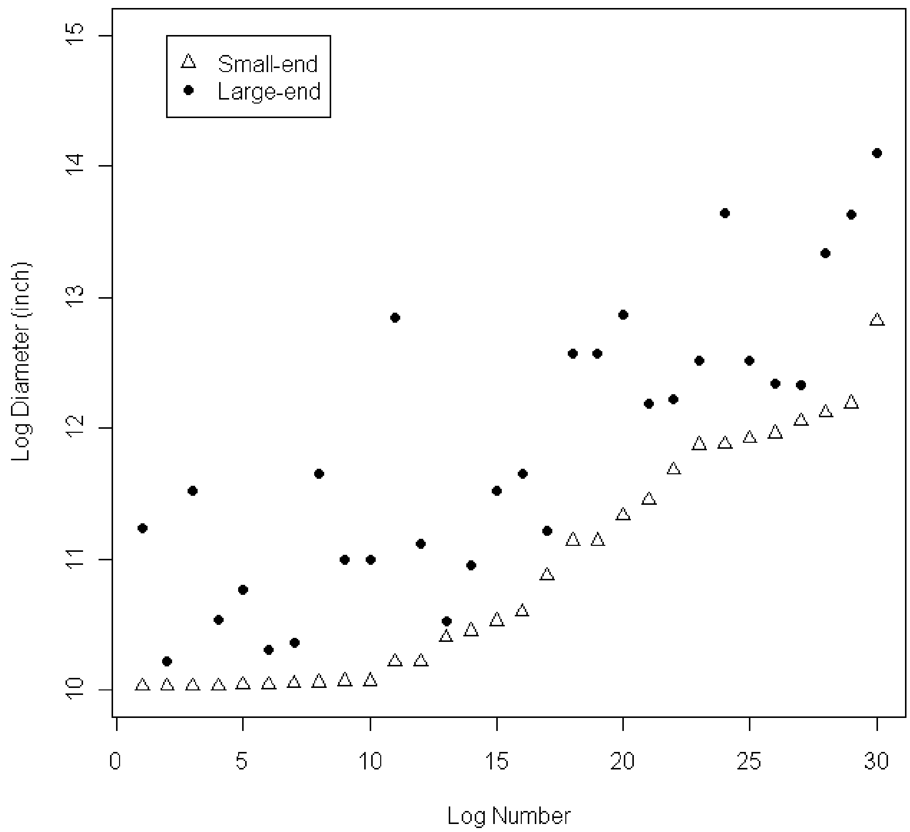


Figure 5.10 Log diameter distribution - order by small end diameter.

Table 5.1. Characteristics of lumber from the sample logs.

Statistic categories	Length(feet)	Width(inch)	Thickness(inch)	SM**	Volume(bd.ft)	Value($)
Min	6	4.00	0.94	2	2.75	0.66
Max	14	9.00	2.25	7	13.13	6.43
Mean	8.69	5.94	1.39	4	5.99	2.49
Stdv*	1.65	1.04	0.14	1.14	1.7	1.13

* Standard deviation. ** Surface measure.

Table 5.2. Lumber prices based on grades ($/MBF).

Species	Thickness (in)	Lumber grades					
		FAS	F1F	Select*	1COM	2COM	3COM
Red oak	4/4	705	695	598	500	375	300
	5/4	850	840	685	530	420	355
	6/4	905	895	763	630	435	375
	8/4	920	910	805	700	445	385
Yellow-poplar	4/4	600	590	475	360	290	235
	5/4	600	590	488	385	305	250
	6/4	615	605	503	400	310	260
	8/4	615	605	513	420	325	260

* the price was the average of price of the F1F and 1COM.

5.3.2. System implementation

The system was implemented via a 3D-based Windows dialog box with four control tabs labeled as logs, defects, shapes, and grades. The log tab is used to display all log data saved in the database. A structured query language (SQL) query was employed to view defects, shapes, and grades associated for a selected log. This is accomplished by clicking one of the other three tabs. Once a log is selected, its 3D image can be generated. Before log sawing simulation, the first opening face needs to be determined by clicking the “Best Open Face” button (Figure 5.11). After the opening face is determined, the user can choose either the heuristic or DP algorithm to saw the log. Prior to the interactive simulation process, some sawing variables needs to be specified (i.e., kerf width, lumber thickness, cant size, and sawing, edging and/or trimming interval) at the bottom left area and choose appropriate commands at each group box. For example, the sawing kerf width and lumber thickness were 1/8 inch and 1-1/8 inch, respectively, and the cant size was 4×6 inches, all of the sawing parameters chosen were the same as those used by the real sawmills. Once these variables are specified, click the sawing buttons to saw the selected log.

In the system, the user can decide whether to saw the central cant or not to. If the user would like to saw it, he can click the “Cant Resaw” button (Figure 5.11). If the cant is left, its value will be computed based on its volume and price. Here, if the user cuts the log and considers the flitch edging and trimming, and the cant resawing optimization simultaneously, the final sawing patterns and sawing results for No. 1 log using heuristic and DP algorithms are shown in Figure 5.11. A total of 9 pieces of lumber were generated with a total lumber value of $20.9 and $21.33 for the heuristic and DP sawing algorithms, respectively.

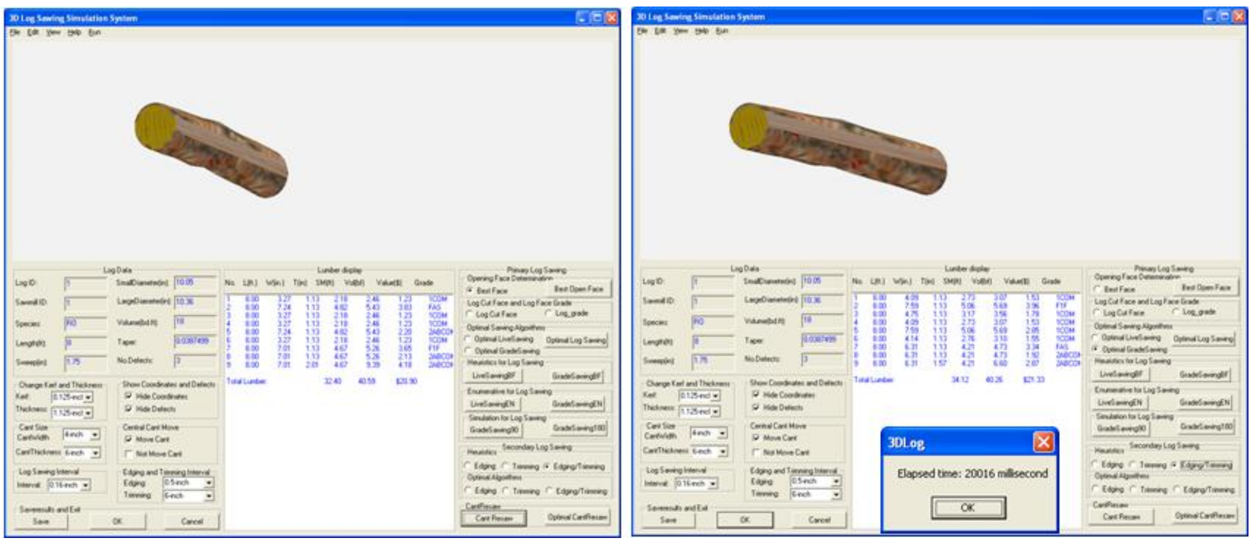


Figure 5.11. Log sawing results by heuristic and dynamic programming.
(a) Heuristic algorithm for log sawing, and flitch edging and trimming. (b) Dynamic programming algorithm for log sawing, and flitch edging and trimming.

5.3.3 Results

<u>Optimal solution vs. sawmill production without edging and trimming</u>

(1) Lumber value and volume recovery

Without considering lumber edging and trimming, the lumber width is assumed to be the narrowest clear width along the flitch length. Comparisons between the optimal solution and sawmill production in terms of lumber value/volume are presented in Figures 5.12 and Figure

5.13. The sawmills could improve lumber value by 7.84% and 10.46%, respectively, by using the heuristic and DP algorithms to aid the sawing process. Suppose that the average board value was priced at $0.5 per board foot and one million board feet went through the log sawing process annually, the potential gain in lumber value could be as high as $39,200 to $52,800 per year. The lumber volume could be increased by 2.2% and 3.5%, respectively, using the optimal algorithms. The comparisons indicated that the lumber volume loss in sawmills was partly attributable to value loss. It was noted that high volume recovery tends to result in high lumber value recovery. For example, when using the heuristic and DP algorithms to optimize log sawing, the average lumber volume per log was 53.53 bd.ft and 54.21 bd.ft, respectively, and lumber value averaged $26.78 and $27.34 per log, respectively. The average lumber value achieved using the DP algorithm was not always greater than the value generated by the heuristic algorithm because the selected interval in dynamic programming process has an effect on the precision of the DP solution.

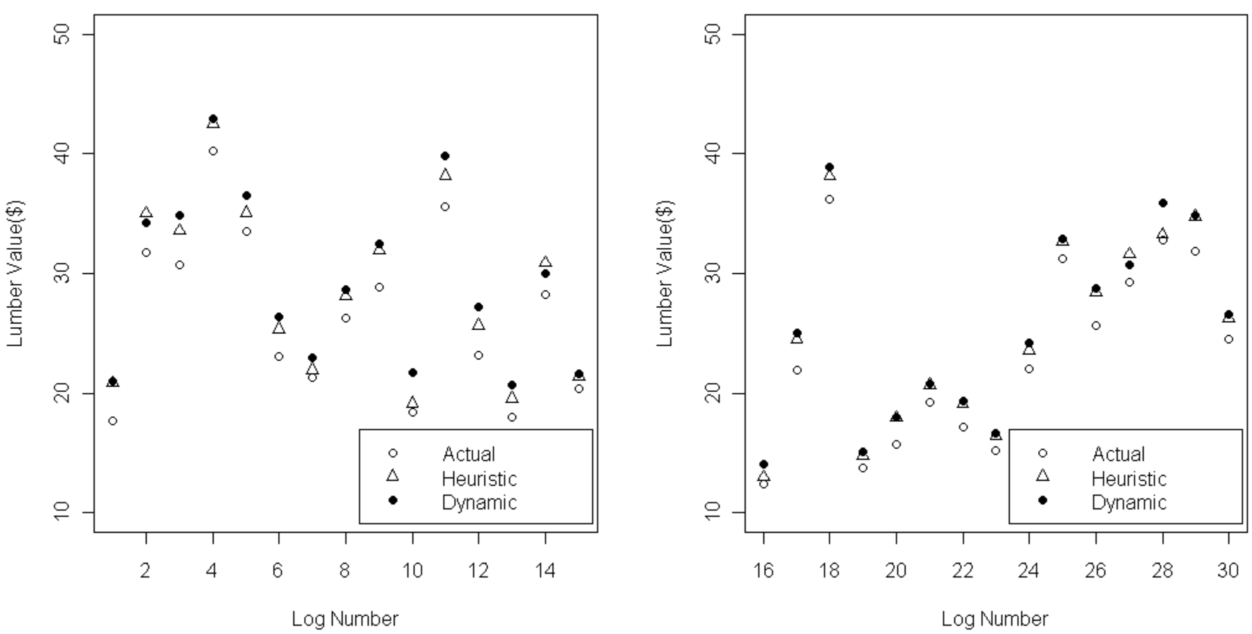


Figure 5.12. Lumber values by log from actual sawmill, heuristic and dynamic programming algorithm without edging and trimming optimization.

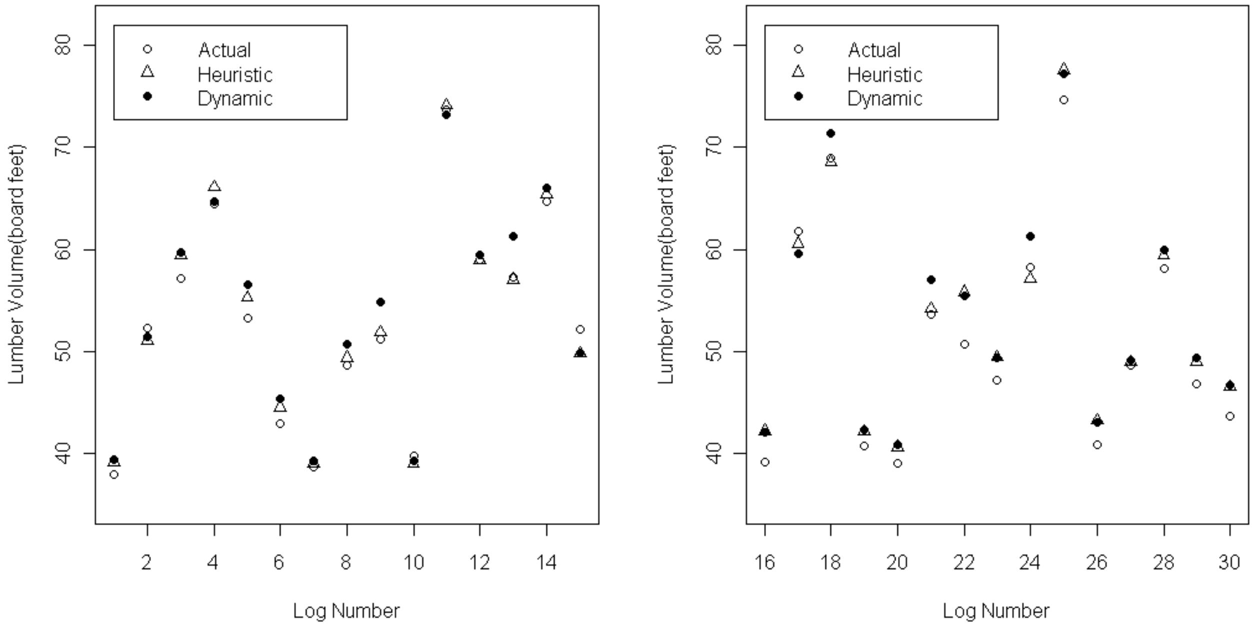


Figure 5.13. Lumber volume by log from actual sawmill, heuristic and dynamic programming algorithm without edging and trimming optimization.

(2) Lumber grade recovery

We found that the distribution of lumber grades differed among different sawing methods (Figure 5.14). Approximately 33.86%, 38.30%, and 41.39% of lumber produced were with grades of Select or higher by sawmills, using heuristic, and dynamic programming algorithms, respectively. In sawmills, 42.28%, 20.64%, and 3.21% of lumber were graded as 1COM, 2COM, and 3COM, respectively. If the heuristic algorithm was used to optimize log sawing, 38.96%, 19.86%, and 2.88% of lumber produced were with grades of 1COM, 2COM, and 3COM, respectively. If using dynamic programming, 37.83% of lumber were 1COM, 18.39% of them were 2COM, and 2.39% of them were 3COM. Therefore, lumber grades could be improved through optimization, resulting in an increase of the final lumber value recovery.

It was found that log sweep has a significant effect on lumber value and lumber volume recovery compared to straight logs. For example, for two logs 8 feet in length and 10.8 inches in small end diameter with 6 defects, the lumber value and volume were $24.54 and 43.72 board feet for the straight log. However, the lumber value and volume could drop to $18.67 and 35 board feet for the log which has 2.75 inches of sweep. In addition, lumber from sweepy logs is also prone to warp during drying (Denig et al. 2005). Therefore, a decision must be made prior to sawing process to avoid unnecessary sawing cost for severely sweepy logs.

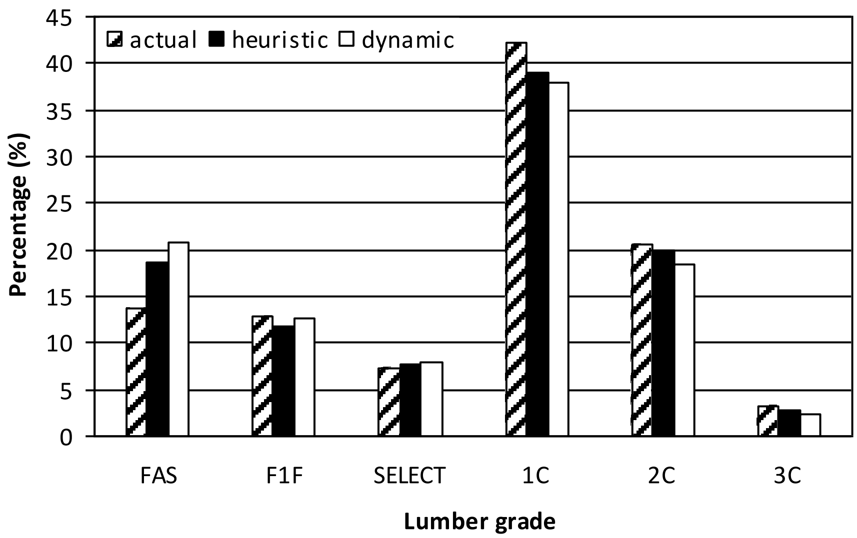


Figure 5.14. Lumber grade distribution without edging and trimming optimization.

Edging or trimming only optimization

The lumber values from edging-only and trimming-only optimization using an exhaustive search and the DP algorithm were compared (Table 5.3). With exhaustive search-based edging-only optimization, an overall average value recovery could be 97.82% or 97.27% by using the heuristic and DP log sawing algorithms, respectively. However, an overall average lumber value recovery could be 94.32% and 95.2% using trimming-only optimization. With DP-based edging-only optimization, an overall average value recovery was 98.41% or 98.02% by using heuristic and DP log sawing algorithms, respectively. An overall average value recovery would be 95.95% or 96.17% using trimming-only optimization. The findings suggest that edging optimization has a greater impact on lumber value than trimming optimization for waney edged boards. In the system, the board length generated from the log sawing was assumed as the same as log length, so there was little wane generated at both ends of the boards.

Table 5.3. Lumber values from edging-only optimization and trimming-only optimization.

		Edging only	Trimming only	Edging and trimming
		…………………………($)…………………………		
Heuristic log sawing	Exhaustive	834.82	804.99	853.42
	Dynamic programming	817.73	791.09	830.97
Dynamic log sawing	Exhaustive	821.70	810.51	844.70
	Dynamic programming	821.47	806.01	838.08

Optimal solution vs. sawmill productions with edging and trimming

(1) Lumber value recovery

In this case, the flitch produced from primary log sawing was edged and trimmed through either exhaustive or dynamic programming optimization. We compared the actual lumber value by sawmills and the simulated solutions (Figure 5.15, Figure 5.16) and found that the lumber value generated from log sawing using heuristic or DP algorithm could increase 12.75% and 15.35% using exhaustive search for flitch edging and trimming, respectively, while the lumber value could improve 11.56 % and 13.94% using DP for flitch edging and trimming. The results indicated that more lumber value recovery can be achieved when exhaustive search was used to optimize flitch edging and trimming. However, it should be noted that the exhaustive search typically needs more computer processing time than dynamic programming.

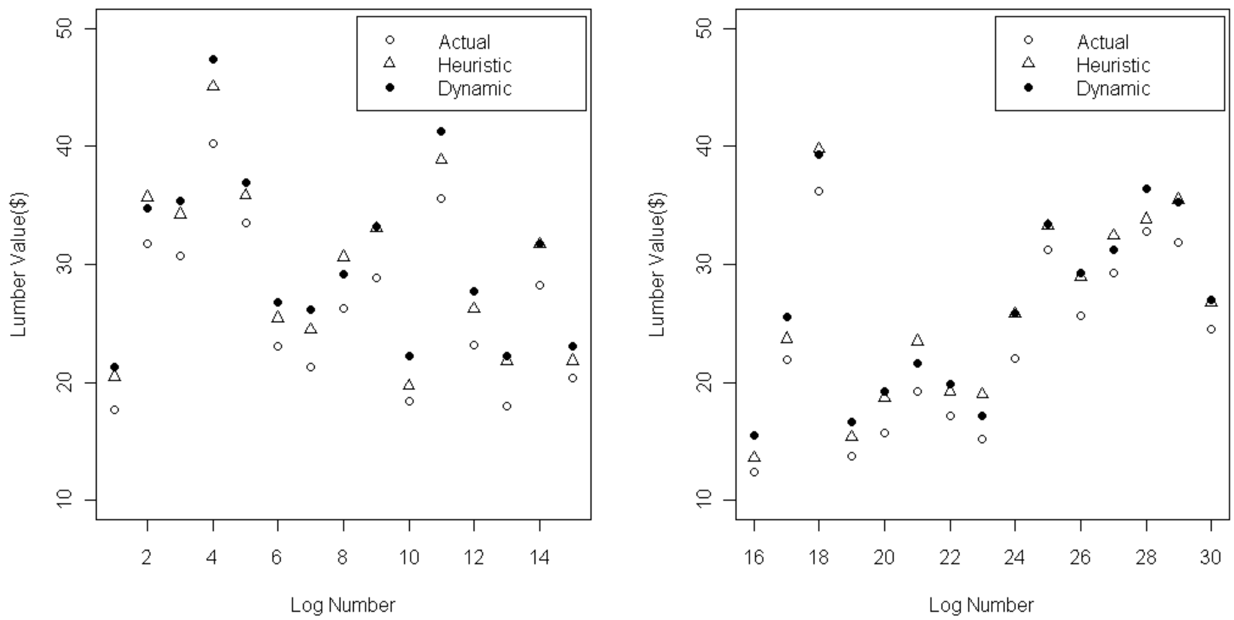


Figure 5.15. Lumber values by log from actual sawmill, heuristic and dynamic programming algorithm with exhaustive search for edging and trimming optimization.

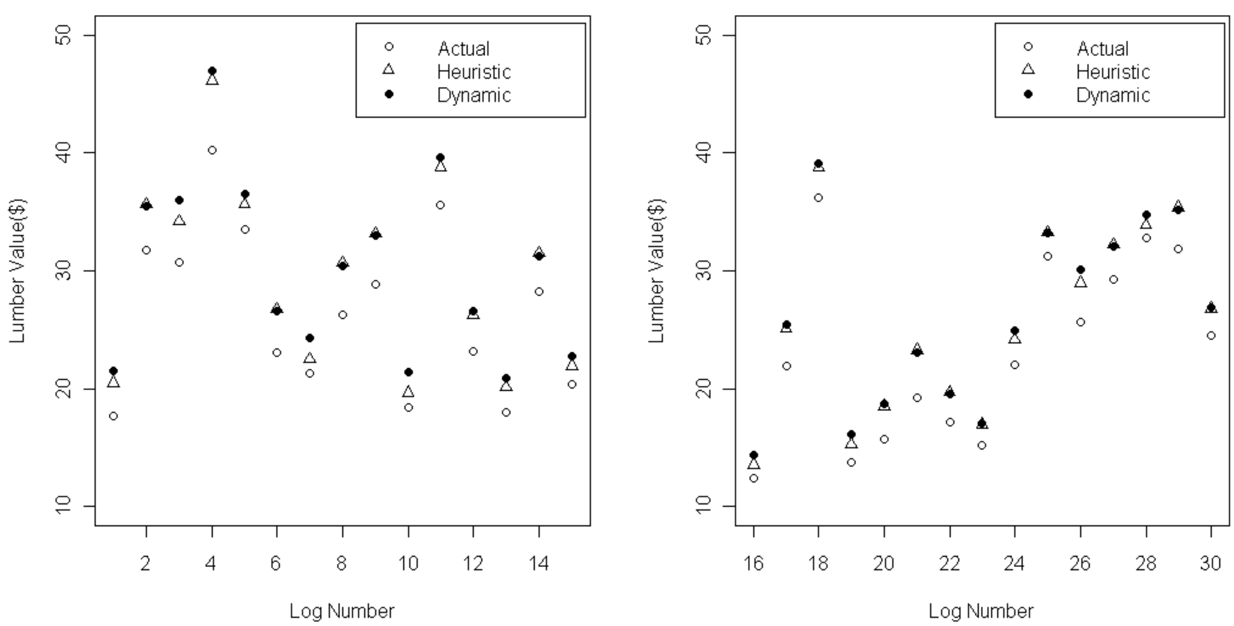
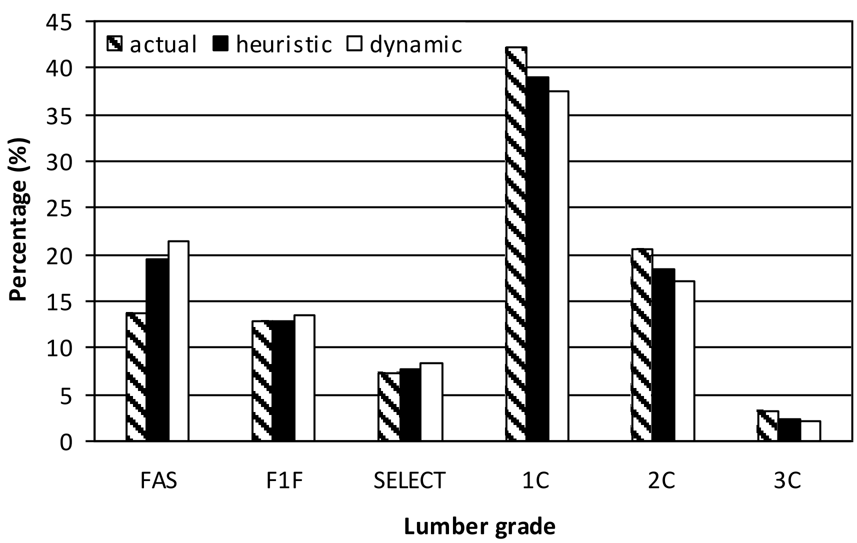


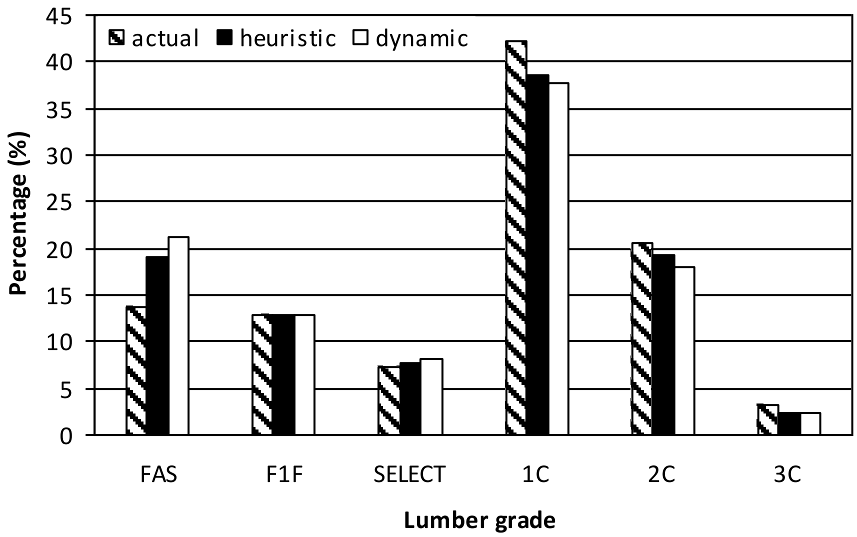
Figure 5.16. Lumber values by log from actual sawmill, heuristic and dynamic programming algorithm with dynamic programming for edging and trimming optimization.

(2) Lumber grade recovery

The distribution of lumber grades produced by using the optimal algorithms and actual lumber production with consideration of edging and trimming is shown in Figures 5.17a and 5.17b. It was found that the distribution of lumber grades was similar between the exhaustive and DP algorithms for edging and trimming operations. However, the lumber grade distribution among different log sawing methods (sawmills, heuristic, and dynamic programming) was very different. For example, when using the exhaustive search algorithm to optimize flitch edging and trimming, 33.86%, 40.15%, and 43.21% of lumber produced were Select or higher grades at swmills, using heuristic, and dynamic programming algorithms, respectively. In the actual log sawing production, 42.28%, 20.64%, and 3.21% of lumber were with grades of 1COM, 2COM, and 3COM, respectively. If the heuristic algorithm was used to optimize log sawing, 39.06%, 18.53%, and 2.26% of lumber were graded as 1COM, 2COM, and 3COM, respectively. When using the dynamic programming algorithm to optimize log sawing, 37.53%, 17.16%, and 2.1% of lumber produced were with grades of 1COM, 2COM, and 3COM, respectively.



(a)Lumber grade distribution with exhaustive edging and trimming



(b)Lumber grade distribution with dynamic programming edging and trimming

Figure 5.17. Lumber grade distribution with optimal edging and trimming operations.

(3) Optimal log sawing with or without optimal edging and trimming

More lumber value recovery could be achieved when log sawing was integrated with flitch edging and trimming optimization. At least 3.5% more value recovery could be obtained when integrating log sawing optimization with flitch edging and trimming, and the maximum value improvement could be as high as 5%. This is reasonable since severe edging can result in a failure to consider the numerous possible combinations of grades and surface measures from each board. Severe edging removes all wane from a board, but it may exceed the minimum requirements specified in the NHLA grading rules. Even though the board grade could be upgraded in some cases, the reduction of surface measure due to sever-edging could result in a total lumber value loss. Therefore, when edging and trimming optimization are ignored, the final log sawing solution is suboptimal.

Sawing and edging/trimming are not independent because log sawing depends on flitch size, wane, and defects. A one tailed t-test was used to test if the final lumber value recovery was significantly different between log sawing with and without edging and trimming optimization. Let d_i represent the difference between lumber values of the two sawing methods for log i. The null hypothesis is that there is no significant difference between the two sawing methods. The alternative hypothesis is that optimal sawing with edging and trimming can significantly increase the average lumber value recovery. Therefore, the null and alternative hypotheses can be expressed as:

$$\begin{cases} H_0 : \bar{d} = 0 \\ H_1 : \bar{d} > 0 \\ d_i = V_{i1} - V_{i2} \end{cases} \tag{5.13}$$

where, V_{i1} is the lumber value for log *i* when using optimal sawing with exhaustive search for edging and trimming, V_{i2} is the lumber value when using optimal sawing without edging and/ trimming optimization. Under the equal variance assumption, the results indicated that at α=0.05 level, the optimal sawing with edging and trimming could significantly (p<0.0001) increase the average lumber value recovery when compared to the optimal sawing without edging and trimming.

5.4 Conclusions and Discussion

This 3D visual log optimization system that integrated primary and secondary log breakdown simultaneously for lumber production, could be used as a decision aid for lumber production planning as well as a training tool to train novice sawyers. A prototype implementation of the system showed significant lumber value recovery gains could be achieved. Without edging and trimming optimization, the sawmills could simply improve lumber value by 7.84% and 10.56%, respectively, if heuristic and dynamic programming algorithms were used for log sawing optimization. With edging and trimming optimization, however, the lumber value recovery could be up to 12.75-15.35% using exhaustive search for flitch edging and trimming, or 11.56-13.94% using dynamic programming for flitch edging and trimming. The results indicated that better solutions could be achieved by integrating primary and secondary log breakdown in the system. Other factors also attributed to the difference of lumber value recovery between sawmills and using optimization algorithms. In a real sawmill, these factors could be operator experience, operation errors, and mill equipment. All these factors need to be considered in the computer simulation system.

The system can be used together with a cost effective and affordable 3D log laser scanning system to enhance the production efficiency and speed up the production process. Without the need of flitch scanning, the integrated log sawing and flitch edging and trimming system can predict internal defects on the flitch and save extra scanning time and cost. In addition, sawing errors may occur when sawing a log without considering flitch edging and trimming simultaneously. Errors in edging and trimming stage including cutting and/ or positioning the flitches causes different flitches to be edged and trimmed. The original (integrated) edging and trimming decisions are not used to these flitches, which should be applied to improve lumber value recovery, so a suboptimal solution will generate accordingly.

As a cautionary remark it should be noted that the log sawing method that combined primary breakdown and secondary breakdown presented here assumes that logs are positioned and opening face was determined before sawing. Of course, the sawyer can choose an alternative angular (such as from 0 to 360 degrees) and opening face with (such as from 3 to 6 inches) placements, and the current method can be nested within that two loops and evaluated at each placement to find the best sawing results. However, increased levels of nesting will increase the computational burden and require enough memory to save millions of variables.

The optimization precision could be improved by reducing the stage interval of sawing, edging and/ trimming optimization at the expense of computing time. When considering sawing, edging and trimming optimization simultaneously, the log breakdown problem becomes a three dimensional log sawing problem, which requires more computer execution time to generate an optimal sawing pattern. A smaller interval would provide more chances to discover better solutions, but the optimization process could be longer, especially for poorly shaped large logs with more defects. In order to balance the number of variables used in the optimization process and obtain better solutions, the intervals selected in this study were 0.16 inch, 0.5 inch, and 6 inch for sawing, edging and trimming interval, respectively. The solutions from heuristics were better than those from the dynamic programming algorithm in some cases due to a relatively larger sawing stage interval. The edging and trimming intervals chosen were also have effect on lumber value recovery. It should be noted that time is of the essence for sawmills. To increase the profitability of the sawing business, the processing decisions at each stage must be delivered in a timely manner. Therefore, appropriate intervals should be determined to optimize log breakdown patterns as well as keep sawmills production running.

It is also noted that there are some limitations associated with this system, which should be taken into account in the future study. These include: (1) considering external log defects, internal defects, and log shapes simultaneously to determine opening face, (2) improving 3D log model by using polygonal obtained by laser scanning instead of circular representation of log cross sections, and (3) employing more sawing, edging, and trimming stage intervals to increase the flexibility of the system.

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CHAPTER 6: SUMMARY

Five typical small-scale hardwood sawmills were investigated to evaluate the effects of log sawing practices on lumber recovery across the state of West Virginia. Three computer systems integrated with optimal algorithms were developed to simulate the log sawing, flitch edging and trimming, combining of primary log breakdown with secondary log breakdown, and applying the systems in the central Appalachian region. Based on the collected field data, sawmill observations, and computer simulation and optimization results, the following conclusions can be drawn:

(1) The average lumber volume recovery factor (LRF) was 6.37 for red oak and 6.87 for yellow-poplar. The average cubic recovery percent (CRP) for each species was 53.15 percent and 57.54 percent, respectively. For lumber value recovery, the average $/MBF for red oak and yellow-poplar were $449.44/MBF and $327.25/MBF, respectively. The average $/HCF for red oak and yellow-poplar was $288.72/HCF and $226.52/HCF, respectively. The average $/MBFLS was $631.53/MBFLS and $462.26/MBFLS red oak and yellow-poplar, respectively. Log grade, log diameter, log species, different headrig types, log sweep, log length, the interaction between log species and grade, and the interaction between log species and log length had significant impacts on volume recovery. Log grade, log species and different headrig types had significant effects on value recovery. Lumber volume/value recovery and grade yield were significantly different among sawmills. Our findings indicate that small sawmills are less efficient in converting hardwood logs into lumber, due mainly to inappropriate selection of opening face, dimensional oversize, and sawing variations. Mill managers can improve these aspects to increase lumber recovery and business profitability.

(2) A 3D log sawing optimization system was developed to perform 3D log generation, opening face determination, sawing simulation, and lumber grading. Fifty sample sawlogs from five typical hardwood sawmills in West Virginia were used to validate the system. Preliminary results have shown that hardwood sawmills can potentially increase lumber value by determining the optimal opening face and optimizing the sawing patterns. Our results found that lumber value could be increased by 4.31percent when using optimal opening face cutting, as compared to the average of lumber value produced from random start angle. In terms of the average of lumber value recovery, sawmills have the potential to improve 10.01 percent or 14.21 percent of the lumber value when using a heuristic or dynamic programming algorithm, respectively. By using the optimal algorithms, the lumber grade was improved significantly. For example, approximately 16 percent of lumber grades were Select or higher grade in the actual operations, while this percentage could be increased to 30 percent if heuristic algorithm is used.

(3) A easy-to-use lumber edging and trimming optimization system was developed for rough hardwood lumber. The system was validated on a sample of 360 boards from six small sawmills in the central Appalachian region. The results showed that the six mills had the potential of increasing their surface measure and lumber value on average by 6.2 percent and 19.97 percent, respectively, through optimal edging and trimming. Lumber grades could be improved significantly by using optimal edging and trimming algorithms. In the actual sawmills, the percentage of No. 1Common or better grade lumber was 73.61 percent. After optimal edging and trimming, No. 1Common or better grade lumber were 85.15 percent and 83.68 percent when using the exhaustive and dynamic programming algorithms, respectively.

(4) The optimal edging and trimming algorithm was embedded as a component in the 3D log sawing optimization system to perform primary and secondary log breakdown

simultaneously. The system could be used as a decision tool for lumber production planning, as well as, a training tool for novice sawyers. A prototype implementation of the system showed significant gains in lumber value recovery when compared to sawmill production. Without edging and trimming optimization, the sawmills could simply improve lumber value by 7.84 percent and 10.56 percent, respectively, if heuristic and dynamic programming algorithms were used during primary breakdown. With edging and trimming optimization, the lumber value generated from log sawing could increase by 12.75-15.35 percent using exhaustive search for flitch edging and trimming, or 11.56-13.94 percent using dynamic programming for flitch edging and trimming. The results indicated that better solutions could be achieved by combining primary and secondary log breakdown in a system, as compared to the model that only considers primary log breakdown.

APPENDIX I: USER'S MANUAL FOR 3D LOG SAWING SYSTEM

I.1 Introduction

This is a user guide for the 3D optimal log sawing program. In this document, the system requirements are briefly reviewed and an example of application is demonstrated.

I.2 Setup OpenGL GLUT in Visual C++ 6.0 of Windows

The system was programmed with Microsoft Visual C++6.0 and Open Graphics Library (OpenGL). So you will need to have OpenGL and GLUT. If you are using Visual C++6.0, you should have OpenGL already installed, but it may not come with GLUT. So you need to set up GLUT in Visual C++6.0 of Windows:

Step 1: Download the glut-3.7.6-bin.zip from http://www.opengl.org/resources/libraries/ or http://www.xmission.com/~nate/glut.html. The OpenGL Utility Toolkit (GLUT) is a library of utilities for OpenGL programs. When you unzip the "glut-3.7.6-bin.zip", four files including "glut.h", "glut32.lib", "glut32.dll", and "readMe.txt" will be shown.

Step 2: Then do the following copies (the directory may be different, dependent of your environment): (1) copy "glut.h" to C:\Program Files\Microsoft Visual Studio\VC98\include\GL (Visual C++ include directory), (2) copy "glut32.lib" to C:\Program Files\Microsoft Visual Studio\VC98\lib (Visual C++ library directory), and (3) copy "glut32.dll" to C:\WINDOWS\SYSTEM or C:\WINNT\SYSTEM32, where your system files are located.

Step 3: In Visual C++ you should do the following steps in order to link an application using GLUT: (1) Select ***Project/Settings*** from the main menu, (2) Select the ***Link*** tab, and (3) Add the following libraries to the ***Object/library*** modules line: opengl32.lib glut32.lib glu32.lib (do not remove the others).

Then you are ready to run OpenGL codes in Visual C++6.0.

I.3 System Requirements

The software system can be implemented on either a desktop or laptop. The recommended system configuration for this optimal log sawing system is Microsoft Windows XP operation system or later version, with Pentium IV processor and at least of 512 megabytes (MB) of RAM. Table I.1 lists the detailed requirements for running this system.

Table I.1. System requirements.

Item	Requirements
Processor	Intel Pentium IV processor or later
Operating System	Microsoft Windows XP or later version
Memory	512 MB RAM
Hard Disk	100 MB of free space
Drive	CD-ROM drive
Display	Super VGA(800 x 600) with 256 colors
Peripherals	Microsoft Mouse or compatible pointing device

I.4 System Installation

This 3D optimal log sawing system is compiled in a release version, and no setup is required. Insert the system CD to CD-ROM, open the file, and copy the „3D optimal log sawing system' folder to your hard drive. To run the optimal sawing system, double click the „Optimal log sawing system' folder from hard drive, and then click the optimalsawing.exe file.

I.5 System running

Log Selection

After running the program, the user needs to click the **3DLog** command under the "**run**" menu in the menu bar (Figure I.1). The log list dialog will pop up for user's selection. There are four tab controls labeled as "Logs", "Shapes", "Defects", and "Grades" in the dialog. The "Logs" tab is used to display all log data saved in the Microsoft Access database. By clicking one of the other three tabs, the defects, shapes, and grades associated with the selected log can be shown in Figure I.2, Figure I.3, and Figure I.4, respectively. A structured query language (SQL) query was used to retrieve the related data from the database.

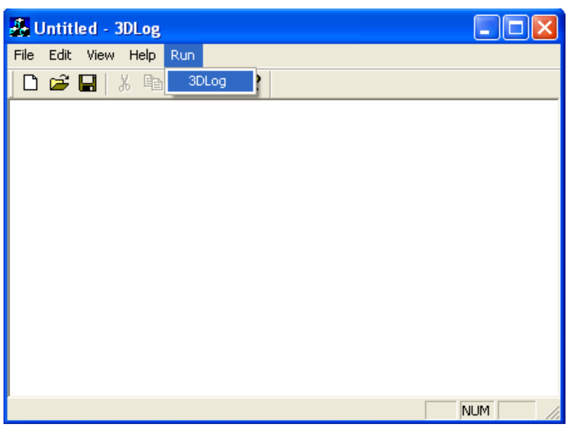


Figure I.1. Running the program.

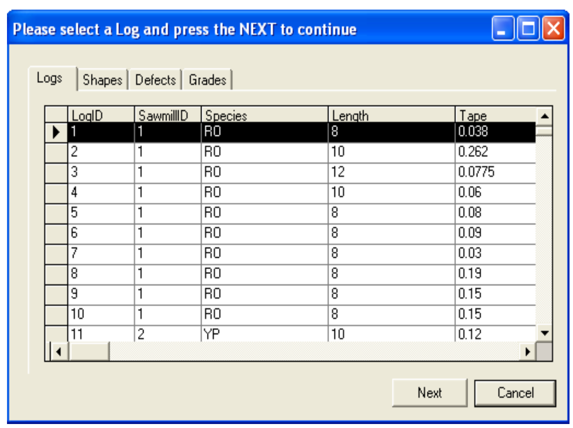


Figure I.2. Choose a log.

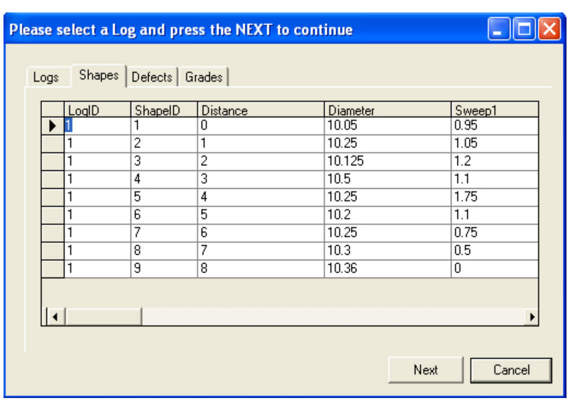


Figure I.3. Log shapes data.

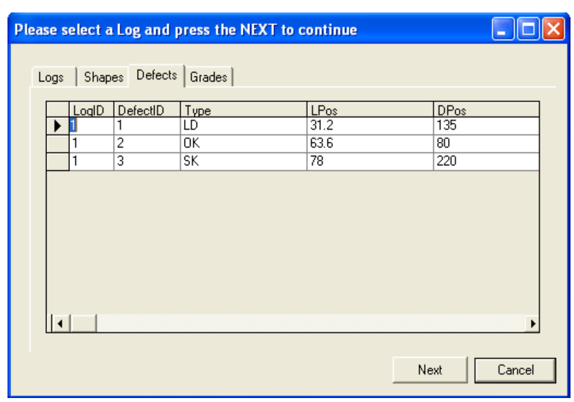


Figure I.4. Log defects data.

3D Log Visualization

Once a log (e.g., No.1 log) is selected, the user can click the “Next” button at the lower right corner of the log list dialog to enter the main interface, which is composed of four major sections: display area (top area), sawing results area (bottom middle area), information area (bottom left area), and command area (bottom right area) (Figure I.5). The selected log in three dimensions is shown in the display area. There are several menus on the top of the interface including “File”, “Edit”, “View”, “Help”, and “Run”. By clicking the “View” menu, the user can opt to move, rotate, and zoom out/in the log. The user can also use the keyboard to change log size and position. For example, the user can zoom out/in by pressing the „W’ and ‘S’ key, and move log to left or right by pressing the „L’ or „R’ key.

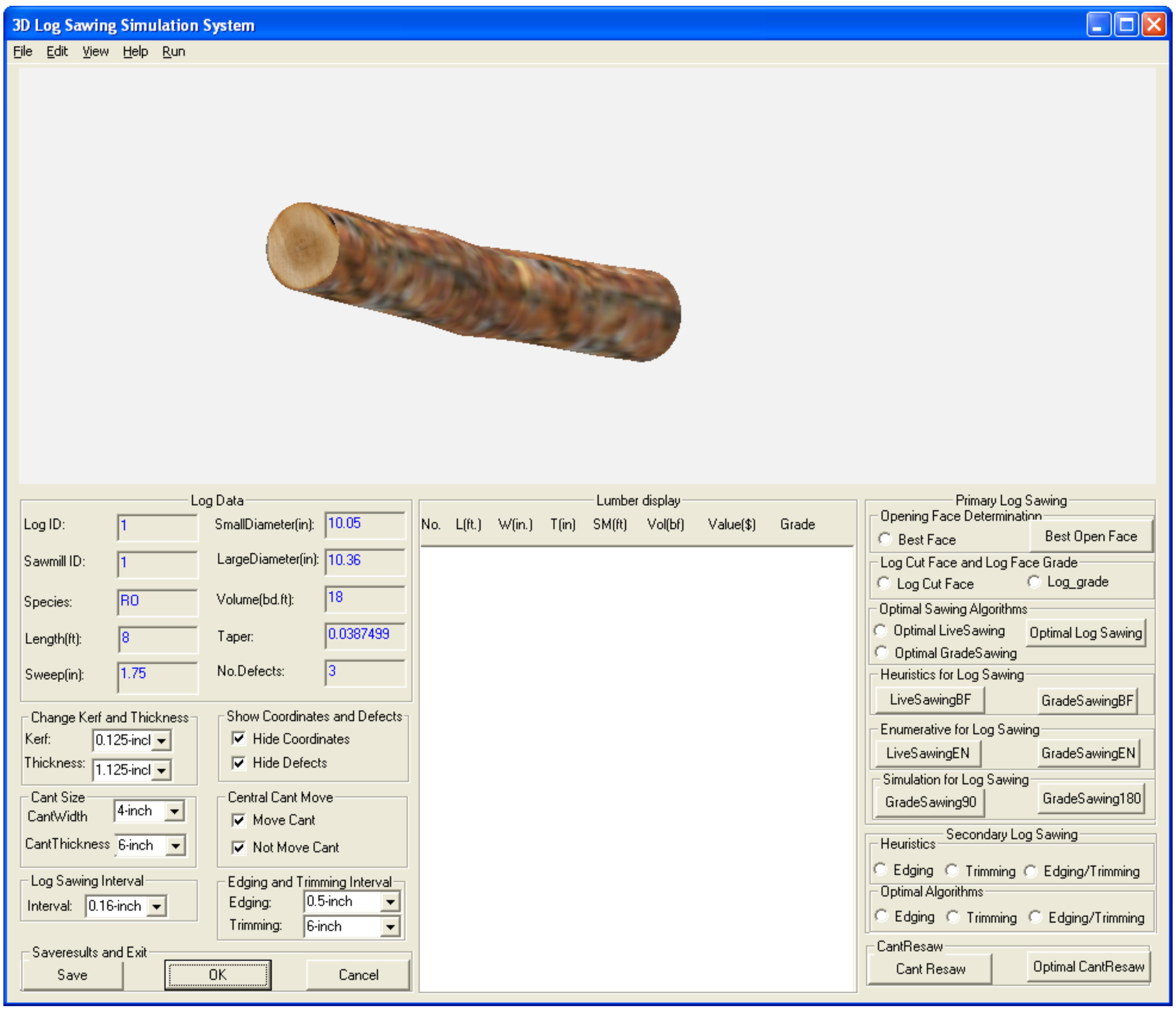


Figure I.5. Main interface for log sawing system.

Opening Face Determination

Before performing log sawing simulation, the first opening face needs to be determined by clicking the "**Best Open Face**" button. When the user clicks the radio button "**Best Face**", the results of the log rotation angle, best face, and the defects on each log face will appear in the upper display area. For example, for the selected No.1 log, the log rotates 0 degree, the best face was face 4, and the number of defects at faces 1 to 4 was 0, 1, 2, and 0, respectively (Figure I.6). If the user clicks the radio button "**Log Cut Face**", the opening face will be generated from face 4 and displayed in the display area. The user can also click the radio button "**Log Grade**" to determine the log grade. In this case, the log grade is F3.

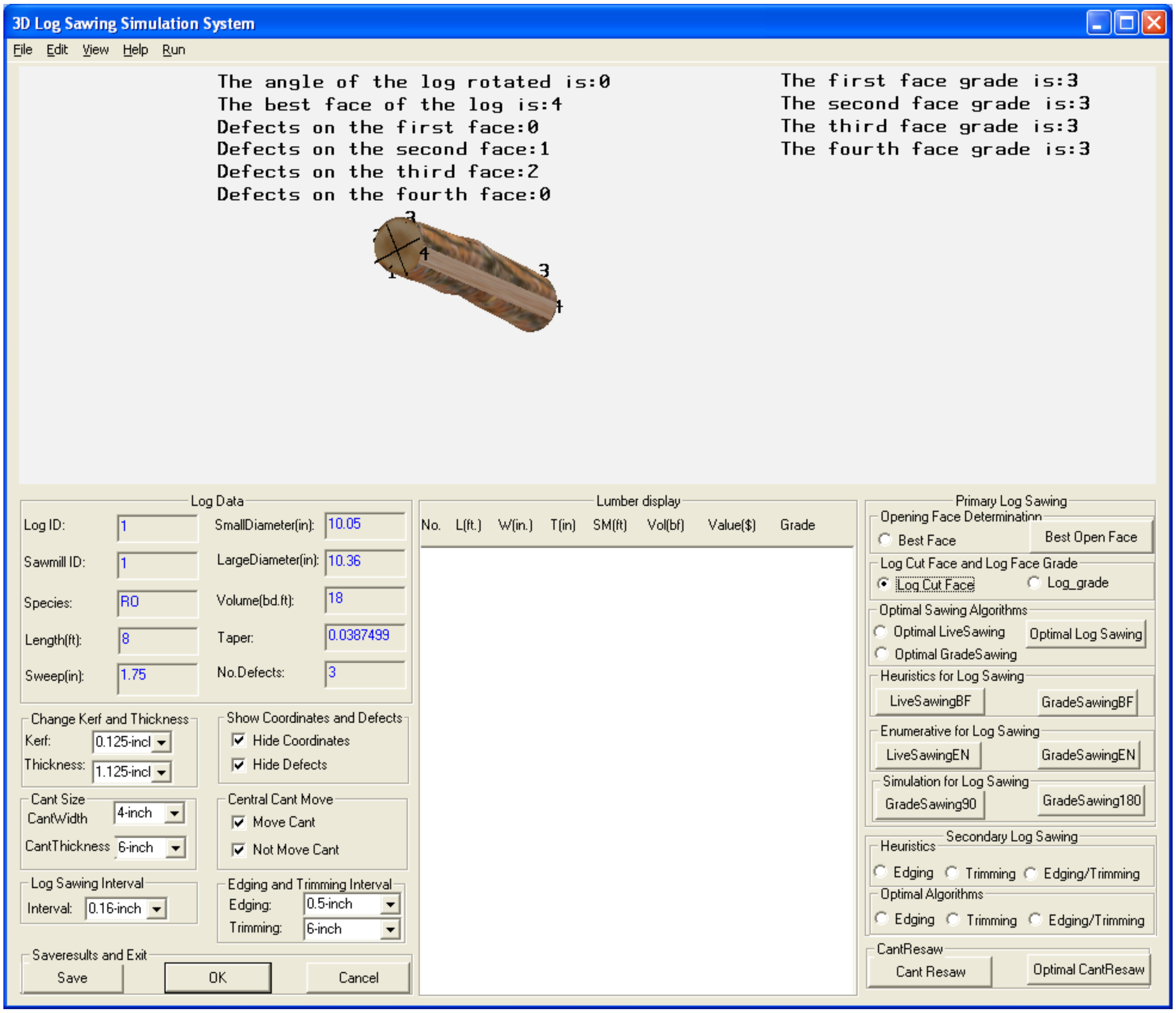


Figure I.6. Determination of the opening face and log grade.

Log Sawing Simulation

After the opening face was determined, the user can choose either the heuristic or dynamic programming algorithm to saw the log. To simulate the log grade sawing process interactively, the user needs to specify some sawing variables (i.e., kerf width, lumber thickness, cant size, sawing interval, and edging and/or trimming interval) at the bottom left area and choose appropriate commands at each group box. For example, the sawing kerf width and lumber thickness were chosen as 1/8 inch and 1-1/8 inch, respectively, same as the sawing parameters used in the sawmills in the central Appalachian region. We assume that the lumber width can be 3, 4, 6, 8, or 10 inches, and lumber length can be 4, 6, 8, 10, 12, or 14 feet. The commonly used cant size 4×6 inches was used in the system (McDonald et al 1996).

When using the dynamic programming algorithm to optimize log grade sawing, a sawing interval must be selected from the left bottom area. The interval between stages in the dynamic programming formulation is very important, which should be a common denominator of all sizes handled (e.g., a common denominator of all thicknesses and saw kerf). Here, the interval was 0.16 inch (4mm), so the sawing kerf and lumber thickness became 4mm and 28 mm, respectively. Another lumber thickness 1 3/8 inch (36mm) was also used when multiple lumber thicknesses was considered in the system. By clicking the "GradeSawingBF" in the "Heuristics for Log Sawing" group box (Figure I.7) or clicking the "Optimal GradeSawing" radio button and the "Optimal Log Sawing" command in the "Optimal Sawing Algorithms" group box (Figure I.8), the simulation results without considering cant resawing are displayed.

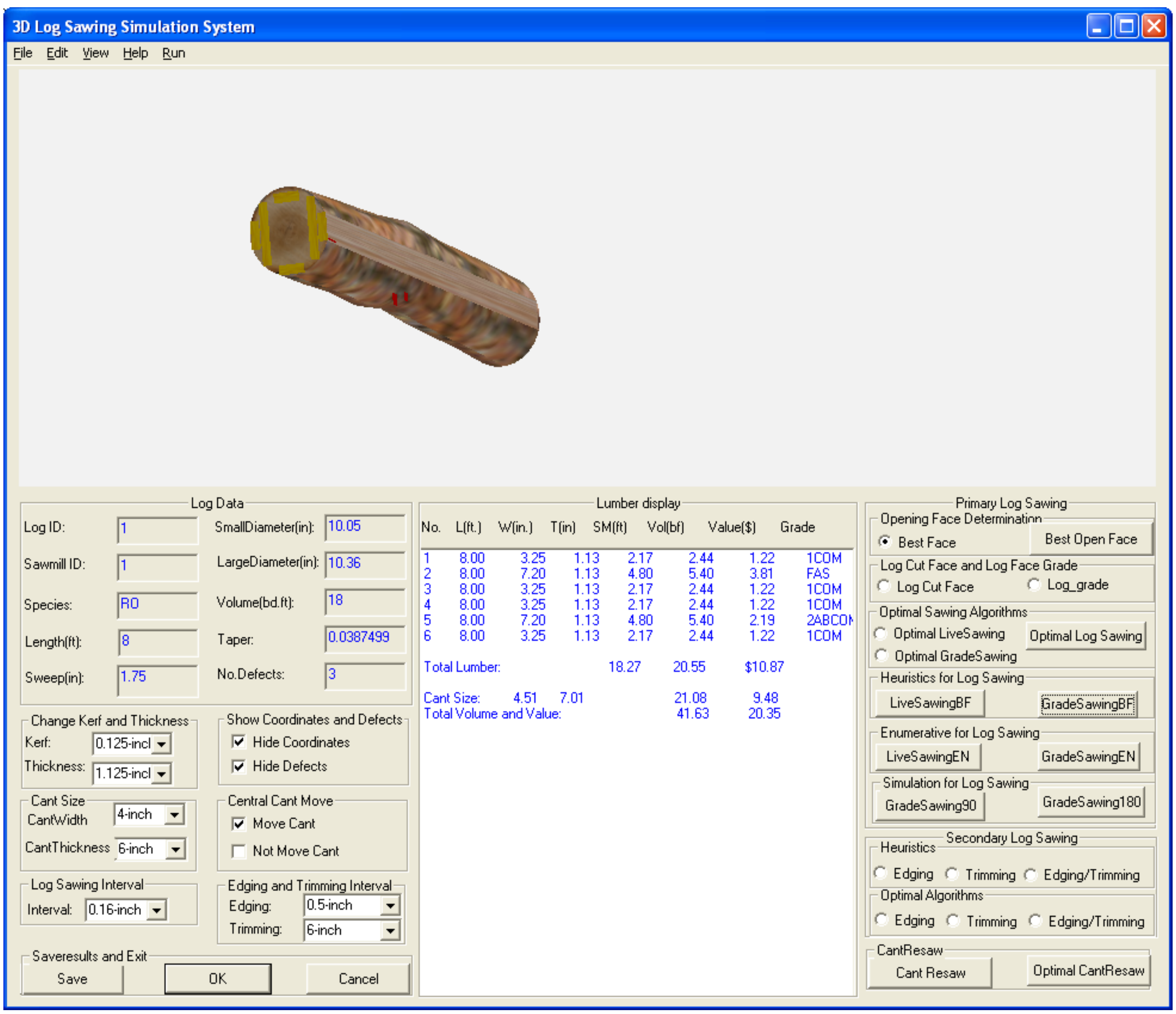


Figure I.7. Heuristic log sawing without cant resawing.

The user may also want to saw the central cant, then he can choose the command buttons from the group box “Cant Resaw”. The left button “Cant Resaw” can make a sequence of equal-thickness parallel cuts, while the right button “Optimal CantResaw” can perform optimal cuts with various thickness by using dynamic programming algorithm. In addition, if the user would like to optimize flitch edging and/or trimming during the log sawing process, edging and/or trimming interval and optimal edging and/or trimming algorithm must be chosen. The edging and/or trimming interval is a common denominator of all lumber width and/ lumber length. In this study, the edging interval was 0.5 inch (12 mm) and trimming interval was 6 inches (150mm). Of course, the user can change the interval to meet his own specifications. The user can click either heuristic or dynamic programming algorithm within the group box “Secondary Log Sawing” to edge and/ trim the flitches produced from primary log sawing.

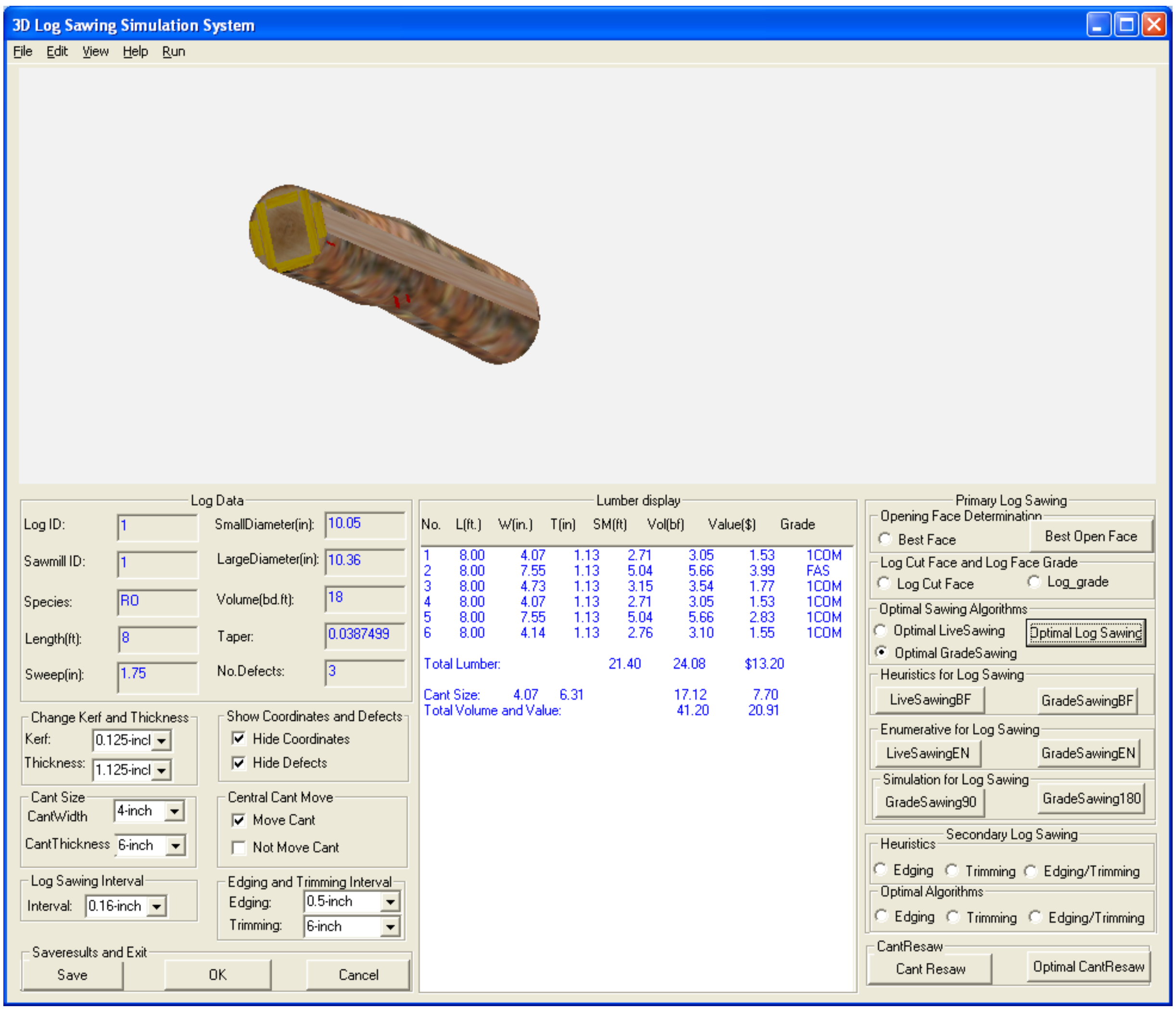


Figure I.8. Dynamic programming log sawing without cant resawing.

The final sawing patterns and sawing results for No. 1 log using heuristic and dynamic programming algorithms were shown in Figure I.9 and Figure I.10, respectively. A total of 9 pieces of lumber were generated and the total lumber value is $20.9 and $21.33, respectively, using the two algorithms. The output of the simulation results was compared to the lumber values that sawmill operators actually obtained from the same logs. In this system, the results of the sawing patterns were indicated by using line markers, without actually performing a log breakdown. These line markers can then be used as a template to perform simulated sawing of the corresponding true log.

The commands in the group boxes “Enumerative for log sawing” and “Simulation for log sawing” are used to simulate log sawing without using optimal sawing, edging and trimming algorithms. “Enumerative for log sawing” enables the selected log to rotate from 0 to 85 degrees at 5 degree increment and the opening face width is 3.25, 4.25, and 6.25 inches, respectively. To do this, the user does not need to determine the opening face at the very beginning. While, the opening face needs to be determined before log sawing if using “Simulation for log sawing”. For example, if the first opening face is face 1 and the user chooses “GradeSawing90”, the log is cut clock wisely from face 1, face 2, face 3, and face 4. If the user chooses “GradeSawing180”, the log is cut from face 1, face 3, face 2, and face 4.

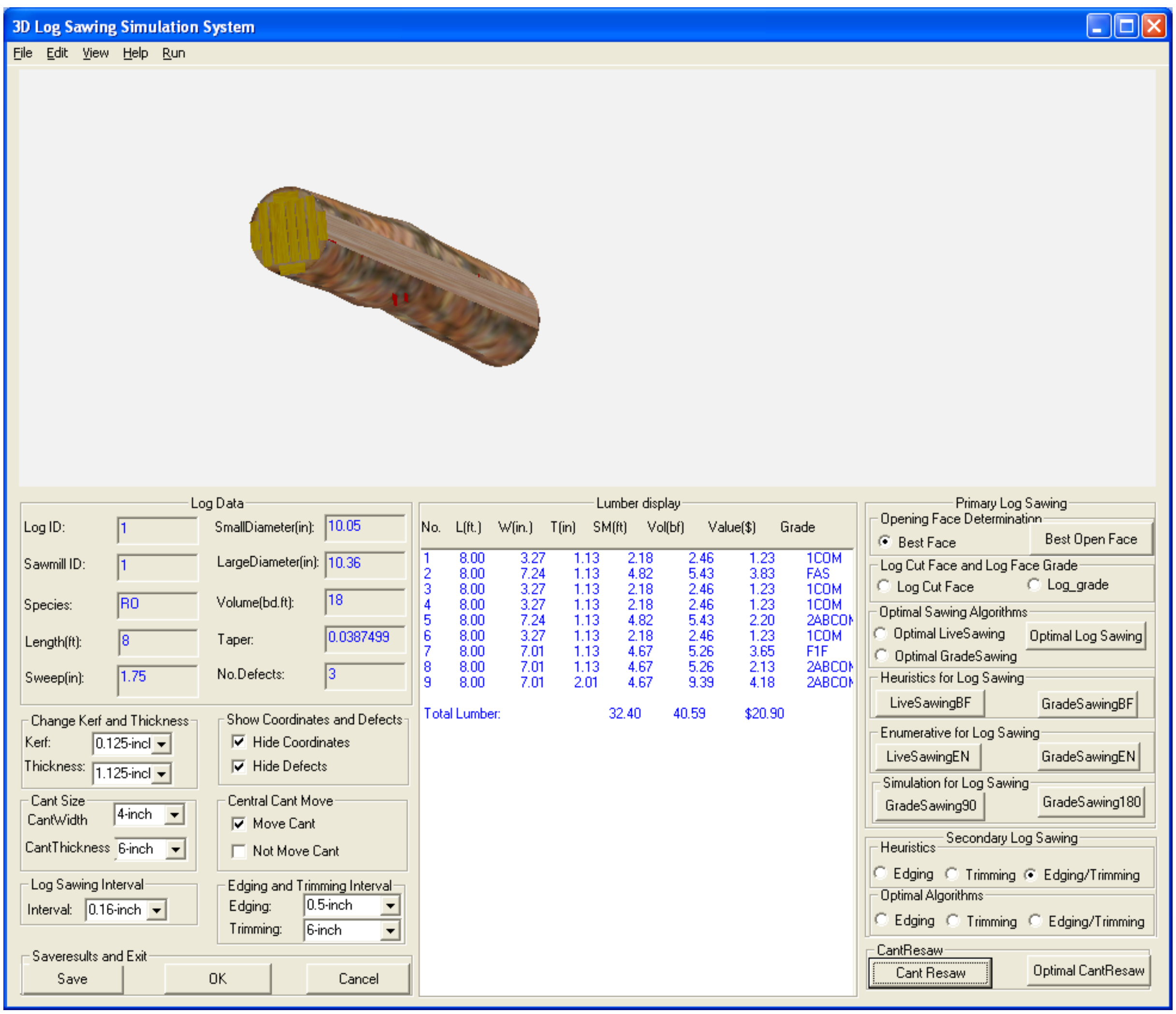


Figure I.9. Heuristic log sawing with edging and trimming.

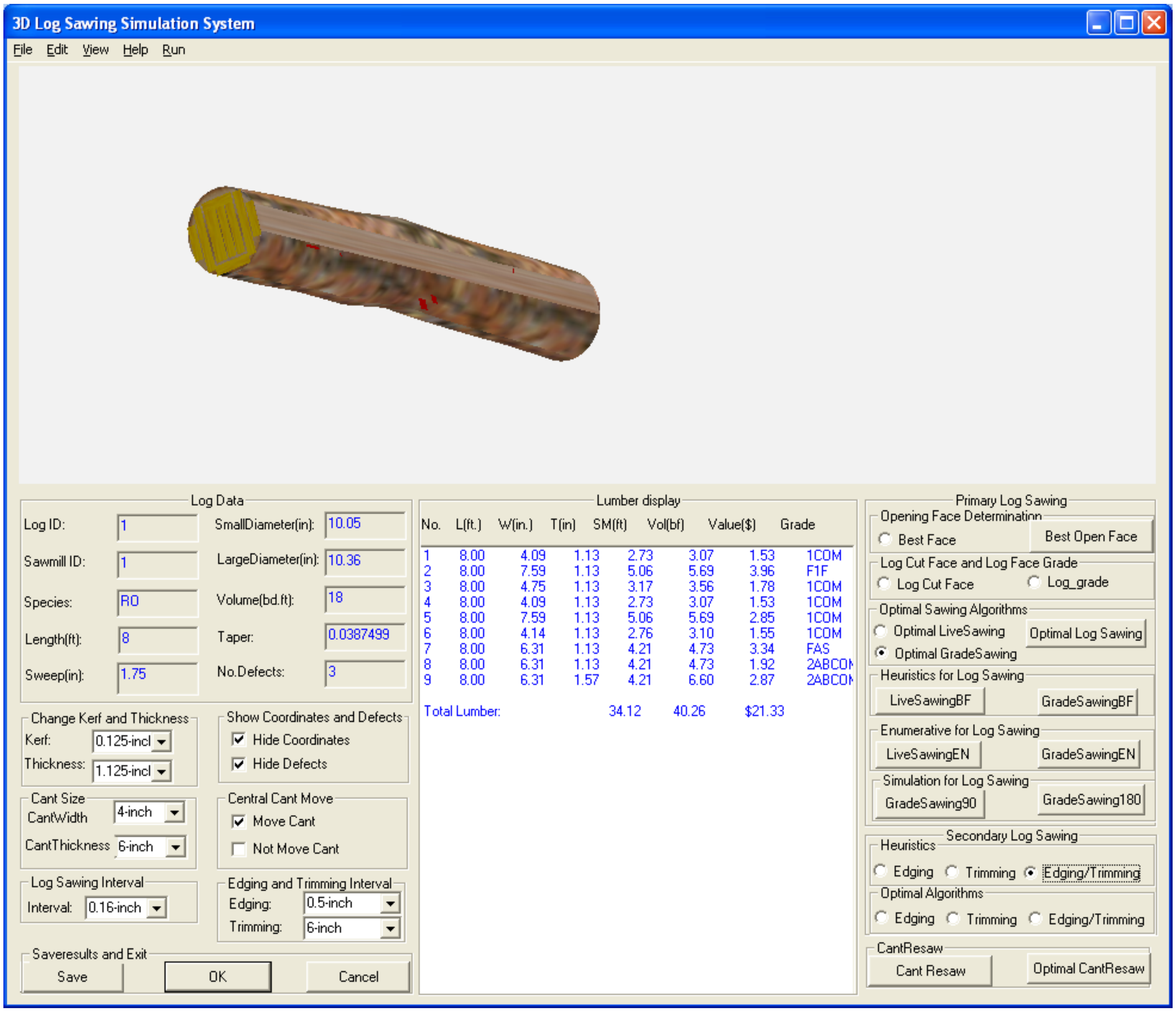


Figure I.10. Dynamic programming log sawing with edging and trimming.

I.6 A detailed illustration of the main interface

The following two figures illustrate the functions for each group box.

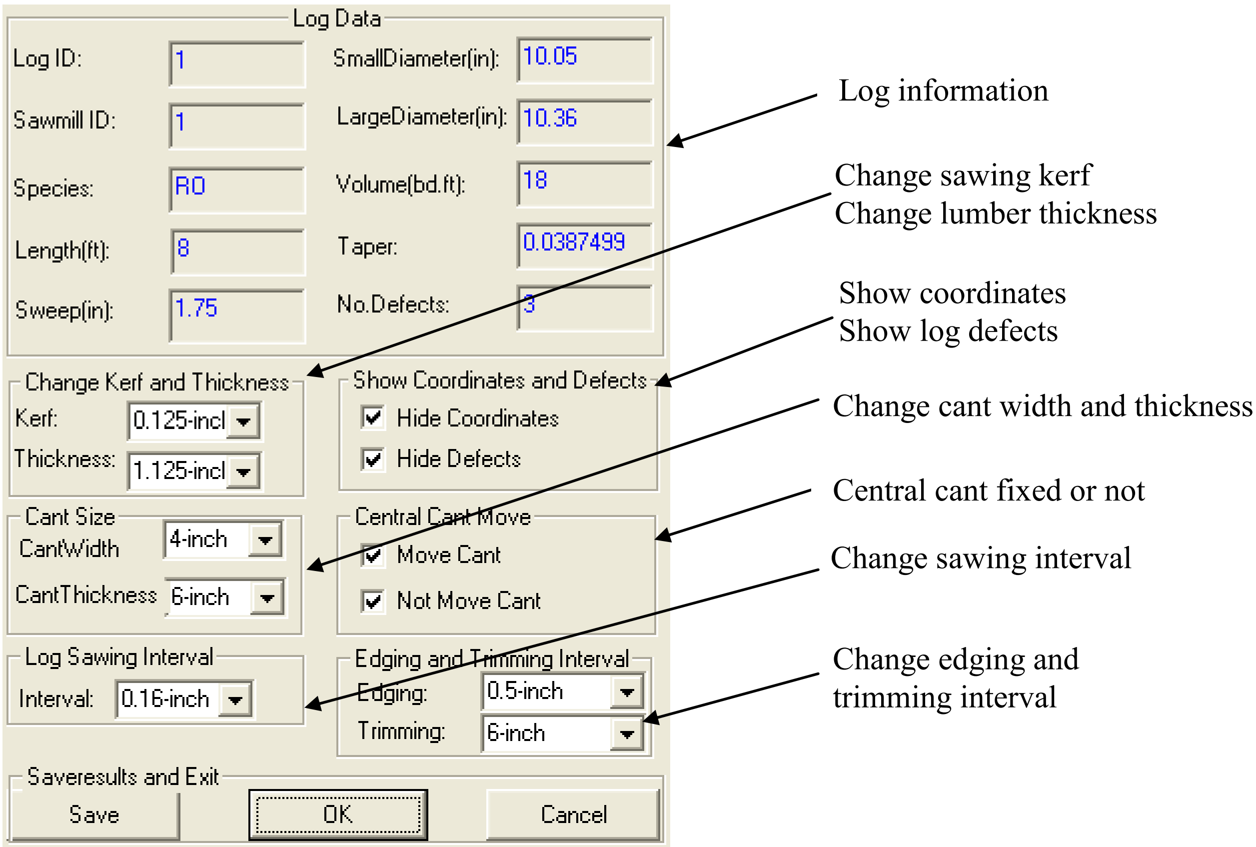


Figure I.11. Illustration of the main interface (left side).

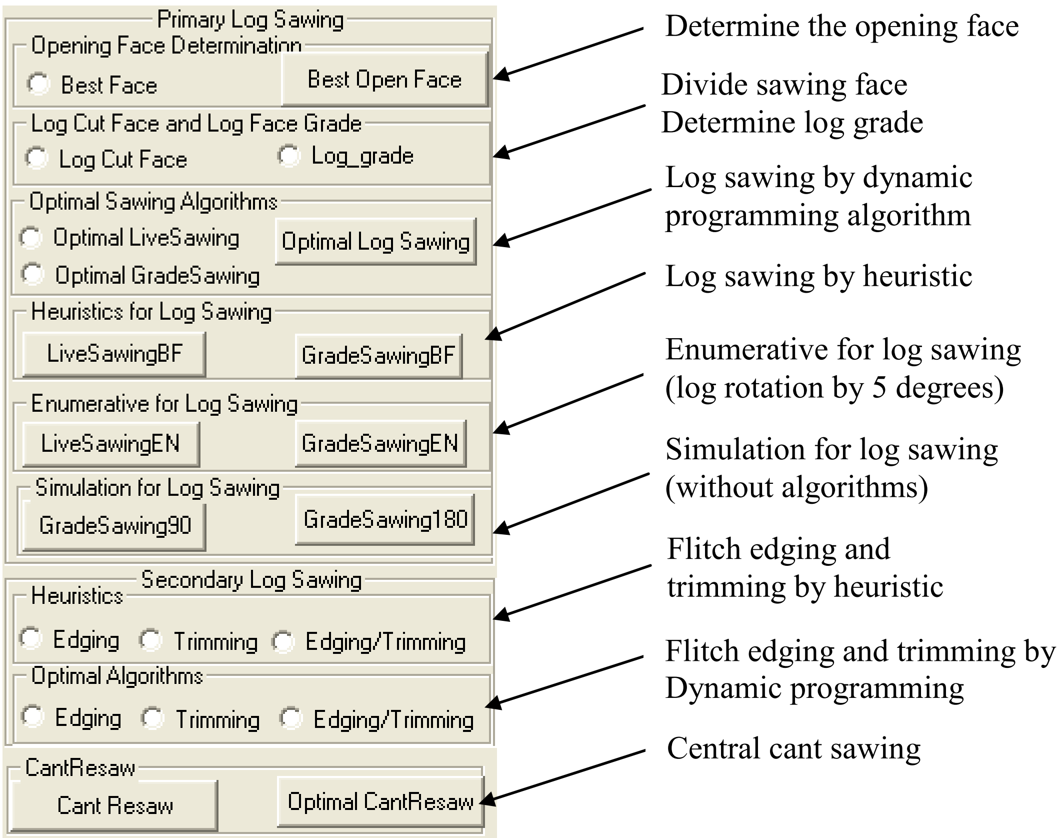


Figure I.12. Illustration of the main interface (right side).

APPENDIX II: USER'S MANUAL FOR 3D LUMBER EDGING AND TRIMMING SYSTEM

II.1 Introduction

This manual is prepared for the 3D optimal lumber edging and trimming program. The manual describes how to install the program and run the program. The detailed manual can be found on the website: **http://www.wdscapps.caf.wvu.edu/LumberRTK/**. In this document, system requirements are briefly reviewed and an example of application is demonstrated.

II.2 System Requirements

The software system can be implemented on either a desktop or laptop. The recommended system configuration for this optimal log sawing system is Microsoft Windows XP or later version, with Pentium IV processor and at least 512 megabytes (MB) of RAM. Table II.1 lists the detailed requirements for running this system.

Table II.1. System requirements.

Item	Requirements
Processor	Intel Pentium IV processor or later
Operating System	Microsoft Windows XP or later version
Memory	512 MB RAM
Hard Disk	100 MB of free space
Drive	CD-ROM drive
Display	Super VGA(800 x 600) with 256 colors
Peripherals	Microsoft Mouse or compatible pointing device

II.3 Software Installation

Step 1: Download 3DLumber.zip
If you have not already downloaded 3DLumber.Zip file, you can download it now from **http://www.wdscapps.caf.wvu.edu/LumberRTK/**. You should save the zipped file in a known location. For illustration, let's assume that the zipped file is saved into the desktop folder on the computer.

Step 2: Extract files from zipped folder
The zipped folder can be extracted to a normal folder by double clicking or right clicking the folder. You should remember the location where you have saved your folder. Figure II.1 uses right mouse clicking and selects "Extract here". This will save the extracted folder on desktop. The extracted folder is named as "3DLumber" which is shown on the right hand side of the same figure.

Step 3: Running Setup

Now, let's double click the extracted folder to navigate inside. Locate "SETUP.EXE" file in the folder and open it. Once this file is opened, the setup process begins instantly (Figure II.2). This step leads to opening of several screens where you need to follow the instructions.

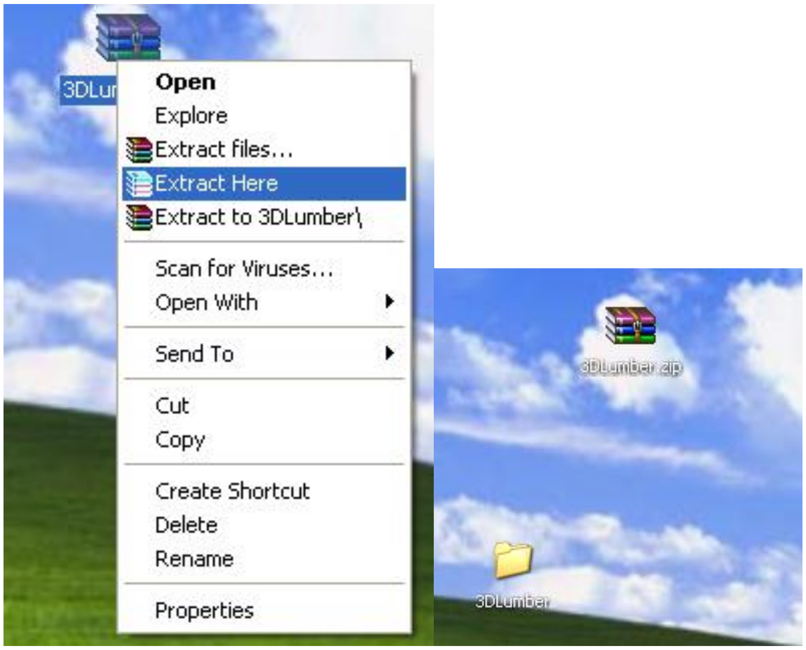
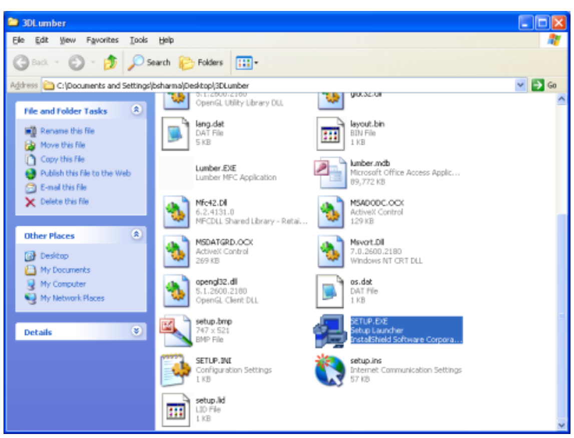


Figure II.1. Extracting the downloaded zipped folder.



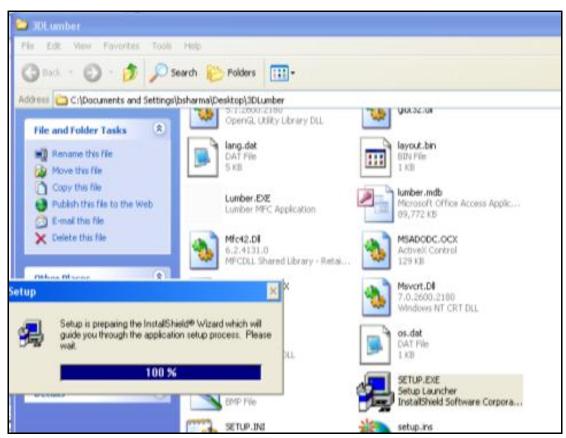
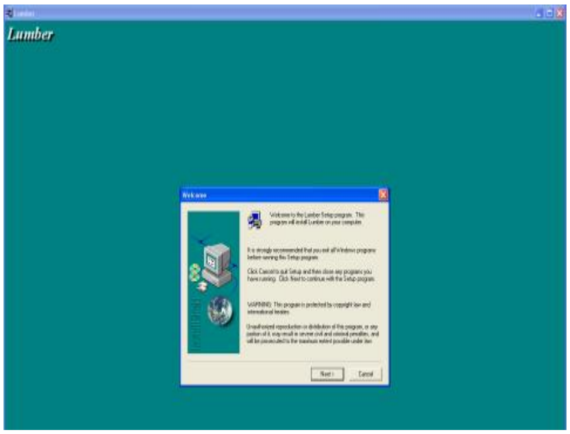


Figure II.2. Navigating for "Setup.exe" file. Figure II.3. Beginning of setup process.



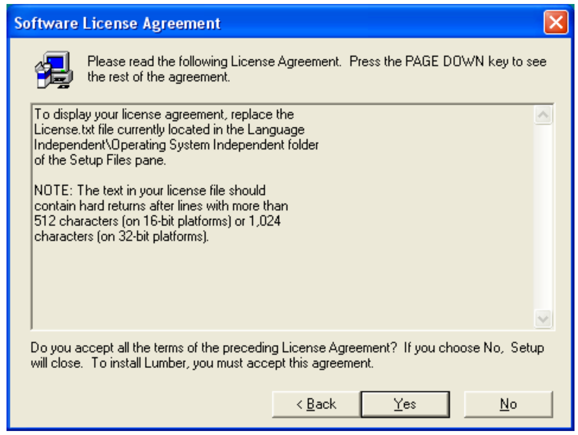
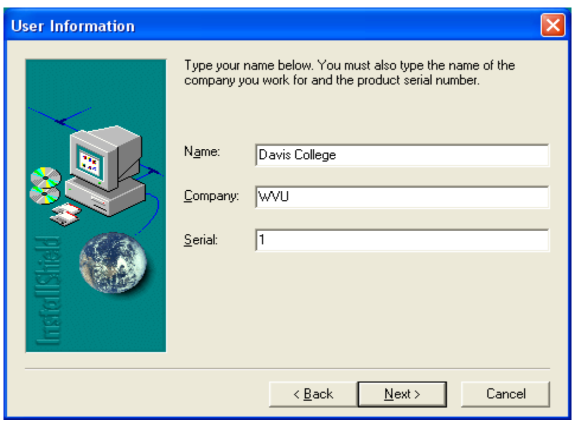


Figure II.4. Setup process continues. Figure II.5. Setup process - license agreement.

Clicking the "**Next**" button in Figure II.4 will take you to next window (Figure II.5) where you need to agree the license agreements by clicking "Yes" to install this software in your machine. Upon pressing the "**Yes**" button, there appears another window where you are required to specify some credential specific to your circumstances. Use any name for name and company. For serial, use a numerical value i.e. 1 and press "**Next**" (Figure II.6).



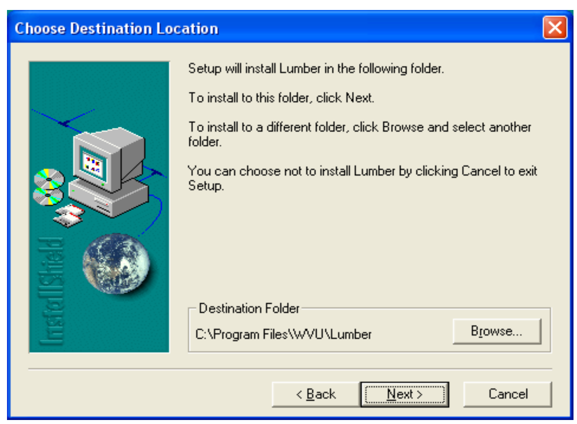


Figure II.6. Setup process-user information. Figure II.7. Setup process-Destination folder.

Next, you need to specify a folder to save the installation file. By default, the saved location is given as **C:\Program Files\WVU\Lumber** (Figure II.7). You can also change the location by clicking the "Browse" button to navigate the desired location. In Figure II.8, you can configure the setup type, or use the default option. Clicking the "Next" button with default will begin file copying to your computer. A successful setup of files will end as shown in Figure II.9.

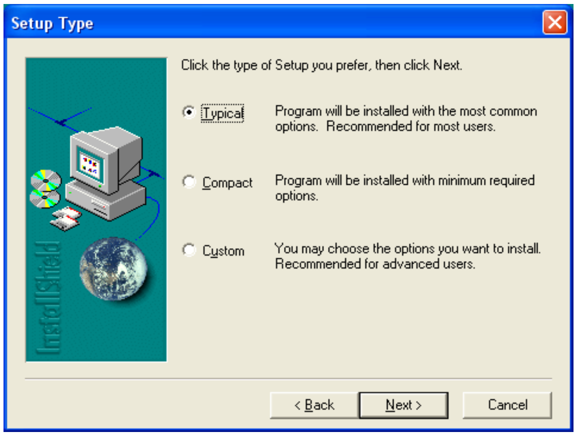


Figure II.8. Setup process – type.

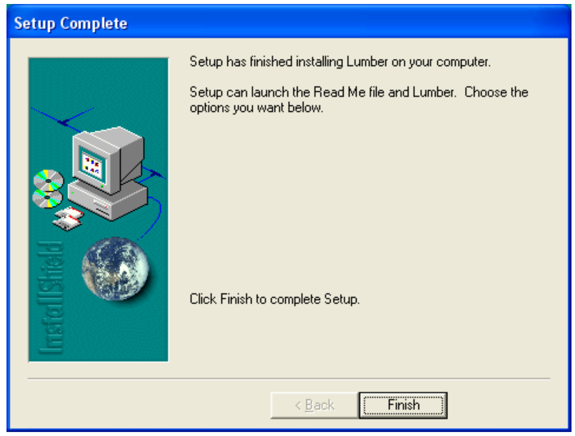


Figure II.9. Setup completion screen.

<u>Step 4: Creating shortcut</u>

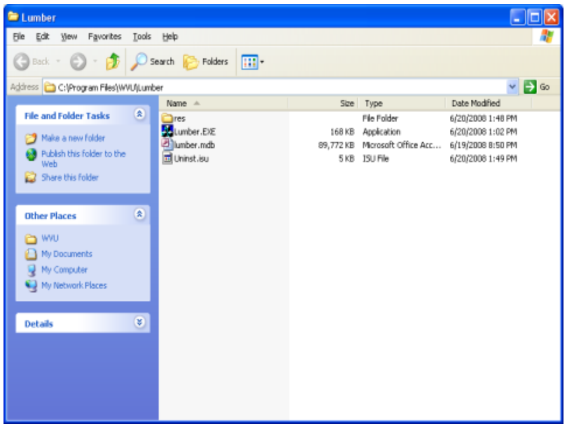
The program and necessary files are now copied into your computer. An application folder is now created at a location in step 3. In this case, that folder was **C:\Program Files\WVU\Lumber.** The lumber program can be run by going inside this folder and clicking the "**lumber.exe**" file. You can go inside this folder by several ways. Some of these are explained below:

a. From internet explorer or other web browser: Copy the folder location **C:\Program Files\WVU\Lumber** and paste in address bar and press enter.
b. Go to windows explorer and look navigate through the folders
c. Press start menu, click run, and paste "**C:\Program Files\WVU\Lumber"** and press enter.

Inside this **Lumber** folder there are 3 files and one folder (Figure II.10). **Lumber.exe** is an application file which is used to start the application. Double clicking this file will start the program. **Lumber.mdb** is database file to store lumber information. You will need to use this file to add your new lumbers or edit the existing lumbers. Resource files are inside **res** folder. All the images are stored in this folder.

You can create shortcut to this program and keep that short cut on your computer for quick access using the following procedures (Figure II.11)

- Right click on "Lumber.exe".
- In the pop-up menu, select "Send To"
- In the next menu, select "Desktop (create shortcut)"



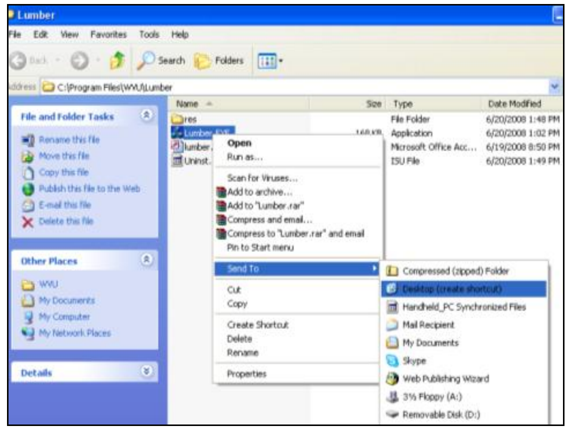
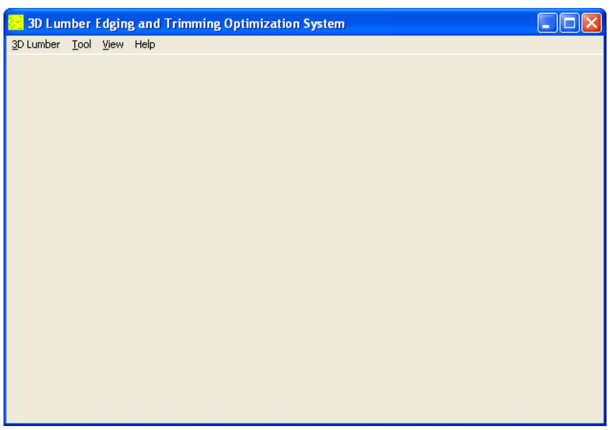


Figure II.10. Contents of application folder. Figure II.11. Procedure to create shortcut.

II.4 Running the program

<u>Main interface generation</u>

The program can be run by double clicking **lumber.exe** file which will open the main window as in Figure II.12. There are four main menus that can be selected in the menu bar, including “3D Lumber”, “Tool”, “View”, and “Help”.



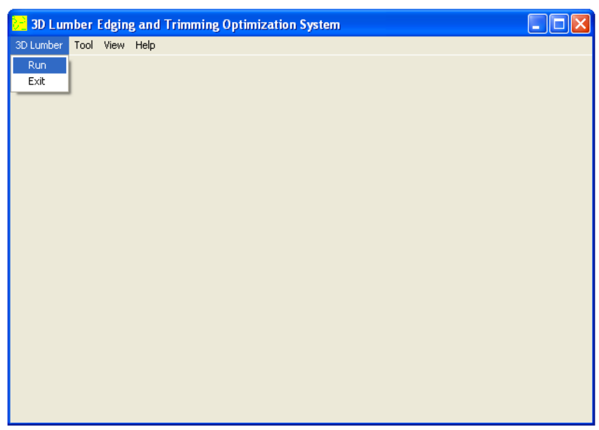


Figure II.12. Start up screen of the system. Figure II.13. Running the system.

<u>Board selection</u>

By clicking the “**Run**” submenu under the “**3D Lumber**” main menu (Figure II.13), another dialog will appear as shown in Figure II.14. Clicking the “**Exit**” submenu under the “**3D Lumber**” will terminate this program (Figure II.13). A board can be selected with left mouse button (Figure II.14) and shape and/or defect information for that board can be viewed or edited by pressing the “shape” (Figure II.15) or “defect” tab (Figure II.16). The “Board” tab is used to display all the board data including BOARDID, MILLID, THICKNESS, NHGRADE (grade assigned by a NHLA grader), NHSM (surface measure assigned by a NHLA grader), SPECIESID, and LENGTH. The “Shape” tab stores the shape information of each board including BOARDID, CUTID, SECTIONID, SHAPEID, DISTANCE, WANE, WANEEDGE, BOARDEND, and WANEEND. The “Defect” tab stores information on defect on a board piece including BOARDID, CUTID, SECTIONID, DEFECTID, TYPE, LENGTH, and WIDTH. Defect type is represented using numerical values in the table DEFECT TYPE.

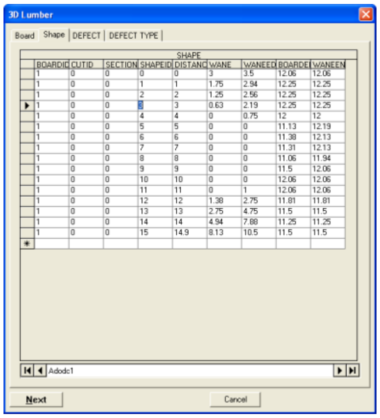
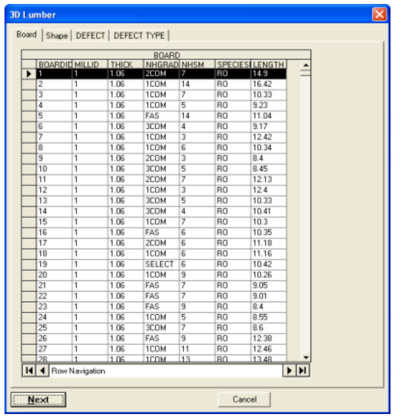
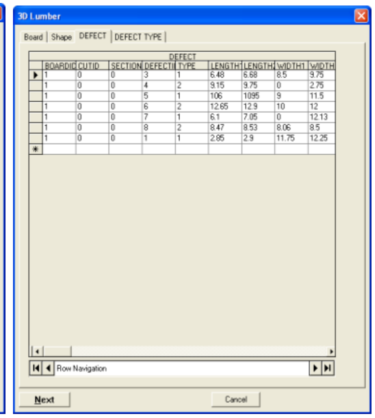




Figure II.14 (left). Board information is displayed in board tab and board 1 is selected.
Figure II.15 (middle). Shape information for the selected board displayed in Shape tab.
Figure II.16 (right). Defect information for selected board displayed in Defect tab.

3D board display

Once a board is selected, clicking the "**Next**" button leads to the final display screen (Figure II.17). The board is displayed on a small rectangular window in white background. Besides the board image, information on length, width, and thickness are also displayed. When the cutting frame is activated, the dimension information represents the board area bounded within four cutting frames. Grade, surface measure and value of the board as assigned by an experienced NHLA grader are displayed in the second. This information is provided so that user can compare their edging and trimming exercise with that of NHLA grader. When "View Defects" is enabled, the defects are shown on the board with different color and a legend key of such defects in the same window.

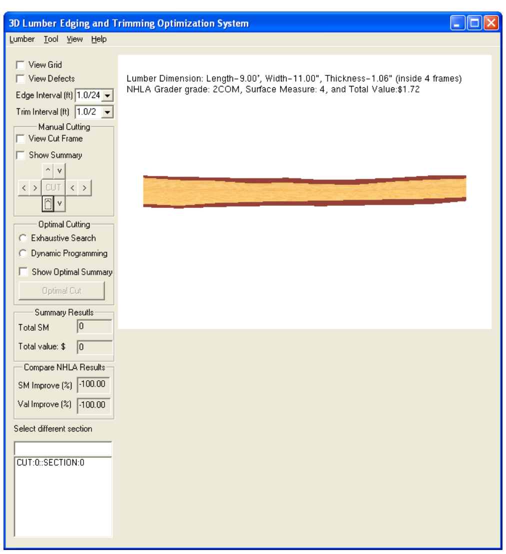


Figure II.17. Displaying a board.

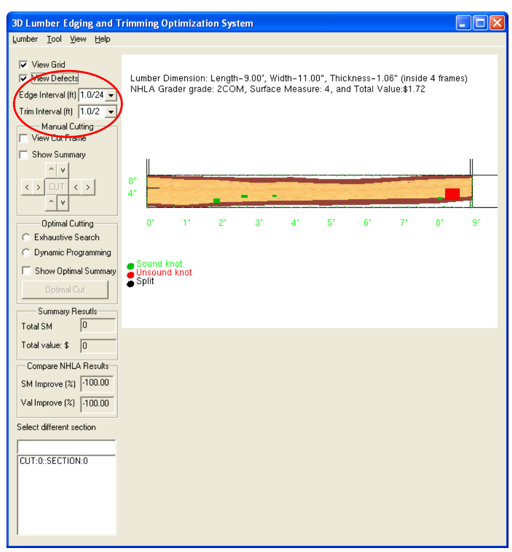


Figure II.18. Board with grid and defects.

Controls chosen

Along the left hand side of the window in Figure II.18, there are many command buttons, control checkboxes, combo boxes, radio buttons, and list box. The two control checkboxes are on the top. By default both checkboxes appear unchecked. Two combo boxes are used to change the edging and trimming intervals. The functions of each of them are described below.

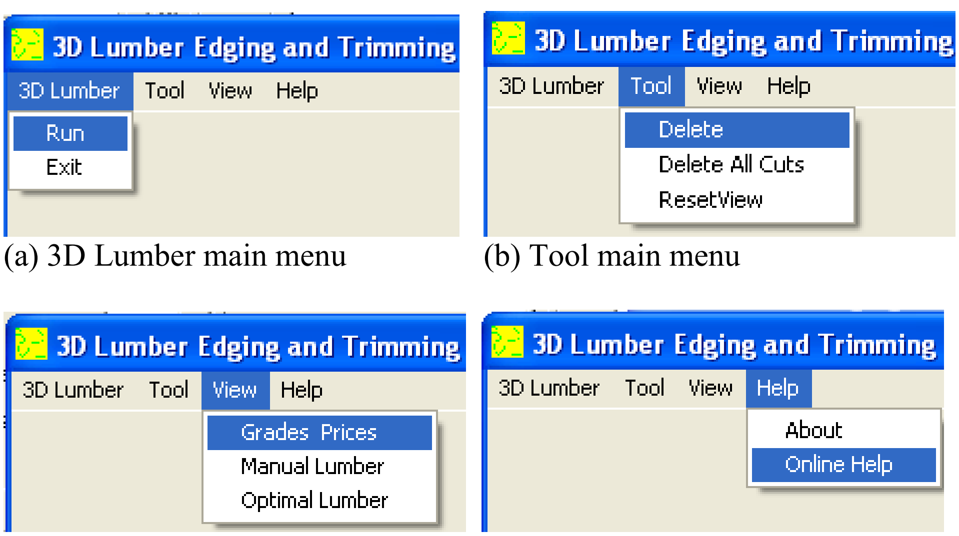
- View Grid – This checkbox is used to display the grid along X, Y and Z axis of the lumber respectively to show length, width, and thickness of the lumber in inches (Figure II.18).

- View Defect – This checkbox, when enabled, displays the defects on the lumber. The legends of the defects are displayed with names in different colors (Figure II.18).

- Edging and Trimming line interval – There are two control combo boxes which are used to change the interval for the edging line and trimming line, see the red circle in Figure II.18. By default, the edging lines were varied in 0.5 inch increments. Half-foot increments were used for trimming variation. The user can change the edging or trimming interval by click the arrow. For edging line interval, 0.25, 0.5, and 1 inch are available to be chosen, while 2, 6, and 12 inches are available for trimming interval.

Menus chosen

Under the "**3D Lumber**" main menu**,** there are two buttons: "**Exit**" and "**Run**" **(**Figure II.19a**)**. Clicking "**Exit**" will terminate the program while clicking "**Run**" will start the program by opening another dialog as in Figure II.14.



(a) 3D Lumber main menu (b) Tool main menu

(c) View main menu (d) Help main menu

Figure II.19. Main menus of the program.

Reset View – A **s**tandard 3 button mouse can be used to change the view of the lumber. The lumber piece can be rotated freely at 360 degrees by clicking the left mouse button, while the right mouse button can be used to change the view scale, and the middle mouse button can be used to move lumber in any direction. If views are not desirable and user wants to get the default view, the user can press the "**TOOL**" menu in menu bar and click "**ResetView**" (Figure II.19b).

Delete pieces - A piece of lumber can be deleted once cutting is performed except for original lumber. Original lumber can be identified by looking at CUTID and SECTIONID which are 0. All other cut pieces except the original lumber can be deleted by clicking the "**Delete ALL Cuts**" under the "**TOOL**" menu or selected pieces can be deleted by first selecting the pieces in the list and clicking "**Delete**" under the "**TOOL**" menu (Figure II.19 b). This action is followed by a message that says "Board(s) Successfully Deleted". This action deletes the board from the list and the summary instantly. Deleted boards are not recoverable.

Lumber prices – The lumber prices were obtained based on Hardwood Market Report 2009 for Appalachian Hardwoods. The user can select the "Grades Price" submenu from "View" menu bar (Figure II.19c). Five species including red oak, yellow-poplar, white oak, black cherry, and red maple are available to be chosen. The lumber grades include FAS, SELECT, 1COM, 2COM, and 3COM.

Lumber results – To see the lumber cut by manual cutting method or optimal cutting method, you can select the submenu "**Manual Lumber**" or "**Optimal Lumber**" from the "**View**" menu bar (Figure II.19c).

Online help – To learn how to grade a lumber, you can select the submenu "Online Help" from the "Help" main menu to find lumber grading rules and examples (Figure II.19 d).

Board edging and trimming

In this program, two sawing methods are available to edge and trim a board: manual cutting, and optimal cutting. In the manual cutting group, two checkboxes can be selected:

- View CutFrames – This will activate trimming and cutting functions in the program by enabling the "**CUT**" button. At this stage, the board is bounded by four red frames, which can be moved by clicking the up and down arrow buttons (see red oval in Figure II.20). The left 2 buttons can be used to move the left edging frames, and the right 2 buttons are used to move the right edging frames. The upper 2 buttons are used to move the upper cutting frames and lower 2 buttons are used to move the lower cutting frames. Once the frames are set up for desired sections, press the "**CUT**" button to cut the lumber. The cutting frames simulate the saws to cut the lumber. The cut lumber will receive appropriate identification number (SectionID) as illustrated in the design document.

- Show Summary – Enabling this control will display the summary of manual cutting lumber. The default lumber does not have any summary associated and only cut pieces whose grades satisfy NHLA grades are shown in the summary table (Figure II.20).

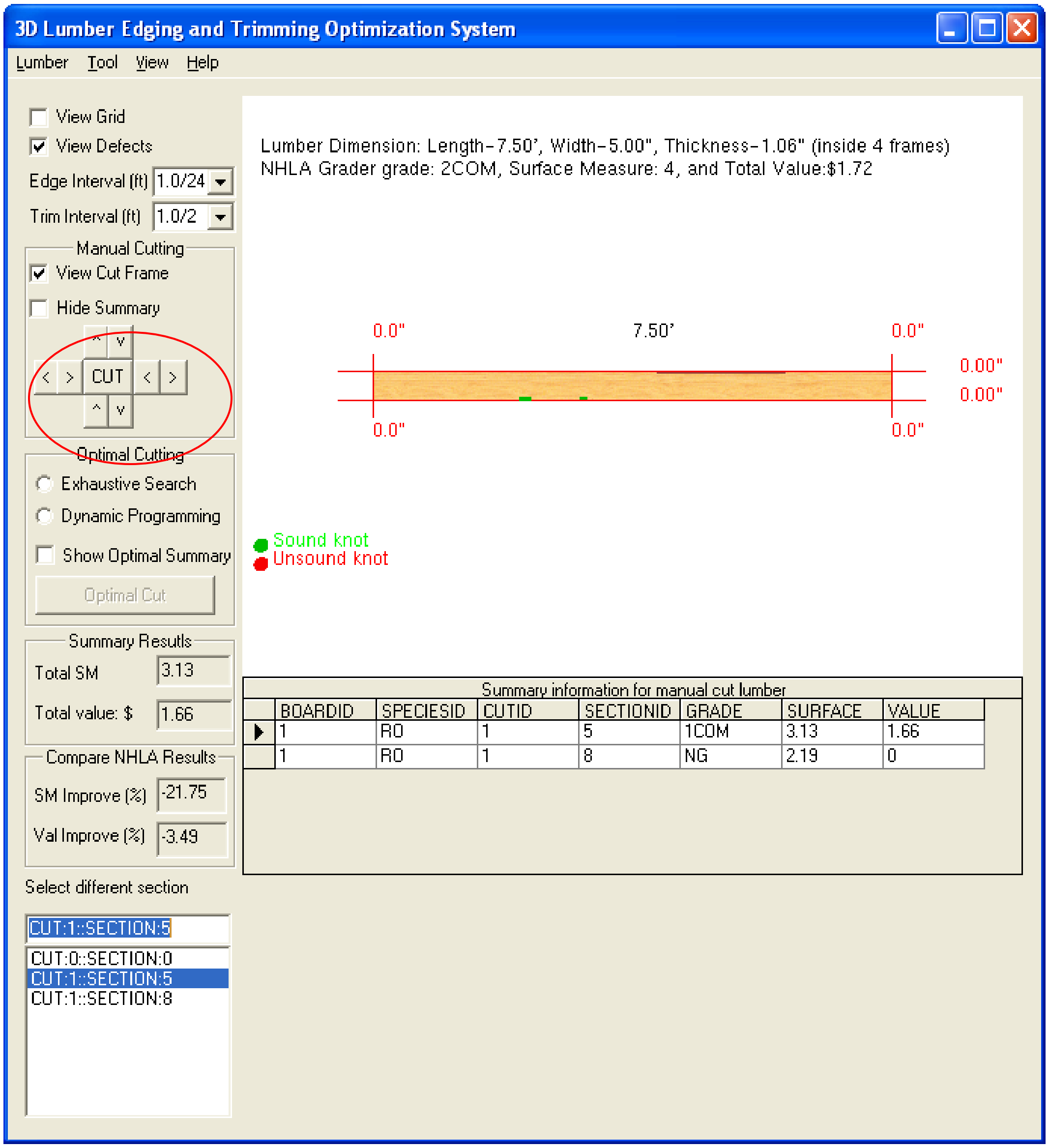


Figure II.20. Manual board cutting results.

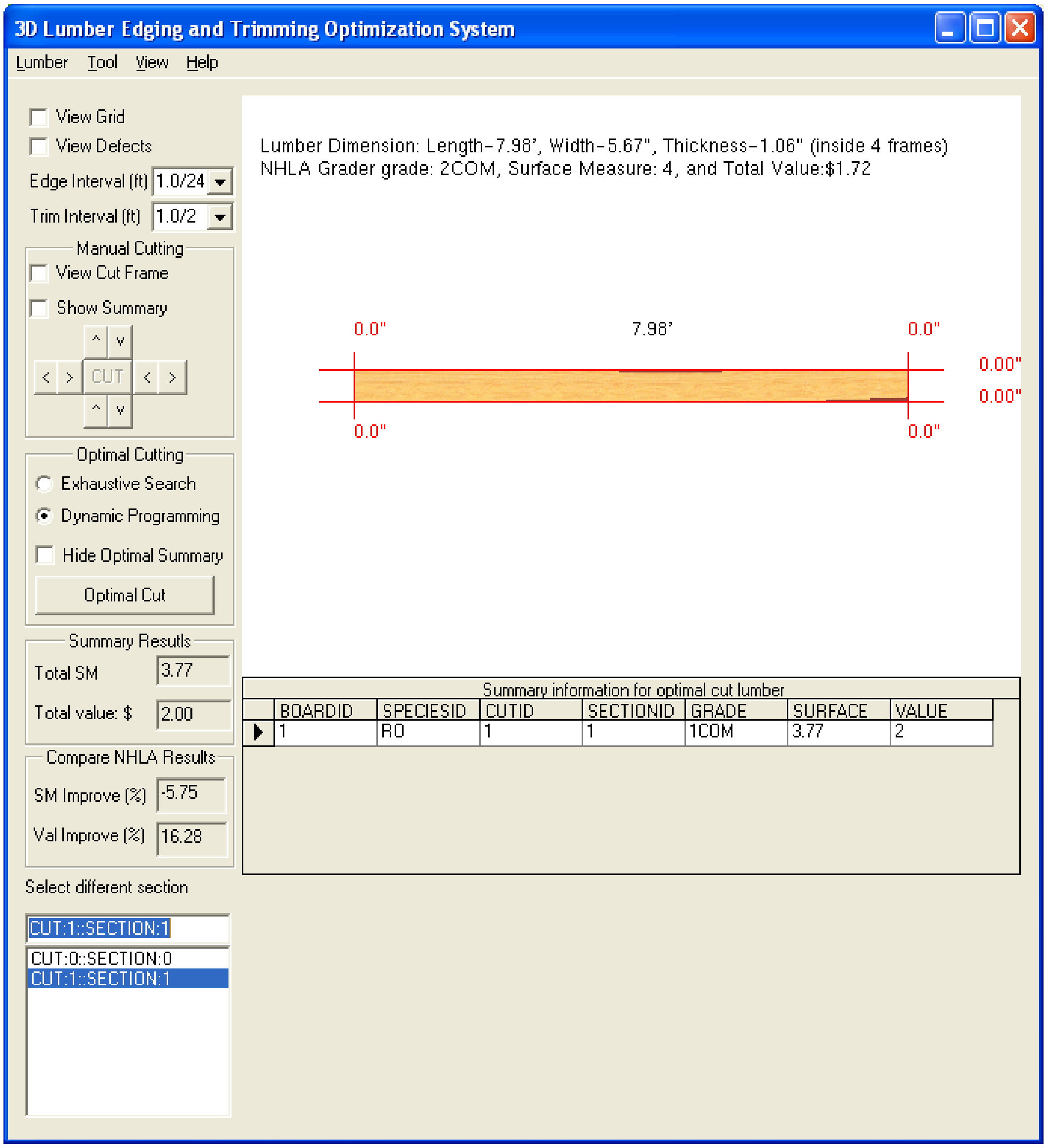


Figure II.21. Optimal board cutting results.

In the optimal cutting group, one radio button, one checkbox, and one command button are available to be selected.

- Exhaustive Search – This method tries all possible combinations of edging and trimming lines within the original size of the board. It is guaranteed to find the maximal solution. Each setting of the edging and trimming lines determines the shape of the board. Information regarding board length, width, surface measure (SM), and defects is then passed to the lumber grading components, which provides a lumber grade for that board. The combination of grade and SM determines the board's value based on prevalent market lumber price. The solution that yields the maximum value is the optimum edging and trimming solution.

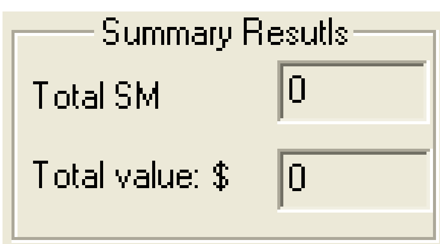
- Show Optimal Summary – Enabling this control will display the summary of optimal cutting lumber. The function of this control checkbox is similar to manual cutting method. The default lumber does not have any summary associated and only cut pieces whose grades satisfy NHLA grads are shown in the summary table.

- Optimal Cut – This button will perform optimal algorithm, and the system will automatically give the optimal lumber value, surface measure, and lumber grade. When this button is activated, a progress bar will appear to indicate that the computer is running the algorithm, and then the total time for computer searching the optimum solution is displayed (Figure II.21).

The system will retain the original piece of lumber, which can be identified by 0 values in both CUTID and SECTIONID. The system will retain the entire cut pieces if they satisfy any of the grades in NHLA grading. If the cut piece does not satisfy any of the grades, then that piece is discarded and removed from memory.

<u>Results comparisons</u>

In the “Total SM” box, the total surface measure for a lumber after edging or trimming (either from manual cutting or optimal cutting method) is displayed. The “Total Value” box displays the $ value of all the cut pieces from the original lumber (Figure II.22). The total SM and total values can be compared with the NHLA SM and NHLA Value for performance evaluation. By default, negative 100 percent for each value is given since the user does not cut the board (Figure II.23).



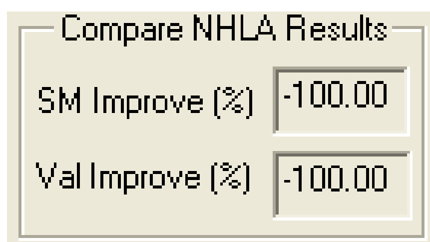


Figure II.22 (left). Summary results for cut lumber.
Figure II.23 (right). Compare results between simulation and NHLA grader’s estimation.

<u>An Example</u>

An illustration of running a board is shown in Figure II.24 - II.26.

Figure II.24 shows that "CUT0: SECTION: 0" is selected, which means it is the original board. The defect information is also displayed with legends (e.g. sound knot and split). On the top of the board image, the dimensions of the original board are displayed as 8′ x 5″ x 1.06″. The NHLA grader graded this board as 3COM with surface measure 5 and $ value of 1.75. The four cutting frames (or saws) are displayed in red with their positions.

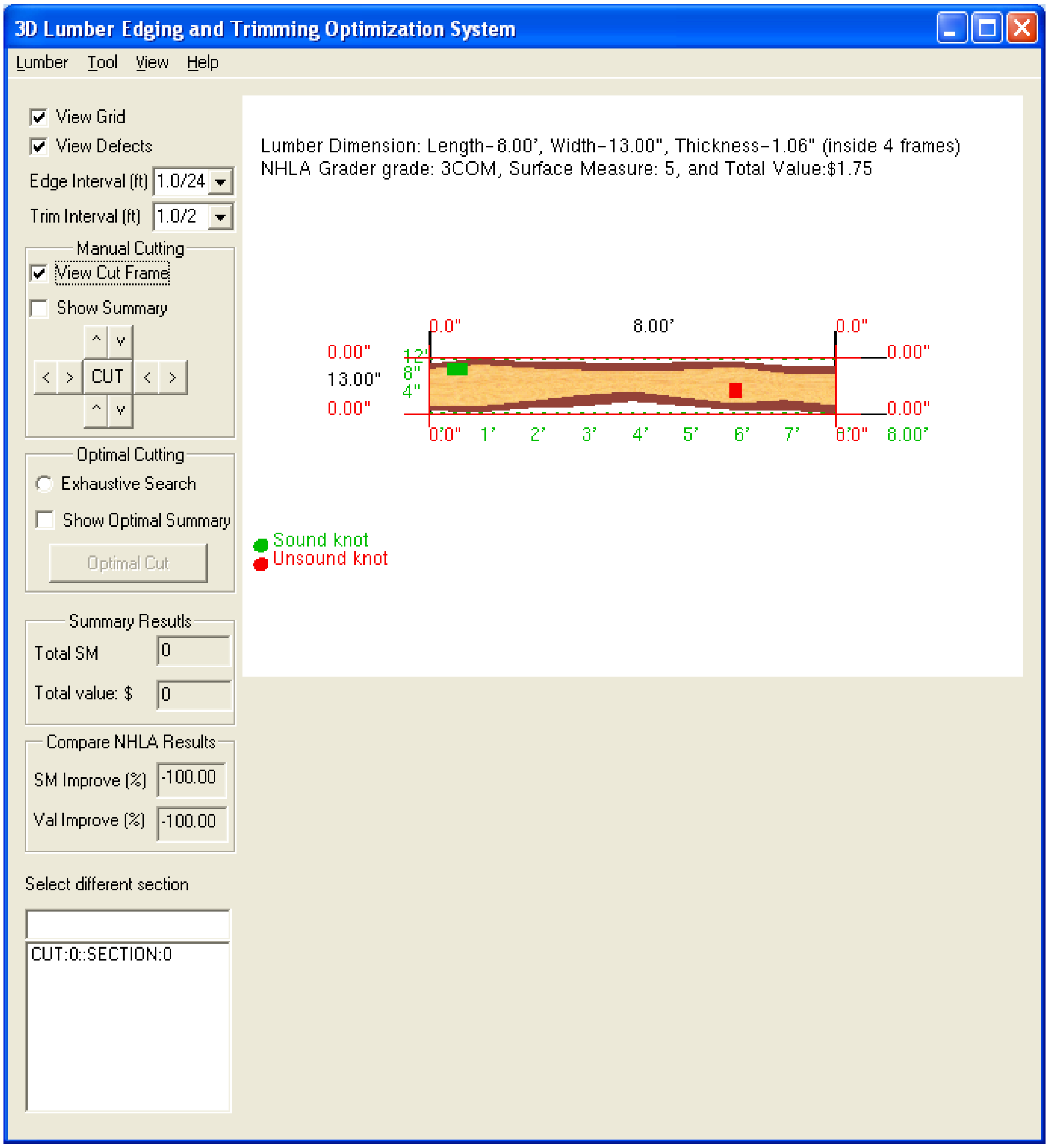


Figure II.24. A board was selected with defect displayed.

If the user chooses the manual cutting method to edge and trim this board, the results will be shown in the list and summary table (Figure II.25). The intermediate piece CUT1::SECTION5 is graded as 2COM. The piece CUT1:SECTION8 is graded as "NG", which means no grade is assigned to this piece. The total surface measure is 3.33 and total value is $1.42. Since CUT1::SECTION8 is not a valid lumber, it can be deleted to avoid unnecessary memory consumption, although any board with NG does not affect the estimated SM and $ value.

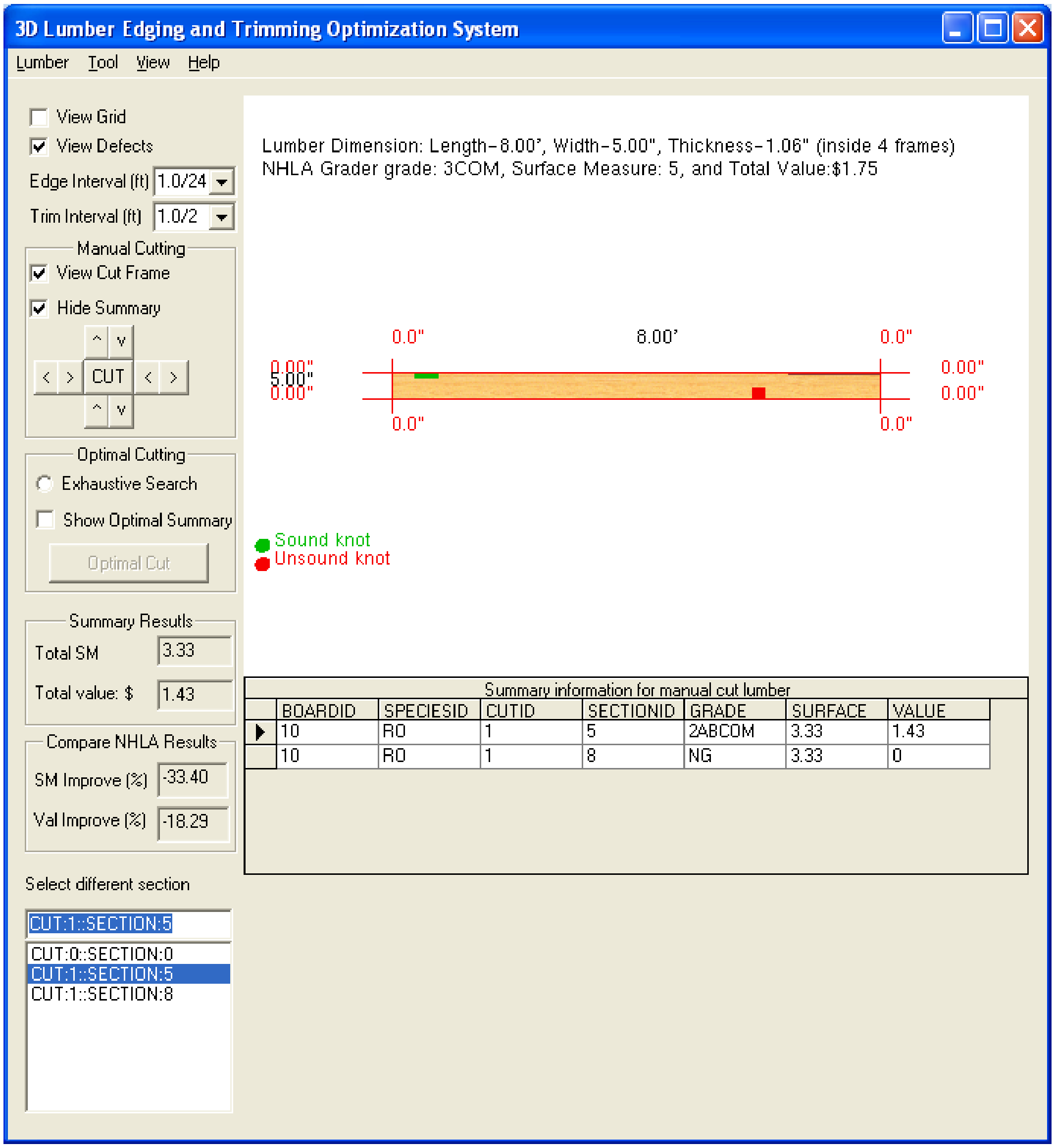


Figure II.25. The selected board was edged and trimmed by manual cutting.

If the user selects the optimal cutting method to edge and trim this board, only one piece of valid lumber can be produced from the original board (Figure II.26). The piece CUT1::SECTION5 is graded as 2COM, which is the same as the results from the manual cutting method. However, the total surface measure is 4.69 and total value is $2.01, which are significantly higher than the results from manual cutting method.

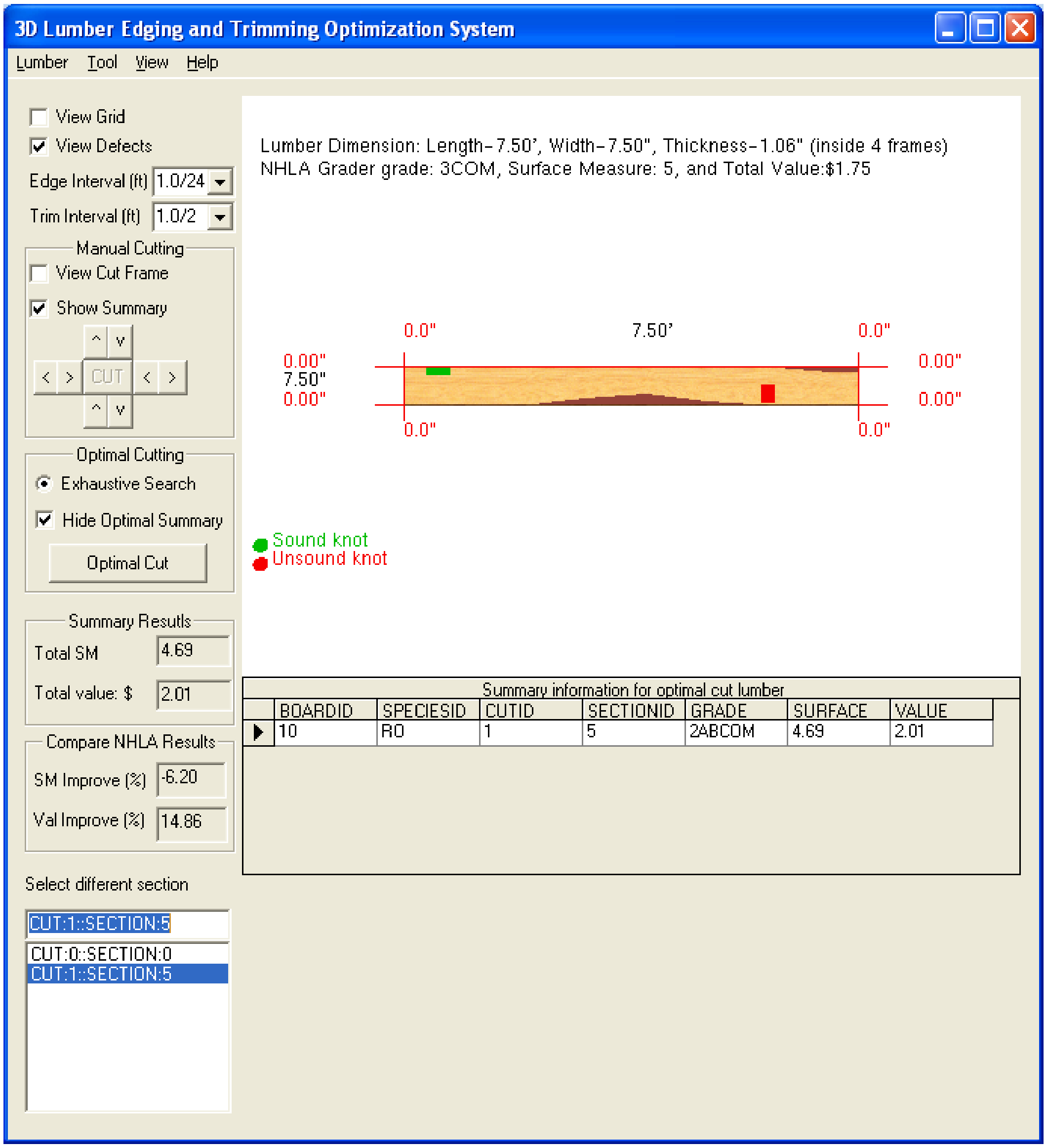


Figure II.26. The selected board was edged and trimmed by optimal cutting.