AN INTEGRATED 3D LOG PROCESSING OPTIMIZATION SYSTEM FOR SMALL SAWMILLS IN CENTRAL APPALACHIA

Wenshu Lin and Jingxin Wang[1]

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, was used to reconstruct 3D virtual logs. Internal log 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. 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.

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 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 central Appalachia is facing a set of challenges including low log quality, limited resource availability, tightened environmental restrictions on timber harvesting, reductions in profit margin, and pressure from foreign competition (Milauskas et al. 2005). Log breakdown practices in this region rely on manual inspection for external log defects, and logs are sawn to either maximize volume or lumber grade (Lee et al. 2001, Zhu et al. 1996). Similarly, edger and trimmer operators visually examine board surfaces and then make quick judgments about the placement of cuts during secondary log breakdown. These practices resulted in low lumber yield, inadequate lumber quality with respect to grade, slow production, and inefficient use 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 (Sarigul et al. 2001, Zhu et al. 1996).

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

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was limited in hardwood sawmills. Computer simulation programs were developed for hardwood log sawing (Adkins et al. 1980; Richards 1973, 1979, 1980) in which a log was represented by a truncated cone and each knot was simulated as a cone with its apex of 24 degrees at the pith. Occeña and Tanchoco (1988) developed a graphic log sawing simulator to automatically perform hardwood log breakdowns. Several studies were also conducted to analyze the impacts of sawing methods, internal defects, and log orientations on the potential lumber value recovery (Chang et al. 2005; Guddanti et al. 1998; Harless et al. 1991; Occeña et al. 2000, 2001; Steele et al. 1993, 1994).

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 (Bhandarkar et al. 2002, 2008; Faaland and Briggs 1984; Geerts 1984; Todoroki and Rönnqvist 1997, 1999). Occeña et al. (1997) and Thawornwong et al. (2003) also designed the heuristic algorithm to optimize log sawing patterns. A computer-based exhaustive enumeration procedure was developed to achieve the optimal edging and trimming solution and analyze the effect of defects on lumber value (Regalado et al. 1992a, 1992b). Todoroki and Rönnqvist (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 simulator to implement the dynamic programming algorithm. Schmoldt et al. (2001) used branch-and-bound (B&B) search to obtain optimal edging/trimming solutions. To date, several edging and trimming computer software systems have been developed to aid in milling operations (Abbott et al. 2000; Araman et al. 1996; Kline et al. 1990, 1992; Lee et al. 2003; Schmoldt et al. 2001).

Decisions made in sawing, edging, and trimming operations are interrelated. For example, any decisions made in primary log breakdown 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 breakdowns to achieve a global optimal solution. Faaland and Briggs (1984) combined primary log sawing and tree bucking using dynamic programming and modeled a log as a cylinder without taper, curvature, and defects. Geerts (1984) used a nested 2D 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 the external profile was used to represent logs. Zeng (1995) further refined this program by including internal defects and an expert system for softwood lumber grading. Todoroki et al. (1999) developed a model that integrated primary and secondary log breakdowns based on dynamic programming principles, and the combined model was incorporated into the AUTOSAW sawing simulation system (Todoroki 1997), which is appropriate only for live-sawing practices.

Existing computer simulations or mathematical programming models for log breakdown optimization differed 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 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 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 breakdowns for softwood or hardwood live sawing, application in hardwood sawmills, which typically use grade sawing, was limited.

Currently, most large softwood 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 percent of all Pennsylvania hardwood sawmills use a computer-aided headrig (Smith et al. 2004). In West Virginia, approximately 68.5 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). These small hardwood producers are key contributors to the industry because they represent a significant share of the market. Application of an appropriate, user friendly, and efficient computer-aided sawing, edging and trimming, and grading system could be one of the important strategies to improve processing performance and enhance producer 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 were to (1) design a heuristic procedure to determine the log opening face based on log shape and external defects, (2) develop heuristic and dynamic programming (DP) algorithms for primary log breakdown, (3) formulate exhaustive search and DP algorithms 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 optimal algorithms, and (6) compare the lumber values generated in sawmills and by the optimization system.

SYSTEM DESIGN

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 (Fig. 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

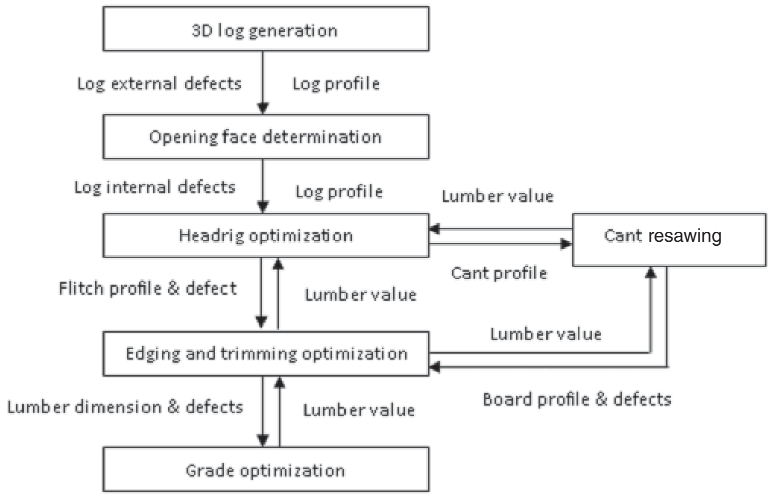

Figure 1.—System components.

patterns with maximum log value by applying either heuristic or DP algorithms. The optimum value of each flitch or cant cut from the log can be determined as well. 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 an exhaustive search or the 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.

System Data Management

Microsoft ActiveX Data Objects (ADO) was used to retrieve data from and save sawing results to an MS Access database. 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 1-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.

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 (Fig. 2a). This model is much closer to real log shape because the data at each cross section were collected as well as log sweep and log crook. 3D modeling techniques, together with OpenGL primitive drawing functions, were used to generate 3D log visualizations. The OpenGL functions such as translation, rotation, and scaling are used to facilitate log visualization

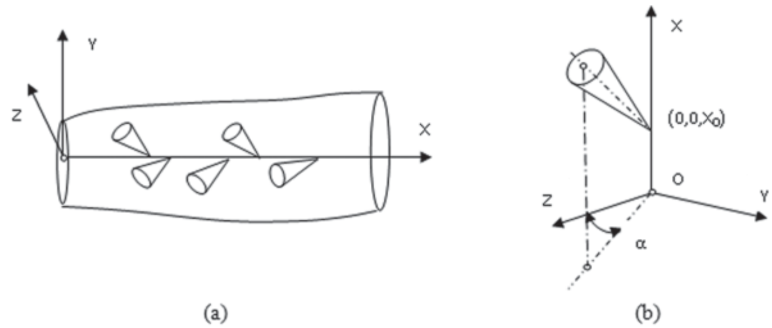

Figure 2.—3D log and defect model. (a) 3D log and knots; (b) knot represented as a cone arbitrarily positioned in the XYZ space.

and the related mathematical modeling was described by Woo et al. (2000). Studies have shown that a strong correlation exists between surface defect indicators such as overgrown knot, overgrown knot cluster, sound knot, and unsound knot and internal knot defects (Thomas 2008). We considered only 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) (Fig. 2b). 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. When a sawing plane passes through an internal knot, a 2D rectangular defect area is assumed to be exposed on the lumber surface. The approximate location and size of the defect area are determined using mathematical procedures.

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. Because no logs are absolutely straight, log sweep is considered to describe the curvature of a log. If a log's sweep is less than 3 inches, the log will be treated as a non-sweepy log; otherwise it will be deemed a sweepy log and log sweep is considered in the modeling process.

Non-Sweepy Logs

Three steps are needed to determine the opening face for non-sweepy logs (Lin et al. 2010): log orientation, 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. 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 U. S. Forest Service log grading rules. After the best log face is identified, the opening face dimension is then determined. The size of the opening face has a direct bearing on profitability (Denig et al. 2005). The width is the only consideration because 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. (2010).

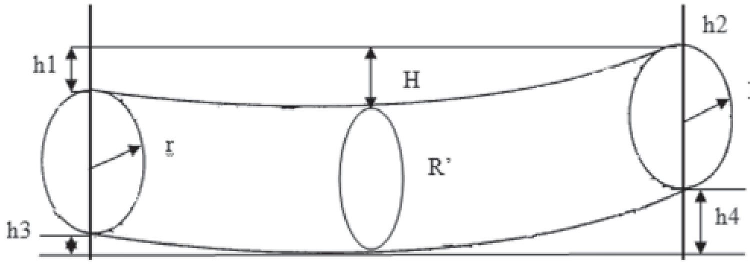

Figure 3.—Log sweep measurement.

Sweepy Logs

For logs with sweep of 3 inches or more, the opening face is based on log sweep rather than clear face (Denig et al. 2005, Malcolm 1965). It is assumed that the concave surface of a log is toward 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 (1):

$$\begin{cases} w_1 = 2 * \sqrt{r^2 - (r - (H - h_1) - (R^{'} - \sqrt{(R^{'})^2 - 1.625^2}))^2} \\ w_2 = 2 * \sqrt{R^2 - (R - (H - h_2) - (R^{'} - \sqrt{(R^{'})^2 - 1.625^2}))^2} \\ w_3 = 2 * \sqrt{r^2 - (r - ((h_4 + R - \sqrt{R^2 - 1.625^2}) - h_3))^2} \\ w_4 = 2 * \sqrt{R^2 - (R - ((h_3 + r - \sqrt{r^2 - 1.625^2}) - h_4))^2} \end{cases} \qquad (1)$$

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 (Fig. 3). 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 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, 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 the small end is computed as w_3 in (1), otherwise the small end opening width will be 3.25 inches and the large end width is computed as w_4 in (1). Once the sweep has been removed from a log, the turning rules and procedures of the log would be the same as for non- sweepy logs during grade sawing process.

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 that is sent to the secondary breakdown to determine the value. An optimal edging and/or trimming solution is then generated for the produced flitch. Specifically, once the log opening face is determined, the system uses either heuristic or DP algorithms to achieve the optimum sawing pattern at the headrig. The generated flitches are then edged and trimmed using 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.

Heuristic Algorithm

Heuristic refers to experience-based techniques for problem solving. It is more easily adaptable to a complex restriction problem, such as the 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 the current sawing face or the current face reaches the central cant. Then the log is rotated to the next face with a potential for the highest lumber grade. This sawing process is repeated until a specified size cant is produced.

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 dynamic programming is to find the recursive relationship. If lumber thicknesses, sawing kerf width, and sawing resolution were given, the recursive function for log grade sawing can be expressed as equation (2), which is a modified recursive function based on Bhandarkar et al. (2008).

$$v^*(i+1) = \max_{j \in [1,m]} \left(v^*\left(i+1-\frac{T_j}{c}-\left\lceil \frac{K}{c} \right\rceil\right) + g\left(i+1-\frac{T_j}{c}, i+1\right) \right) \quad (2)$$

where $T_j = (T_1, T_2, \cdots, T_m)$ is a set of lumber thicknesses, and m is the total number of lumber thickness, c is the sawing plane resolution (4 mm in this study), 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.

Flitch Edging and Trimming

Flitches produced during 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 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. Because edging and trimming operations are interrelated, the placement of edging lines has an effect on the trimming decision and vice versa. The two operations must be considered simultaneously 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. 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 is treated as defects and represented with rectangles. If the current flitch satisfies the FAS lumber grade, then the edging and trimming optimization will terminate and return the lumber

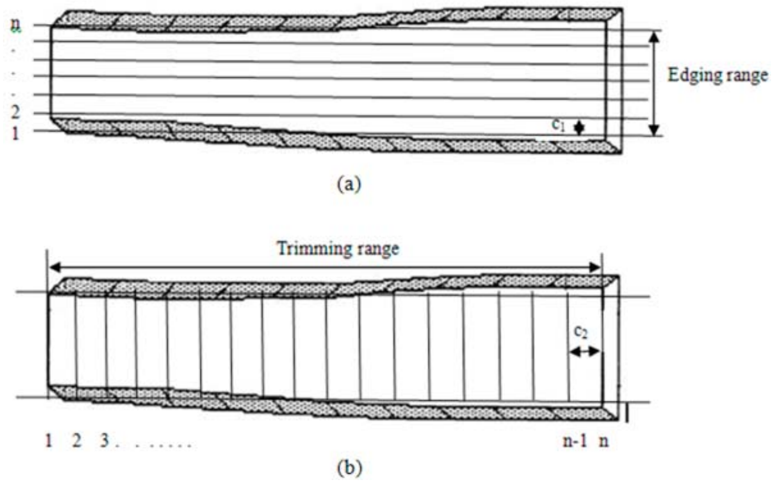

Figure 4.—Potential cutting lines for flitch edging and trimming.

value because no improvement can be achieved by edging and/or trimming operation. Otherwise, the edging and/or trimming algorithms will be recalled to achieve the optimal solution, and multiple pieces of lumber will be generated.

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 ends, 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 on 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.

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 horizontal (Fig. 4a) and vertical (Fig. 4b) directions, respectively. This allows the lumber edging and/or trimming problem to be formulated as a set packing problem to maximize the total lumber value. 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 (3) based on Bhandarkar et al. (2008).

$$\begin{cases} v^*(i+1) = \max\limits_{k \in [1,m]} \left(v^*\left(i+1-\left\lceil \frac{W_k}{c_1} \right\rceil - \left\lceil \frac{K}{c_1} \right\rceil\right) + g\left(i+1-\left\lceil \frac{W_k}{c_1} \right\rceil, i+1\right)\right), \ \textit{for edging only} \\ v^*(i+1) = \max\limits_{l \in [1,n]} \left(v^*\left(i+1-\left\lceil \frac{L_l}{c_2} \right\rceil - \left\lceil \frac{K}{c_2} \right\rceil\right) + g\left(i+1-\left\lceil \frac{L_l}{c_2} \right\rceil, i+1\right)\right), \ \textit{for trimming only} \end{cases} \quad (3)$$

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), the integrated edging and trimming flitch problem can be formulated as equation 4 as follows:

$$v^*(i+1, j+1) = \max_{k\in[1,m]}(\max_{l\in[1,n]}((v^*(i+1-\left\lceil\frac{W_k}{c_1}\right\rceil-\left\lceil\frac{K}{c_1}\right\rceil, j+1-\left\lceil\frac{L_l}{c_2}\right\rceil-\left\lceil\frac{K}{c_2}\right\rceil)+ g(i+1-\left\lceil\frac{W_k}{c_1}\right\rceil, i+1, j+1-\left\lceil\frac{L_l}{c_2}\right\rceil, j+1)))) \quad (4)$$

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 edging and trimming interval was 0.5 inch and 6 inches, respectively. 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.

Cant Resawing and Lumber Grading

Deciding whether to make a cant or to saw the cant into lumber is a common issue for sawmill personnel. If they 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 based on a hardwood lumber grading routine developed by Klinkhachorn et al. (1988). The heuristic algorithm is designed to assign the National Hardwood Lumber Association (NHLA) lumber grade to a piece of lumber (Lin et al. 2010). The basic principle is that the potential lumber grades are tested sequentially, starting from the highest lumber grade and working downward 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.

SYSTEM APPLICATION

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 (Fig. 3). 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 ends were computed

Table 1.—Characteristics of lumber from the sample logs

Statistic categories	Length (feet)	Width (inch)	Thickness (inch)	SM[a]	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[b]	1.65	1.04	0.14	1.14	1.7	1.13

[a] Surface measure.
[b] Standard deviation.

Table 2.—Lumber prices based on grades ($/thousand board feet)

Species	Thickness (inch)	Lumber grades FAS	F1F	Select[a]	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

[a] Price was the average of price of the F1F and 1COM.

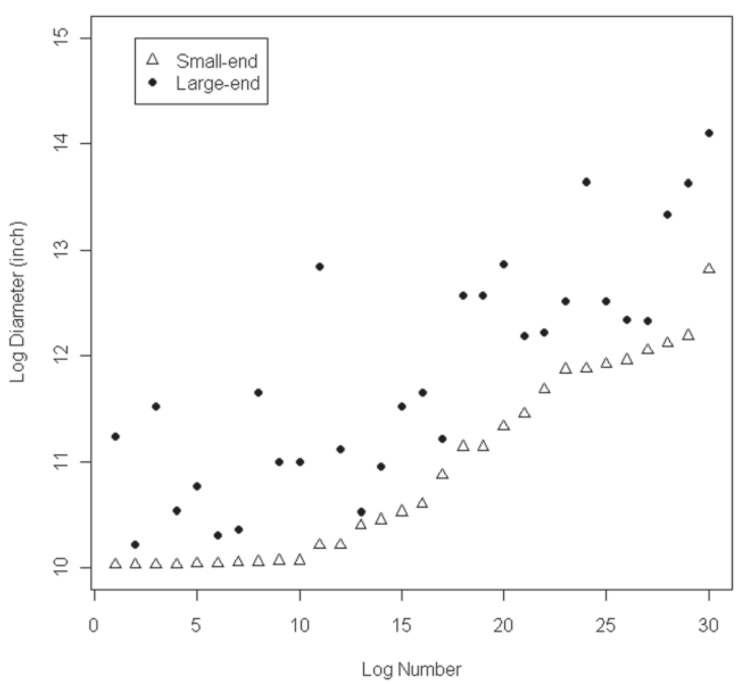

Figure 5.—Log diameter distribution order by small-end diameter.

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 using the models developed by the U.S. Forest Service (Thomas 2008). The small-end diameters of the sample logs ranged from 10 to 13 inches with log length from 8 to 14 feet (Fig. 5). Log tapers range from 0.01 to 0.026 inch/foot and log sweep ranged from 0 to 3.25 inches. Lumber length (feet), width and thickness (inches), and volume (board feet) were measured (Table 1). The grade and surface measurement of the lumber were determined by a certified NHLA grader at each sawmill. Lumber prices were based on Hardwood Market Report for Appalachian Hardwoods in April 11, 2009 (Table 2).

RESULTS

Optimal Solution vs. Sawmill Production without Edging and Trimming

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 Table 3. The sawmills could improve lumber value by 7.8 percent and 10.3 percent, respectively, by using the heuristic and DP algorithms to aid the sawing process. Suppose that the average board value was priced at $0.50 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 $39,000 to $51,500 per year. However, we did not consider the

Table 3.—Lumber values and volume by log from actual sawmill, heuristic, and dynamic programming algorithm without edging and trimming optimization

	Lumber value ($)			Lumber volume (board foot)		
Log number	Actual	Heuristic	Dynamic	Actual	Heuristic	Dynamic
1	17.67	20.83	21.03	38	39.15	39.46
2	31.76	35.05	34.24	52.31	51.07	51.4
3	30.77	33.6	34.87	57.13	59.42	59.75
4	40.27	42.52	42.89	64.44	66.12	64.69
5	33.51	35.06	36.48	53.31	55.31	56.5
6	23.07	25.37	26.34	43	44.52	45.43
7	21.33	21.95	23	38.69	38.97	39.29
8	26.28	28.07	28.69	48.63	49.41	50.74
9	28.89	31.94	32.49	51.19	51.92	54.83
10	18.46	19.14	21.76	39.81	38.97	39.29
11	35.61	38.18	39.87	73.75	74.12	73.19
12	23.15	25.67	27.22	59.01	58.96	59.44
13	18.03	19.58	20.7	57.31	57.06	61.3
14	28.22	30.89	30.05	64.69	65.36	66.06
15	20.33	21.36	21.62	52.19	49.8	49.86
16	12.42	13.01	14.02	39.13	42.23	42.09
17	21.9	24.52	25.06	61.75	60.59	59.55
18	36.16	38.12	38.86	69	68.57	71.34
19	13.73	14.74	15.12	40.75	42.18	42.35
20	15.74	17.96	18	39.06	40.66	40.92
21	19.22	20.69	20.83	53.69	54.2	57.05
22	17.12	19.12	19.31	50.73	55.84	55.52
23	15.21	16.42	16.63	47.19	49.42	49.36
24	22.03	23.58	24.24	58.31	57.15	61.3
25	31.22	32.66	32.9	74.69	77.58	77.23
26	25.69	28.39	28.81	40.88	43.23	43.07
27	29.25	31.63	30.72	48.63	48.97	49.17
28	32.77	33.29	35.87	58.13	59.43	59.95
29	31.88	34.79	34.82	46.81	48.97	49.36
30	24.54	26.23	26.54	43.72	46.57	46.74

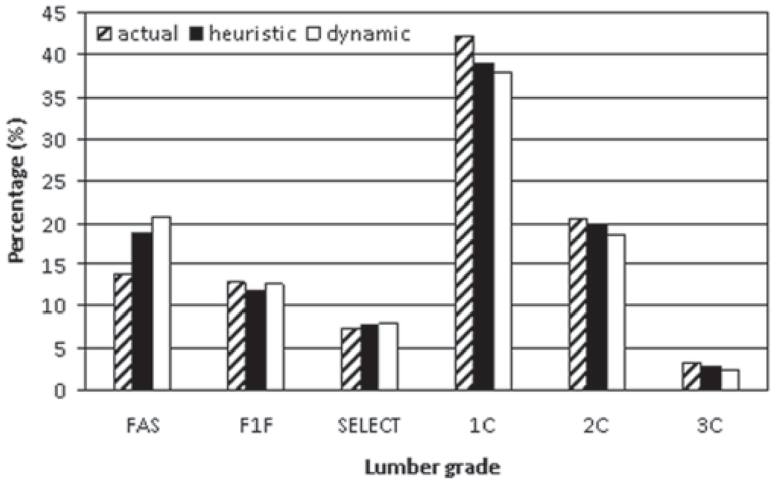

Figure 6.—Lumber grade distribution without exhaustive edging and trimming.

cost of measuring out the defects on every log when calculating lumber value recovery. The lumber volume could be increased by 1.9 percent and 3.2 percent, 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 53.19 board feet and 53.87 board feet, respectively, and lumber value averaged $26.81 and $27.43 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.

Lumber Grade Recovery

We found that the distribution of lumber grades differed among different sawing methods (Fig. 6). Approximately 33.9 percent of lumber produced was graded as Select or higher grades by sawmills, while the number improved to 38.3 percent and 41.4 percent using the heuristic and dynamic programming algorithms, respectively. In sawmills, 42.3 percent, 20.6 percent, and 3.2 percent of lumber were graded as 1COM, 2COM, and 3COM, respectively. If the heuristic algorithm was used to optimize log sawing, 39.0 percent, 19.9 percent, and 2.9 percent of lumber produced were with grades of 1COM, 2COM, and 3COM, respectively. If using dynamic programming, 37.8 percent of lumber were 1COM, 18.4 percent were 2COM, and 2.4 percent 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 six 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 another log with 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 before the sawing process to avoid unnecessary sawing costs for severely sweepy logs.

Table 4.—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

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 4). With exhaustive search-based edging-only optimization, an overall average value recovery could be 97.8 percent or 97.3 percent by using the heuristic and DP log sawing algorithms, respectively. However, an overall average lumber value recovery could be 94.3 percent and 95.2 percent using trimming-only optimization. With DP-based edging-only optimization, an overall average value recovery was 98.4 percent or 98.0 percent by using heuristic and DP log sawing algorithms, respectively. An overall average value recovery would be 96.0 percent or 96.2 percent 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.

Optimal Solution vs. Sawmill Productions with Edging and Trimming

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 (Table 5) and found that the lumber value generated from log sawing using heuristic or DP algorithms could increase 11.9 percent and 14.3 percent using exhaustive search for flitch edging and trimming, respectively, while the lumber value could improve 10.9 percent and 12.8 percent using DP for flitch edging and trimming. The results indicated that more lumber value recovery can be achieved when exhaustive search is 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.

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 7a and 7b. 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 different. For example, when using the exhaustive search algorithm to optimize flitch edging and trimming, 33.9 percent, 40.2 percent, and 43.2 percent of lumber produced were Select or higher grades at swmills, using heuristic, and dynamic programming algorithms, respectively. In the actual log sawing production, 42.3 percent, 20.6 percent, and 3.2 percent of lumber were with grades of 1COM, 2COM, and 3COM,

Table 5.—Lumber values by log from actual sawmill, heuristic and dynamic programming algorithm with exhaustive search and dynamic programming for edging and trimming optimization

		Exhaustive edging and trimming		Dynamic edging and trimming	
Log number	Actual	Heuristic	Dynamic	Heuristic	Dynamic
1	17.67	20.5	21.53	20.5	21.47
2	31.76	35.72	34.74	35.66	34.46
3	30.77	34.24	35.37	34.23	35.03
4	40.27	45.08	47.39	46.17	46.97
5	33.51	35.85	36.98	35.68	36.48
6	23.07	25.44	26.84	26.75	26.55
7	21.33	24.46	26.18	22.53	24.33
8	26.28	30.64	29.19	30.66	30.46
9	28.89	33.08	33.19	33.19	32.99
10	18.46	19.72	22.26	19.66	21.46
11	35.61	38.83	41.29	38.79	39.59
12	23.15	26.23	27.72	26.26	26.56
13	18.03	21.84	22.2	20.14	20.94
14	28.22	31.71	31.81	31.49	31.29
15	20.33	21.82	23.12	21.93	22.73
16	12.42	13.59	15.52	13.56	14.36
17	21.9	23.7	25.56	23.1	25.4
18	36.16	39.81	39.36	38.73	39.07
19	13.73	15.4	16.62	15.29	16.09
20	15.74	18.67	19.25	18.52	18.72
21	19.22	23.49	21.67	23.27	23.07
22	17.12	19.77	19.81	19.69	19.59
23	15.21	18.98	17.13	16.98	17.08
24	22.03	25.84	25.83	24.16	24.96
25	31.22	33.25	33.4	33.26	33.16
26	25.69	28.94	29.31	28.98	30.08
27	29.25	32.46	31.22	32.24	32.04
28	32.77	33.85	36.37	33.91	34.71
29	31.88	35.49	35.32	35.41	35.21
30	24.54	26.78	27.03	26.72	26.92

respectively. If the heuristic algorithm was used to optimize log sawing, 39.1 percent, 18.5 percent, and 2.3 percent of lumber were graded as 1COM, 2COM, and 3COM, respectively. When using the dynamic programming algorithm to optimize log sawing, 37.5 percent, 17.2 percent, and 2.1 percent of lumber produced were with grades of 1COM, 2COM, and 3COM, respectively.

Optimal Log Sawing with or without Optimal Edging and Trimming

Greater lumber value recovery could be achieved when log sawing was integrated with flitch edging and trimming optimization. At least 3.1 percent more value could be recovered when integrating log sawing optimization with flitch edging and trimming, and the maximum value improvement could be as high as 4.1 percent. This is reasonable because severe edging can result in a failure to consider

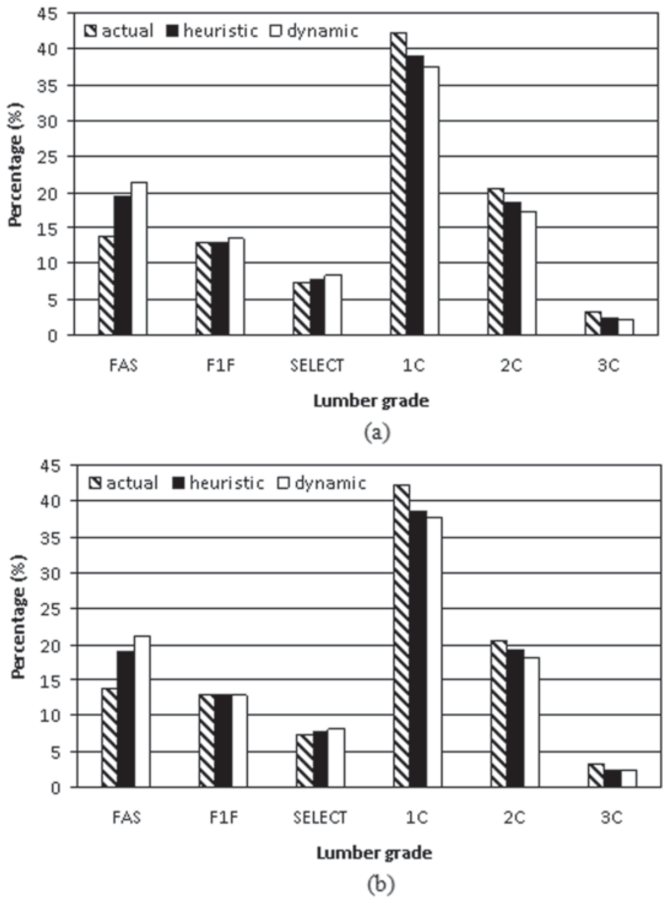

Figure 7.—Lumber grade distribution with optimal edging and trimming operations. (a) Lumber grade distribution with exhaustive edging and trimming; (b) lumber grade distribution with dynamic programming edging and trimming.

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 severe-edging could result in a total lumber value loss. Therefore, when edging and trimming optimization are ignored, the final log sawing solution is suboptimal.

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 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, sawmills could improve lumber value by 7.8 percent and 10.3 percent, 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 11.9 to 14.3 percent using exhaustive search for flitch edging and trimming, or 10.9 to 12.8 percent 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. The U.S. 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 2006). 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.

A cautionary note: the log sawing method that combined primary breakdown and secondary breakdown presented here assumes that logs are positioned and an 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 width (such as from 3 to 6 inches) placements. In addition, the current method can be nested within that two loops (angular and opening face width) and evaluated at each placement to find the best sawing results. However, increased levels of loop will increase the computational burden and need 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 3D log sawing problem, which requires more computer execution time to generate an optimal sawing pattern. A smaller interval provides more opportunities to discover better solutions, but the optimization process can take longer, especially for poorly shaped large logs with more defects. The solutions from the heuristic algorithm 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 also had an effect on lumber value recovery. It should be noted that time is important 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.

We should also note three limitations associated with this system, which should be taken into account in future studies: (1) considering external log defects, internal defects, and log shapes simultaneously to determine opening face, (2) improving 3D log model by using polygonal data 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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LITERATURE CITED

Abbott, A.L.; Schmoldt, D.L.; Araman, P.A. 2000. **A next generation processing system for edging and trimming.** In: Meyer, D.A., ed. Proceedings, 28th annual hardwood symposium. Memphis, TN: National Hardwood Lumber Association: 141-149.

Adkins, W.K.; Richards, D.B.; Lewis, D.W.; Bulgrin, E.H. 1980. **Programs for computer simulations of hardwood log sawing.** FPL-RP-357. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Araman, P.A.; Kline, D.E.; Winn, M.F. 1996. **A computer program you can use: edging and trimmer trainer.** In: Meyer, D.A., ed. Proceedings, 24th annual hardwood symposium. Memphis, TN: National Hardwood Lumber Association: 61-68.

Bhandarkar, S.M.; Faust, T.D.; Tang, M. 2002. **Design and development of a computer vision-based lumber production planning system.** Image Vision and Computing. 20: 167-189.

Bhandarkar, S.M.; Luo, X.; Daniels, R.; Tollner, E.W. 2008. **Automated planning and optimization of lumber production using machine vision and computer tomography.** IEEE Transactions on Automation Science and Engineering. 5(4): 677-695.

Chang, S.J.; Cooper, C.; Guddanti, S. 2005. **Effects of the log's rotational orientation and the depth of the opening cut on the value of lumber produced in sawing hardwood logs.** Forest Products Journal. 55(10): 49-55.

Denig, J. 1993. **Small sawmill handbook: doing it right & making money.** San Francisco, CA: Miller Freeman. 182 p.

Denig, J.; Wengert, G. 2005. **Sawing, edging, and trimming hardwood lumber: putting theory into practice.** Madison, WI: Forest Products Society. 104 p.

Faaland, B.; Briggs, D. 1984. **Log bucking and lumber manufacturing using dynamic programming.** Management Science. 30(2): 245-247.

Funck, J.W.; Zeng, Y.; Brunner, C.C.; Butler, D.A. 1993. **SAW3D: A real shape log breakdown model.** In: Szymani, R., ed. Proceedings, fifth international conference on scanning technology and process control for the wood products industry. San Francisco, CA: Miller Freeman: 1-9.

Geerts, J.M. 1984. **Mathematical solution for optimizing the sawing pattern of a log given its dimensions and its defect core.** New Zealand Journal of Forestry Science. 14(1): 124-134.

Guddanti, S.; Chang, S.J. 1998. **Replicating sawmill sawing with TOPSAW using CT images for a full-length hardwood log.** Forest Products Journal. 48(1): 72-75.

Hallock, H.; Galiger, L. 1971. **Grading hardwood lumber by computer.** FPL-RP-157. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Hallock, H.; Stern, A.l.R.; Lewis, D.W. 1976. **Is there a 'best' sawing method.** FPL-RP-280. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Harless, T.E.G.; Wagner, F.G.; Steele, P.H.; et al. 1991. **Methodology for locating defects within hardwood logs and determining their impact on lumber-value yield.** Forest Products Journal. 41(4): 25-30.

Kline, D.E.; Wengert, E.M.; Araman, P.A. 1990. **Automatic edging and trimming of hardwood lumber**. In: American Society of Agricultural Engineers winter meeting proceedings. St. Joseph, MI: American Society of Agricultural Engineers.

Kline, D.E.; Wengert, E.M.; Araman, P.A.; Klinkhachorn, P. 1992. **Hardwood lumber edger and trimmer training system.** Forest Products Journal. 42(1): 53-57.

Klinkachorn, P.; Connors, R.W.; Huber, H.A. 1988. **Automated computer grading of hardwood lumber.** Forest Products Journal. 38(3): 67-69.

Lee, S.M.; Abbott, A.L.; Schmoldt, D.L. 2001. **A modular approach to detection and identification of defects in rough lumber.** Review of Progress in Quantitative Nondestructive Evaluation. 20: 1950-1957.

Lee, S.M.; Abbott, A.L.; Schmoldt, D.L.; Araman, P.A. 2003. **A system for optimal edging and trimming of rough hardwood lumber.** Proceedings, fifth international conference on image processing and scanning of wood. San Francisco, CA: Miller Freeman: 25-34.

Lewis, D.W. 1985. **Sawmill simulation and the best opening face system: a user's guide.** Gen. Tech. Rep. FPL-48. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 29 p.

Lin, W.; Wang, J.; Thomas, E. 2010. **A 3D optimal sawing system for small sawmills in central Appalachia.** In: Fei, S.; et al., eds. Proceedings, 17th central hardwoods forest conference. Gen. Tech. Rep. NRS-78. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 67-76.

Malcolm, F.B. 1965. **A simplified procedure for developing grade lumber from hardwood logs.** FPL-RN-098. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Milauskas. S.J.; Anderson, R.B.; McNeel, J. 2005. **Hardwood industry research priorities in West Virginia.** Forest Products Journal. 55(1): 28-32.

Occeña, L.G.; Tanchoco, J.M.A. 1988. **Computer graphics simulation of hardwood log sawing.** Forest Products Journal. 38(10): 72-76.

Occeña, L.G.; Schmoldt, D.L.; Thawornwong, S. 1997. **Examining the use of internal defect information for information-augmented hardwood log breakdown.** Proceedings, ScanPro, seventh international conference on scanning technology & process optimization for the wood products industry. 8 p.

Occeña, L.G.; Schmoldt, D.L.; Thawornwong, S. 2000. **Evaluation of information-augmented and information-limited heuristics for the primary breakdown of hardwood logs.** Columbia, MO: University of Missouri-Columbia, Department of Industrial and Manufacturing Systems Engineering.

Occeña, L.G.; Rayner, T.J.; Schmoldt, D.L.; Abbott A.L. 2001. **Cooperative use of advanced scanning technology for low-volume hardwood processors.** In: Proceedings, first international precision forestry cooperative symposium. Seattle, WA: University of Washington: 83-91.

Regalado, C.; Kline, D.E.; Araman, P.A. 1992a. **Optimum edging and trimming of hardwood lumber.** Forest Products Journal. 42(2): 8-14.

Regalado, C.; Kline, D.E.; Araman, P.A. 1992b. **Value of defect information in automated hardwood edger and trimmer systems.** Forest Products Journal. 42(3): 29-34.

Richards, D.B. 1973. **Hardwood lumber yield by various simulated sawing methods.** Forest Products Journal. 23(10): 50-58.

Richards, D.B.; Adkins, W.K.; Hallock, H.; Bulgrin, E.H. 1979. **Simulation of hardwood log sawing.** Res. Pap. FPL-355. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.

Richards, D.B.; Adkins, W.K.; Hallock, H.; Bulgrin, E.H. 1980. **Lumber value from computerized simulation of hardwood log sawing.** Res. Pap. FPL-356. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 10 p.

Sarigul, E.; Abbott, A.L.; Schmoldt, D.L. 2001. **Nondestructive rule-based defect detection and identification system in CT images of hardwood logs.** Review of Progress in Quantitative Nondestructive Evaluation. 20: 1936-1943.

Schmoldt, D.L.; Song, H.; Araman, P.A. 2001. **Real-time value optimization of edging and trimming operations for rough, green hardwood lumber.** In: Proceedings, ScanTech 2001, ninth international conference on scanning technology and process optimization for the wood industry. Berkeley, CA: Wood Machining Institute: 87-100.

Smith, P.M; Dasmohapatra, S.; Luppold, W.G. 2004. **A profile of Pennsylvania's hardwood sawmill industry.** Forest Products Journal. 54(5): 43-49.

Steele, P.H.; Wagner, F.G.; Kumar, L.; Araman, P.A. 1993. **The value versus volume yield problem for live-sawn hardwood sawlogs.** Forest Products Journal. 43(9): 35-40.

Steele, P.H.; Harless, T.E.G.; Wagner, F.G.; et al. 1994. **Increased lumber value from optimum orientation of internal defects with respect to sawing pattern in hardwood sawlogs.** Forest Products Journal. 44(3): 69-72.

Thawornwong S.; Occeña, L.G.; Schmoldt, D.L. 2003. **Lumber value differences from reduced CT spatial resolution and simulated log sawing.** Computers and Electronics in Agriculture. 41: 23-43.

Thomas, E. 2008. **Predicting internal yellow-poplar log defect features using surface indicators.** Wood and Fiber Science. 40(1): 14-22.

Thomas, L. 2006. **Automated detection of surface defects on barked hardwood logs and stems using 3-D laser scanner data.** Blacksburg, VA: Virginia Polytechnic Institute and State University. 131 p. Ph.D. dissertation.

Todoroki, C.L. 1997. **Developments of the Sawing Simulation Software, AUTOSAW: linking wood properties, sawing, and lumber end-use.** In: Nepveu, G., ed. Proceedings, second workshop, IUFRO S5.01-04, INRA: 241-247.

Todoroki, C.L.; Rönnqvist, E.M. 1997. **Secondary log breakdown optimization with dynamic programming.** Journal of the Operational Research Society. 48(5): 471-478.

Todoroki, C.L.; Rönnqvist, E.M. 1999. **Combined primary and secondary log breakdown optimisation.** Journal of the Operational Research Society. 50(3): 219-229.

Wang, J.; Liu, J.; LeDoux, C.B. 2009. **A three-dimensional bucking system for optimal bucking of central Appalachian hardwoods.** International Journal of Forest Engineering. 20(2): 26-35.

West Virginia Division of Forestry (WVDOF). 2004. **Green lumber production directory.** Available at www.wvforestry.com/Green%20Lumber.DIR.pdf. (Accessed May 10, 2010).

Woo, M.; Neider, J.; Davis, T.; Shreiner, D. 2000. **OpenGL programming guide: the official guide to learning OpenGL,** Version 1.2. Reading, MA: Addison-Wesley. 730 p.

Zeng, Y. 1991. **Log breakdown using dynamic programming and 3-D log shape.** Corvallis, OR: Oregon State University. 128 p. M.S. thesis.

Zeng, Y. 1995. **Integration of an expert system and dynamic programming approach to optimize log breakdown using 3-dimensional log and internal defect shape information.** Corvallis, OR: Oregon State University. 146 p. Ph.D. dissertation.

Zhu, D.; Conners, R.W.; Schmoldt, D.L.; Araman, P.A. 1996. **A prototype vision system for analyzing CT imagery of hardwood logs.** IEEE Transactions on Systems, Man, and Cybernetics – Part B: Cybernetics. 26(4): 522-532.