Development of an Optimal Three-Dimensional Visualization System for Rough Lumber Edging and Trimming in Central Appalachia

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Abstract

An optimal three-dimensional visualization system was developed for edging and trimming of rough lumber in central Appalachia. ActiveX Data Objects were implemented via MS Visual C++/Open Graphics Library to manipulate board data at the backend supported by a relational data model with four data entity types: Board, Shape, Defect, and Defect Type. Exhaustive search procedures and a dynamic programming algorithm were used to achieve the optimal edging and trimming solution. A lumber grading module was also developed to grade hardwood lumber based on National Hardwood Lumber Association grading rules. The system was validated through comparing the total lumber values generated by the system with those generated by six local sawmills. A total of 360 boards were measured for board dimensions, defects, shape, wane, and the results of edging and trimming. Results indicated that the lumber value and surface measure gained in these six sawmills could be increased, on average, by 21.37 and 6.1 percent, respectively, using the optimal edging and trimming system. The optimal edging and trimming system not only can be used as a training tool but also can be installed on a field PC to aid the edging and trimming process.

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. 2003b). Many factors can impact the edging and trimming process, including visual estimates of board surface measure (SM), fluctuating prices, numerous edging and trimming solutions, operator experience, and others (Abbott et al. 2000). Therefore, even for experienced operators, it is difficult to obtain the optimal edging and trimming solution, and previous studies have found that substantial losses can 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 remove an excessive amount of wood, which can result in value losses of 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 a foot of SM and that the average value loss ranged from 0.5 to 24.1 percent. Therefore, it is necessary to optimize the edging and trimming operations to increase sawmill profits and to ensure continued operations of hardwood mills (Abbott et al. 2000).

Several studies have been conducted to optimize hardwood lumber edging and trimming. Steele and Wengert (1987) studied the effects of edging and trimming practices

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Forest Prod. J. 61(5):401–410.

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. Those authors 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 could 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 and 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 edging and trimming training system that could be used as both a training and a 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 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 can be detected in the system and a modular artificial neural network was also used to locate clear wood, knots, and decay.

Although 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 manufacture less than 4 million board feet (MMBF) of lumber per year (West Virginia Division of Forestry 2004). The small sawmills are less able to apply the advanced systems because of initial cost, payback period, and modifications to operations. According to a survey of the small hardwood sawmills in the central Appalachian region (Hassler 2000), lumber grading and edging and trimming were two of the top five priorities in terms of importance and educational needs. In these sawmills, the lumber trimming and edging and the 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 these 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 (1) to develop algorithms to determine the optimum edging and trimming solution to maximize lumber value from rough lumber, (2) to develop a user-friendly software system to implement the optimum algorithms within a three-dimensional (3D) visual simulation environment, and (3) to evaluate the differences in lumber volume, lumber grade, and lumber value obtained from the optimum edging and trimming and those recovered from the actual sawmilling operations.

Optimal Edging and Trimming System Design

System structure

The optimal edging and trimming system consists of four major components: (1) data manipulation/storage, (2) 3D modeling, (3) lumber grading, and (4) edging and trimming

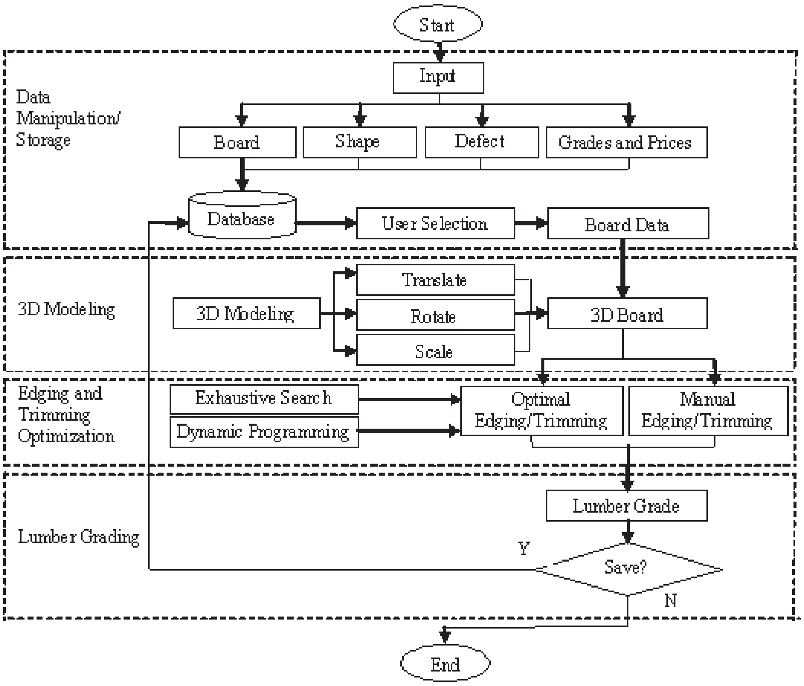


Figure 1.—Architecture of the optimal lumber edging and trimming system.

optimization (Fig. 1). A component object model using the principles of object-oriented programming was used to integrate the system. 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 Microsoft Windows applications, whereas 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 a laptop and run on a Windows platform.

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 provider (Microsoft Developer Network Platforms 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 to 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 and included four entity types: (1) Board, (2) Shape, (3) Defect, and (4) Defect Type. Once a board has been edged and trimmed, the results, including SM, lumber grade, and lumber value, can be stored in a summary table within the database.

3D lumber modeling

Three-dimensional modeling techniques together with OpenGL primitive drawing functions were used to generate 3D 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 and OpenGL Utility Toolkit, were used to make visual representation of lumber and of the edging and trimming process. A board is visualized using simple triangular 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 the 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)

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

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'_2, 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 as (Wang et al. 2009b)

$$\begin{bmatrix} x'_1 & x'_2 & \dots & x'_{n-1} & x'_n \\ y'_1 & y'_2 & \dots & y'_{n-1} & y'_n \\ z'_1 & z'_2 & \dots & z'_{n-1} & z'_n \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} = R_x(\alpha) \times \begin{bmatrix} x_1 & x_2 & \dots & x_{n-1} & x_n \\ y_1 & y_2 & \dots & y_{n-1} & y_n \\ z_1 & z_2 & \dots & z_{n-1} & z_n \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix}$$

$$\mathrm{TS}' = R_x(\alpha) \times \mathrm{TS} \tag{2}$$

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 after transformation. Similarly, the coordinate matrices for the triangle strip can be rotated around the *y* and *z* axes.

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

Lumber grading

The lumber grading component is based on Klinkhachorn's hardwood lumber grading routine (Klinkhachorn et al. 1988) and the National Hardwood Lumber Association (NHLA) lumber grading rules (NHLA 2007). To determine a possible grade for a lumber, the width, length, and SM of the lumber are computed, a potential grade from the highest to the lowest is assigned to the poor face, and the potential number of clear cuttings and cutting units (CUs) can then 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 species, the lumber value can be determined.

Optimal edging and trimming algorithm

Because 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, SM, 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, SM, species, and 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 that can be used to achieve the optimum edging and trimming solution. All potential edging and trimming line positions are predefined 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 $N_e = \mathrm{ER}/c_1$ horizontal edging lines and $N_t = \mathrm{TR}/c_2$ vertical trimming lines, where ER and TR are edging range and trimming range, respectively, and 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 let $v^*(i, j)$ be the corresponding lumber value. Based on the functions for edging and trimming presented in Bhandarkar et al. (2008), if $v^*(k, l)$ and $s^*(k, l)$ for all $k \leq i$ are known, then the combined edging and trimming flitch problem can be formulated as a recursive function:

$$\begin{aligned} v^*(i+1, j+1) &= \max_{k\in[1,m]} \Bigg(\max_{l\in[1,n]} \Bigg(v^*\Bigg(i+1-\left\lceil \frac{W_k}{c_1} \right\rceil \\ &\quad -\left\lceil \frac{K}{c_1} \right\rceil, j+1-\left\lceil \frac{L_l}{c_2} \right\rceil - \left\lceil \frac{K}{c_2} \right\rceil \Bigg) \\ &\quad + g\Bigg(i+1-\left\lceil \frac{W_k}{c_1} \right\rceil, i+1, j+1 \\ &\quad -\left\lceil \frac{L_l}{c_2} \right\rceil, j+1 \Bigg)\Bigg)\Bigg) \qquad (3) \end{aligned}$$

where $W_k = \{W_1, W_2, \ldots, W_m\}$ is the allowed set of lumber width, $L_l = \{L_1, L_2, \ldots, L_n\}$ is the allowed set of lumber length, K is the saw kerf, 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 a lumber width of ≥ 3 inches and a lumber length of ≥ 4 feet.

Optimal Edging and Trimming System Implementation

All the computer simulations were performed on a regular desktop PC equipped with a 3.16-GHz CPU, 3.25 GB of RAM, and a 300-GB hard drive under a 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). Each board can be divided into nine possible sections, named from 1 to 9, from the top left corner all the way through the bottom right corner. The section determination for each cutting board is illustrated in Figure 2, and the measurements of shape and defect information are illustrated in Figure 3.

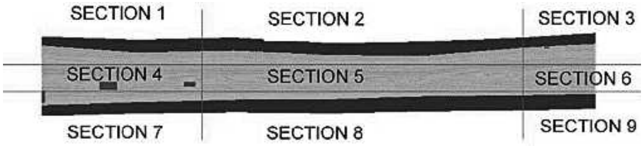


Figure 2.—Section determination for a cutting board.

Once a board is selected, its 3D image can then be generated (Fig. 4). The interface consists of three major sections: (1) display area (right top area), (2) results area (right bottom area), and (3) 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 an NHLA grader is displayed in the upper portion of the display area and includes lumber length, width, thickness, grade, SM, and value. This information was used to compare the edging and trimming results produced by the optimal system. On the top of the control and command area are two control checkboxes (View Grid and View Defect). By default, both checkboxes appear unchecked. The first is used to display the grid along the x, y, and z axes to show the length, width, and thickness, respectively, of the lumber in inches, and the second is used to display the defect with legend in different colors. Two control combo boxes are used to change the intervals for edging lines and trimming lines. By default, the interval is 0.5 inch 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, whereas 2, 6, and 12 inches are available for trimming intervals.

Edging and trimming simulations can be performed by two approaches: (1) optimal cutting and (2) manual cutting. For optimal cutting, an exhaustive search or dynamic programming algorithm is available to optimize the edging and trimming process for the selected board. During the optimal simulation, the program shows the searching progress and, finally, the total running time. For example, for Board 1 (red oak [*Quercus rubra*] lumber), the lumber grade, SM, and total lumber value were 2COM, 5, and US$2.15, respectively, when using exhaustive search, but the grade, SM, and lumber value were 1COM, 4, and US$2.12, respectively, using the dynamic programming algorithm. The controls and commands in the manual cutting group can be used to train edger and trimmer operators. When the user clicks the View Cut Frame

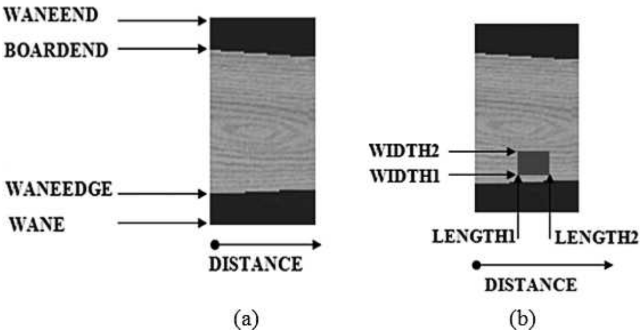
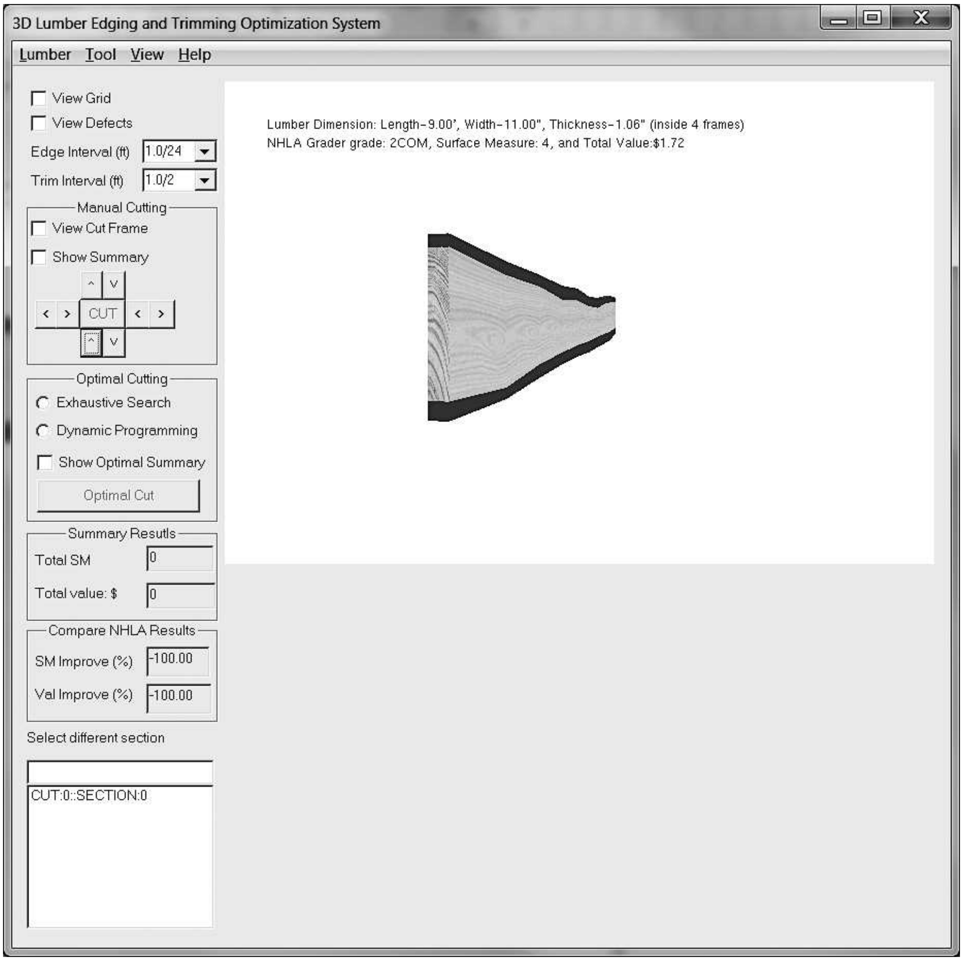


Figure 3.—Illustration of measuring shape (a) and defect (b) information.



Lumber Dimension: Length-9.00', Width-11.00", Thickness-1.06" (inside 4 frames)
NHLA Grader grade: 2COM, Surface Measure: 4, and Total Value:$1.72

☐ View Grid
☐ View Defects
Edge Interval (ft) 1.0/24
Trim Interval (ft) 1.0/2
☐ View Cut Frame
☐ Show Summary
○ Exhaustive Search
○ Dynamic Programming
☐ Show Optimal Summary
Total SM 0
Total value: $ 0
SM Improve (%) -100.00
Val Improve (%) -100.00
CUT:0::SECTION:0

Figure 4.—An interface for the optimal lumber edging and trimming system.

checkbox, the edging and trimming function will be activated and the CUT button 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 two left buttons can be used to move the left trimming lines, and the two right 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 is regenerated, and the updated lumber length, width, and SM are displayed. Once the frames are set up for desired sections, users can press the CUT button to cut the board. If unsatisfied with the current operation, the user can delete the generated lumber and process the board again. The detailed user's manual and system design for this system can be found online (Wang et al. 2010).

Optimal Edging and Trimming System Applications

Board data collection

A total of 360 boards of five species were assessed in six sawmills across West Virginia between June and September of 2006 (Wang et al. 2009a; Fig. 5). Flitches were gathered directly after being sawn from logs, which enabled measurements for the pieces before further processing. Flitches were collected randomly, but they 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. The information regarding defects on both faces of the flitch, including type, size, and location, was recorded. The flitches 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 an NHLA-certified grader and a sawmill grader, respectively. All the collected data were entered into a Microsoft Access database. Lumber prices were based on the Hardwood Market Report for Appalachian Hardwoods for April 11, 2009.

Optimal versus actual edging and trimming by sawmills

The averages of lumber SM and lumber value generated by the optimization system were compared with the values by the actual sawmills (Fig. 6). It was found that the mills had the potential to increase their average SM by an average 6.1 percent through optimal edging and trimming. Two of the six sawmills could even improve by 10.73 and 12.36 percent (Fig. 6a). The average SM per board was 6.05 units in the actual sawmills, 6.59 units using exhaustive search,

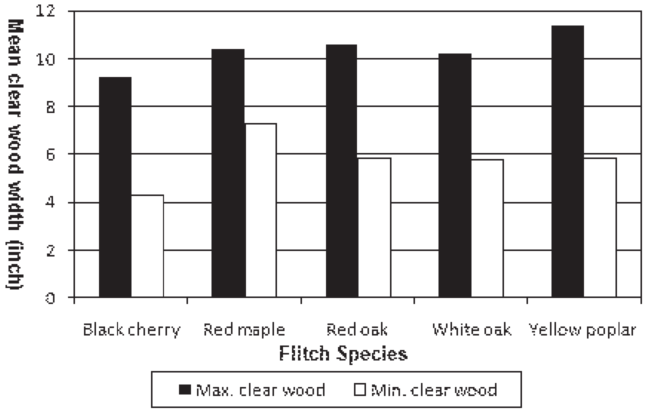


Figure 5.—Sample characteristics of the 360 flitches by species.

and 6.24 units using dynamic programming, 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 21.37 percent (Fig. 6b). If the average value of lumber produced is US$0.50 per board foot and 1 MMBF go through the edging and trimming process annually, the potential recovery in lumber value could be as high as US$106,850/y. The lumber value per board averaged US$4.8 in the actual sawmills, US$6.02 using exhaustive search, and US$5.56 using dynamic programming. It should be noted, however, that even though excessive cutting may lead to a higher-grade lumber, the final lumber value can still be lower than the optimal solution because of smaller SM.

The edging and trimming of each flitch was dependent on the flitch's shape, size, and clear area. A 1-way analysis of variance (ANOVA) was conducted to test the null hypothesis that the three treatments or groups (sawmill, exhaustive search, and dynamic programming) have equal mean lumber value. A significant difference of mean lumber value was found among the three groups ($P < 0.0001$). The Tukey multiple comparison test was then conducted, and the results further indicated significant differences of lumber values between sawmills and using optimal computer simulations. However, no significant difference existed in mean lumber values between using exhaustive search and dynamic programming optimizations (Table 1).

Optimal versus actual edging and trimming by species

In the sawmills surveyed, red oak had the largest SM, followed by white oak (*Quercus alba*), red maple (*Acer rubrum*), yellow-poplar (*Liriodendron tulipifera*), and black cherry (*Prunus serotina*) (Table 2). Although black cherry lumber had the smallest SM, 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 SM could improve 11.45 percent for yellow-poplar and 9.86 percent for white oak, whereas the lumber value improved 39.21 percent for black cherry and 27.55 percent for yellow-poplar. If the dynamic programming algorithm was used, the two largest improvements for SM were 5.48 percent for white oak and 5.39 percent for yellow-poplar, whereas the two largest improvements for lumber value were 23.72 percent for black cherry and 15.38 percent for red oak. The improvements of lumber SM and lumber value were significantly different among species, which indicates that mill operators must carefully edge and trim the valuable species, such as black cherry in this case. It should be noted, however, that higher SM does not always mean more lumber value recovery, because lumber value is also affected by other factors, such as grade and price.

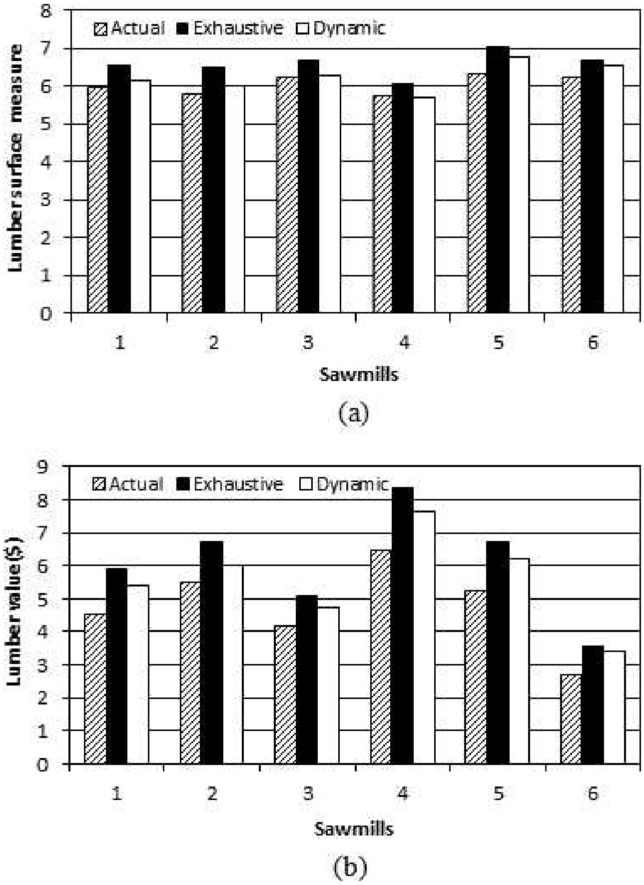


Figure 6.—Actual versus optimal surface measure and lumber value on average by sawmills: (a) lumber surface measure on average and (b) lumber value on average.

Optimal versus actual edging and trimming by grades

The comparisons indicated that lumber grade was improved significantly using optimal edging and trimming

Table 1.—Tukey multiple comparisons 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 vs. dynamic	0.4984	−0.1859 to 1.1827	
Exhaustive vs. sawmill	1.2975	0.6132 to 1.9818	***
Dynamic vs. exhaustive	−0.4984	−1.1827 to 0.1859	
Dynamic vs. sawmill	0.7991	0.1148 to 1.4833	***
Sawmill vs. exhaustive	−1.2975	−1.9818 to −0.6132	***
Sawmill vs. dynamic	−0.7991	−1.4833 to −0.1148	***

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

Table 2.—Actual versus optimal lumber surface measure (SM) and value on average by species.

	Actual		Exhaustive		Dynamic		Exhaustive improvement (%)		Dynamic improvement (%)	
Species[a]	SM	Value	SM	Value	SM	Value	SM	Value	SM	Value
RO	6.79	4.29	7.42	5.29	7.12	4.95	9.28	23.31	4.86	15.38
YP	5.94	2.65	6.62	3.38	6.26	3.04	11.45	27.55	5.39	14.72
BC	4.96	8.39	5.22	11.68	5.10	10.38	5.24	39.21	2.82	23.72
RM	6.21	4.42	6.38	5.02	6.42	5.09	2.74	13.57	3.38	15.16
WO	6.39	4.18	7.02	5.21	6.74	4.73	9.86	24.64	5.48	13.16

[a] RO = red oak; YP = yellow-poplar; BC = black cherry; RM = red maple; WO = white oak.

Table 3.—Actual lumber grade versus optimal lumber grade distribution.

	Actual		Exhaustive search		Dynamic programming	
Lumber grade[a]	No. of boards	Percentage	No. of boards	Percentage	No. of boards	Percentage
FAS/SELECT	87	24.17	125	31.89	107	27.94
1COM	178	49.44	217	55.32	223	58.22
2COM	65	18.06	35	8.93	36	9.40
3COM	30	8.33	15	3.83	17	4.44
Total	360	100	392[b]	100	383[b]	100

[a] FAS = First and Seconds; 1COM, 2COM, and 3COM = 1Common, 2Common, and 3Common, respectively.

[b] Extra pieces are permitted through optimal edging and trimming.

algorithms (Table 3). In the studied sawmills, 73.61 percent of lumber produced were 1COM or better grades. The percentages of lumber with 1COM or better grades were 87.18 or 86.32 percent when using the exhaustive search or the dynamic programming algorithm, respectively. A higher grade improvement was observed in black cherry species boards than in boards of other species (Table 4).

Table 4.—Actual lumber grade versus optimal lumber grade distribution by lumber species.

Species	Grade[a]	Actual (%)	Exhaustive search (%)	Dynamic programming (%)
Red oak	FAS/SELECT	29.89	36.84	31.65
	1COM	51.12	51.29	51.71
	2COM	13.76	8.18	11.76
	3COM	5.23	3.69	4.88
Total		100	100	100
Yellow-poplar	FAS/SELECT	21.02	30.59	26.71
	1COM	51.3	57.06	61.47
	2COM	21	9.41	7.35
	3COM	6.68	2.94	4.47
Total		100	100	100
White oak	FAS/SELECT	23.11	28.63	25.81
	1COM	42.12	55.5	57.74
	2COM	24.88	10.63	11.23
	3COM	9.89	5.24	5.23
Total		100	100	100
Black cherry	FAS/SELECT	22.68	32.29	27.88
	1COM	49.32	58.71	59.18
	2COM	18.05	5.63	8.59
	3COM	9.95	3.37	4.36
Total		100	100	100
Red maple	FAS/SELECT	24.13	29.83	27.36
	1COM	52.97	54.06	59.09
	2COM	13.03	11.6	9
	3COM	9.87	4.5	4.55
Total		100	100	100

[a] FAS = First and Seconds; 1COM, 2COM, and 3COM = 1Common, 2Common, and 3Common, respectively.

To determine the lumber value distribution, all the boards were grouped based on lumber grade (Table 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 when the potential FAS/SELECT boards were dropped to a lower grade in sawmills, because the price gaps between successive lumber grades are significant. Therefore, extra lumber value recovery can be achieved using edging and trimming optimization. Specifically, the total lumber value could be improved by 26.46 percent using exhaustive search or by 16.84 percent using dynamic programming. Even though the exhaustive search showed more improvements when compared with dynamic programming, more execution time was needed. For example, the average execution time for each board was 506 seconds using exhaustive search, whereas the optimization time averaged 258 seconds using dynamic programming.

Factors Affecting Lumber SM and Lumber Value

Factors that could affect board SM or value include species, mill requirements, board length, board clear width (board width without wane on both edges), number of defects, defect size, and others. A generic general linear model was used to determine the impacts of these individual factors and their interactions on board SM or value through edging and trimming, which can be expressed as

$$\begin{aligned}\text{BMV}_{ijklmnop} = {} & \mu + \text{SP}_i + M_j + \text{MAXW}_k + \text{MINW}_l + L_m \\ & + \text{ND}_n + \text{DTS}_o\text{MAXW}_k \times \text{MINW}_l \\ & + \text{MAXW}_k \times L_m + \text{MINW}_l \times L_m \\ & + \text{SP}_i \times \text{ND}_n + \text{SP}_i \times L_m + \varepsilon_{ijklmnop}\end{aligned} \qquad (4)$$

Table 5.—Actual lumber value versus optimal lumber value distribution by lumber grade.

Lumber grade[a]	Actual value (US$)	Exhaustive search value (US$)	Dynamic programming value (US$)	Difference from actual value: Exhaustive search	Difference from actual value: Dynamic programming
FAS/SELECT	789.31	1,095.93	936.93	306.62	147.62
1COM	764.21	960.35	954.68	196.14	190.47
2COM	102.05	76.11	75.86	−25.94	−26.19
3COM	52.89	28.21	28.83	−24.68	−24.06

[a] FAS = First and Seconds; 1COM, 2COM, and 3COM = 1Common, 2Common, and 3Common, respectively.

where $i = 1, 2, \ldots, 5$; $j = 1, 2, \ldots, 6$; $k = 1, 2, \ldots, 5$; $l = 1, 2, \ldots, 5$; $m = 1, 2, \ldots, 5$; $n = 1, 2, \ldots, 5$; $o = 1, 2, \ldots, 5$; $BMV_{ijklmno}$ is the pth observation of board SM or lumber value obtained by sawmills 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 with 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; and p is the number of observations within each treatment (sawmill, exhaustive, and dynamic programming).

Based on the ANOVA analysis, the board SM 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; $P < 0.0019$). No significant difference was found among mills with respect to board SM. If exhaustive search was used in edging and trimming, the board SM was significantly different among maximum board clear widths ($F = 9.17$; df = 4,277; $P < 0.0001$), minimum board clear widths ($F = 16.02$; df = 3,277; $P < 0.0001$), lengths ($F = 20.53$; df = 4,277; $P < 0.0001$), interactions between maximum board clear width and length ($F = 2.19$; df = 15,277; $P < 0.0068$), and interactions between minimum board clear width and length ($F = 1.84$; df = 11,277; $P = 0.048$). If using dynamic programming, a significant difference also existed in board SM among maximum board clear widths ($F = 7.32$; df = 4,277; $P < 0.0001$), minimum board clear widths ($F = 11.32$; df = 3,277; $P < 0.0001$), lengths ($F = 19.09$; df = 4,277; $P < 0.0001$), number of defects ($F = 2.96$; df = 3,277; $P = 0.0326$), total defect size ($F = 2.5$; df = 4,277; $P = 0.0432$), and interactions between maximum board clear width and length ($F = 1.78$; df = 15,277; $P = 0.0378$). However, the SM was not significantly affected by species but was affected by total defect 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; $P = 0.0002$), total defect 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 ($F = 21.60$; df = 5,277; $P < 0.0001$), maximum clear widths ($F = 4.18$; df = 4,277; $P = 0.0026$), minimum clear widths ($F = 9.33$; df = 3,277; $P < 0.0001$), length ($F = 7.39$; df = 4,277; $P < 0.0001$), number of defects ($F = 22.90$; df = 3,277; $P < 0.0001$), total defect size ($F = 3.75$; df = 4,277; $P = 0.0054$), species ($F = 38.73$; df = 4,277; $P < 0.0001$), and interactions between maximum clear board width and board length ($F = 3.07$; df = 15,277; $P = 0.0001$), between species and number of defects on board ($F = 8.42$; df = 8,277; $P < 0.0001$), and between species and length ($F = 2.20$; df = 11,277; $P = 0.0149$). The board value using dynamic programming was significantly different among sawmills ($F = 20.55$; df = 5,277; $P < 0.0001$), maximum clear widths ($F = 6.31$; df = 4,277; $P < 0.0001$), minimum clear widths ($F = 7.97$; df = 3,277; $P < 0.0001$), lengths ($F = 7.01$; df = 4,277; $P < 0.0001$), number of defects ($F = 36.36$; df = 3,277; $P < 0.0001$), total defect size ($F = 3.46$; df = 4,277; $P = 0.0089$), species ($F = 37.63$; df = 4,277; $P < 0.0001$), and interactions between maximum clear board width and board length ($F = 4.67$; df = 15,277; $P < 0.0001$), between species and number of defects on board ($F = 10.98$; df = 8,277; $P < 0.0001$), and between species and length ($F = 2.35$; df = 11,277; $P = 0.0087$). As expected, the board SM was mainly determined by board dimensions, whereas board value mainly depends on species, defects, and board dimensions.

Lumber Edging and Trimming Simulation for Training

Training is essential for sawmills employees to realize the maximum product value, because their decisions 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 edging lines, 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 resulting 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, and 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 and understand the impacts of edging and trimming line placements on final lumber value. At the same time, the user's decisions can also be compared with an optimum edging and trimming solution determined by the system, and the percentage recovery in lumber value can be known. The nondestructive simulation of edging and trimming can help users obtain a better understanding of edging, trimming, and grading.

Discussion and Conclusions

Currently, small mills in the central Appalachian hardwood region still rely on trained workers to make quick decisions about 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 for understanding quality-control, decision-making, and optimization strategies. The 3D system described here is a useful tool for simulating lumber edging, trimming, and grading and for improving lumber utilization and lumber value recovery. As a training tool, the user can observe how the placement of edging and trimming lines affects 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, SM, and prices on lumber value and processing decisions.

The optimal edging and trimming system can effectively increase the lumber value recovery compared with the actual sawmill operations. The results showed that sawmills had the potential to increase their SM and lumber value, on average, by 6.1 and 21.37 percent, respectively, through optimal edging and trimming. Lumber grade could be improved significantly using optimal edging and trimming algorithms. For example, lumber with 1COM or better grades could be improved 13.57 percent using exhaustive search and 12.71 percent using dynamic programming algorithms, respectively. Therefore, opportunities for value improvement exist for boards with higher grade potentials through edging and trimming optimization. The total lumber value could be improved by 26.46 percent using exhaustive searching or by 16.84 percent using dynamic programming for six sawmills. Although the exhaustive search algorithm presented slightly more improvements in lumber value recovery compared with dynamic programming, it took more execution time per optimization run. In addition, many factors, including experience and error of operators, mill equipment, and others, have effects on edging and trimming decisions in sawmills, so care must be taken when interpreting potential lumber value gains.

Whereas the optimal lumber edging and trimming system has the potential to improve lumber value recovery, some limitations are 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 improvement to increase the system efficiency. Finally, lumber specifications are 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.

Acknowledgments

The authors thank Mr. William A. Goff and the six sawmills in West Virginia for their assistance in field data collection. This study was supported by the USDA Wood Education and Resource Center.

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