# A Three-Dimensional Bucking System for Optimal Bucking of Central Appalachian Hardwoods

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## ABSTRACT

An optimal tree stem bucking system was developed for central Appalachian hardwood species using three-dimensional (3D) modeling techniques. ActiveX Data Objects were implemented via MS Visual C++/OpenGL to manipulate tree data which were supported by a backend relational data model with five data entity types for stems, grades and prices, logs, defects, and stem shapes. A network analysis algorithm was employed to achieve the optimal bucking solution with four different alternative stage intervals under the bucking by value principle. A total of 264 tree stems were measured in the field including stem dimensions, defects, sweep, and the manual bucking solution of each stem. Results when using the 3D optimal bucking system suggest that compared to manual bucking the total log value and volume gain from each tree stem could be increased on average by 31 to 38 percent and 16 to 17 percent, respectively. Results also show the individual tree stem utilization rate could be increased by 10 to 11 percent. The optimal bucking system developed can be used as a training tool on desktop PCs and can also be installed on field PCs to aid field buckers and operators of sawbucks. The 3D bucking optimization system developed in this research should be valuable to operators in the central Appalachian region due to the variability in tree stems and species of hardwoods.

**Keywords:** *optimal bucking, 3D modeling, mathematical programming, network analysis, Appalachian hardwoods, manual bucking, log grades, log prices*

## Introduction

Tree stem bucking is a complex problem because the decision of where to cut depends on various factors including species and size of the stem, grades of logs within the stem length, market value for end products, and number, location and severity of defects (Bobrowski 1994). During the last six decades, scientists throughout the world have paid particular attention to optimal bucking because it is not only one of the most effi-
cient ways to increase profits for forest industries, but is also considered an opportunity to more fully utilize forest resources.

Optimal bucking problems have been solved involving mathematical programming techniques including linear programming, dynamic programming, and network analysis extensively (Smith and Harrell 1961, Pnevmaticos and Mann 1972, Lawrence 1986, Sessions 1988, Wang et al. 2004). These techniques can be applied separately or linked together to solve optimal bucking problems for individual stems or at the stand or forest level. In recent years, some heuristic approaches including Tabu search (Laroze and Greber 1997, Laroze 1999), genetic algorithm approach (Kivinen 2004), and fuzzy logic (Kivinen and Uusitalo 2002) have also been explored to solve optimal bucking problems.

Several optimal bucking systems have been developed, and experimental applications of these systems indicated that great value increases can be obtained. Previous studies reported that the average manual log bucking practice typically reduced the potential value obtainable from a tree by 20 percent compared to what was considered to be good practice (Faaland and Briggs 1984). Using dynamic programming in New Zealand, Geerts and Twaddle (1985) developed a program named AVIS to maximize the value of a single tree stem. Studies of softwood bucking practices in New Zealand and the Pacific Northwest have revealed gross value losses ranging from 5 to 26 percent (Geerts and Twaddle 1985, Sessions et al. 1989, Twaddle and Goulding 1989). Two mechanized bucking operations in the southeastern United States were compared with the optimal values computed using AVIS by Boston and Murphy (2003), and they reported that log value loss could be up to 6 percent for a final harvesting or 42 percent for a thinning operation. Optimal bucking also demonstrated a 12-percent increase of value per cubic meter for bucking the northeastern species in China (Wang et al. 2004).

BUCK, developed at Oregon State University (Sessions 1988), is an interactive tree optimizer using network analysis that explicitly considered alternative mill prices, transport distances, and equipment capability. Garland et al. (1989) compared value recovery from manual log bucking and from using BUCK on a HP handheld computer. They reported that 14.2 percent and 11.9 percent of total log value increases could be achieved when bucking old-growth and second-growth Doug-

las-fir trees, respectively. BUCK has also been tested on a mechanized harvester, with a reported increase in recovery of 7.5 percent for the total value (Olsen et al. 1991).

A program being tested in the region, HW-BUCK, was primarily developed for optimal bucking northern hardwoods (Pickens et al. 1992). A study of 166 northern hardwood trees in Michigan indicated that the gross delivered values of optimal solutions were 39 to 55 percent higher than those chosen by buckers (Pickens et al. 1992). This program selects the optimal sequence of bucking for each stem, and optimization is a process whereby all possible combinations of logs and cull sections are evaluated (Haynes and Visser 2004). HW-BUCK and other computer programs are useful training tools for operators (Murphy et al. 2004) to gain bucking experience, which would improve value recovery through the hardwood log bucking process.

In central Appalachia, difficult terrain and hardwood species make harvesting and bucking more difficult. This could be due to the fact that hardwood species usually have more defects and sweep than softwoods and the variation of their values could be up to 50 percent by tree species, grade, dimensions, and mill. Ground-based harvesting is still the dominant system used in the region and bucking with a chainsaw or a sawbuck at a landing is the typical practice (Milauskas and Wang 2006, Wang et al. 2007). Most of the loggers are not well trained for bucking, and they make their bucking decisions based purely on their past experience or based on mill order requirements. These factors make bucking of hardwood species more difficult than bucking softwood species. A field survey of bucking practices in the central Appalachian region demonstrated the need for a three-dimensional (3D) bucking aid tool for training and field applications. Accordingly, the objectives of this study were to:

1.  develop an optimal tree stem bucking system for central Appalachian hardwood species with 3D visual simulation environment,

2.  examine contemporary hardwood log bucking practices in the field, and

3.  statistically evaluate the optimal bucking system in comparisons with manual bucking for a robust sample of tree stems.

## Optimal Bucking System Design

### System Structure

The optimal bucking system consists of three major components: data manipulation/storage, 3D modeling, and bucking optimization (**Fig. 1**), including the following functional requirements: data acquisition, data standardization, value calculation, bucking optimization, 3D environmental normalization, 3D image display, 3D image manipulation, and data storage and analysis. Component object model (COM) was employed to integrate the system that was designed using the principle of object-oriented programming (OOP). The system was programmed with 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 the 3D virtual bucking environment. Users can easily build a Windows compatible graphical user interface (GUI) and link the system to data objects through MFC and ActiveX controls. The 3D objects created can be rotated, scaled, and translated by performing OpenGL transformation. MFC's integrated development environment (IDE) facilitates the management of the bucking system during development process.

### Data Manipulation and Storage

ActiveX Data Object (ADO) was employed to retrieve data from and save bucking results to an Access database. ADO serves as a layer inserted between an object linking and embedding database (OLE DB) and the client, which enables indirect access to the OLE DB provider, and helps programmers easily use OLE DB without knowing the complexity behind the C++ class templates. ADO consists of seven basic objects: connection, recordset, command, error, field, property, and parameter, and they are related interactively.

The entity-relationship (ER) model for the optimal bucking system was implemented via Microsoft Access, including five entity types: stems for storing stem number and basic stem information; shapes for storing stem sweeps and diameters data at each 4-foot intersection; grades and prices for storing grading rules and price matrix; defects for storing defects data associated with each stem; and logs for bucking results (**Fig. 2**). Five relationships among these entity types were defined in the model, which reflect the interrelationships among these entities.

### 3D Stem Modeling

In order to provide the user with a realistic tree stem, 3D modeling techniques were used together with OpenGL primitives drawing functions to generate a 3D tree stem visualization which is composed of simple triangle strips filled with stem images, such as bark or the butt end image (**Fig. 3**). The user may select commands/functions to rotate the log and/or move the stem or logs around to facilitate visualization of the stem/logs
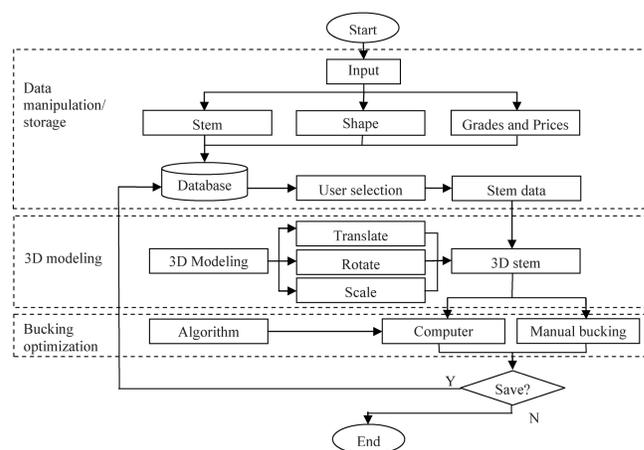


**Figure 1.** ~ *Architecture of the 3D optimal bucking system.*
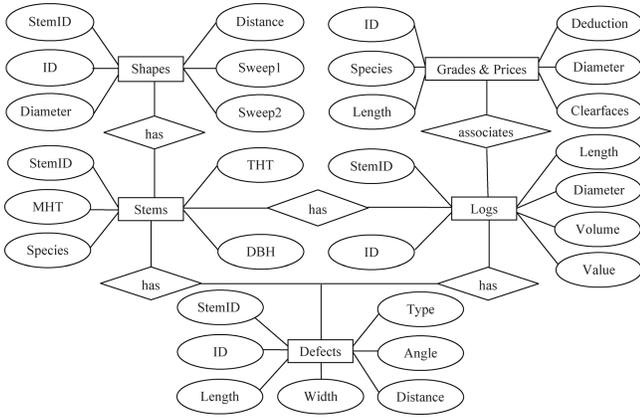
**Figure 2.** ~ *Diagram of the entity-relationship model for the 3D optimal bucking system.*
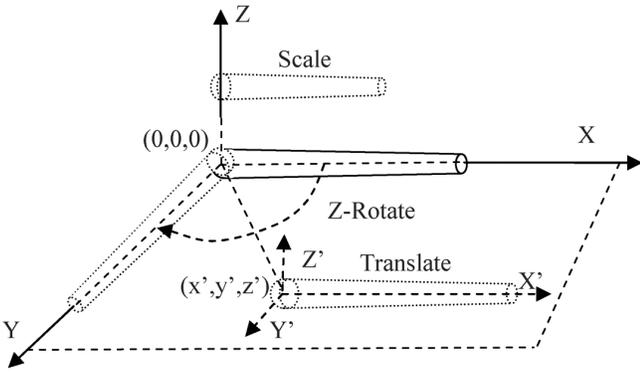


**Figure 3.** ~ *Diagram of the modeling transformation for a 3D tree stem.*

to better understand the stem's/log's superficial characteristics at different scales. Let the coordinates of the vertices of a triangle (basic unit for a tree stem) be $(x_1, y_1, z_1)$, $(x_2, y_2, z_2)$, $(x_3, y_3, z_3)$, respectively. Based on the generic matrix of rotation $\alpha$ angle around the x-axis (Woo et al. 2000), the coordinate matrix for this triangle after rotating by $\alpha$ degrees around the x-axis can be expressed as Equation [**1**]:

$$
\begin{cases}
R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\[2em]
\begin{bmatrix} x_1' & x_2' & x_3' \\ y_1' & y_2' & y_3' \\ z_1' & z_2' & z_3' \\ 1 & 1 & 1 \end{bmatrix} = R_x(a) \times \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \\ 1 & 1 & 1 \end{bmatrix} \\[2em]
TS' = R_x(\alpha) \times TS
\end{cases}
$$

[**1**]

where:

$TS$ = the coordinate matrix for one triangle strip on the surface of a tree stem before transformation and

$TS'$ = the coordinate matrix after transformation.

Similarly, the coordinate matrices for the triangle strip can be rotated around the y- and x-axes. The scale and translation are performed by calling glScale $(S_x, S_y, S_z)$ and glTranslate $(d_x, d_y, d_z)$ functions, respectively. $S_x, S_y, S_z$ are the scales to x, y, z coordinates of the stem while $d_x, d_y, dz$ are the units of distances to be translated along the x-axis, y-axis, and z-axis, respectively. The above transformation procedures can be applied to all of the triangle strips that form a 3D tree stem.

## Optimal Bucking Algorithm

A network analysis technique (Dykstra 1984, Näsburg 1985, Sessions 1988) was implemented in the system to generate the optimal bucking patterns. The Dijkstra's algorithm, known as the labeling algorithm, has been shown to be among the fastest algorithms available for solving the shortest path problem and is particularly well suited to being programmed on a computer (Dykstra 1984). The principle of the Dijkstra's algorithm for the single-source shortest path problem was adopted to find the longest path in the weighted, directed graph of tree stem bucking, which maintains a set of Y cutting points or nodes whose final longest-path weights from the origin $X_1$ have been already determined. The algorithm repeatedly selects the potential cutting point $X_i \in X-Y$ with the maximum longest path estimate, adds $X_i$ to Y, and relaxes all of the edges or arcs leaving $X_i$.

The efficiency or running time of Dijkstra's algorithm depends on how the maximum-priority queue of potential cutting points or nodes is implemented (Cormen et al. 2002). If the maximum-priority queue is maintained by taking advantage of the cutting points or nodes being numbered 1 to *n*, we can simply store these nodes associated with weights into a one-dimensional array with *n* elements. The running time of this algorithm consists of three parts:

1. searching the cutting point with maximum weight,

2. adding this point or node to the point set Y, and

3. removing this node from the set X–Y.

Since adding or removing a node from a point set takes constant time, $O(1)$, and searching a point takes $O(n)$, the efficiency or running time of the algorithm for *n* potential cutting points along a tree stem can be expressed as:

$$T(n) = [2O(1) + O(n)] \times n$$

$$= O(n^2)$$

[**2**]

where:

$O(n^2)$ = the asymptotic upper bound of $n^2$ and

$O(1)$ = the constant time.

## Bucking System Implementation

### Scaling, Grading Rules, and Price Matrix

The two most commonly used log rules in the region, i.e., Doyle and International 1/4-inch log rules, were implemented in the system (Avery and Burkhart 2001). Although the bucking system uses both International 1/4 and Doyle rules, the results in this paper reflect Doyle scale. Mail surveys of log grading rules and price matrixes were sent to ten saw mills in the central Appalachian region (**Tables 1 and 2**). Logs are usually classified as veneer, prime, select, common, and below common class according to size, species, position in tree stem, and defects. Although there are grade variations among different sawmills, the minimum 2.44 m (8 ft) length and 25.4 cm (10 in) small-end diameter requirements are the same for saw and veneer logs in all sawmills. The grading rules and corresponding price matrix were set as the default rules and prices in the optimal bucking system.

For all of the grades, a 7.62-cm (3-in) trim allowance is required. Log length is rounded down to the nearest even foot length for all species except yellow-poplar in which log length is rounded down to the nearest foot, with the maximum log length being 4.87 m (16 ft).

A scale deduction of 2.54 cm in diameter is made for every 7.62 cm sweep or for every 7.62 cm diameter hole or rot in the end of the log. Logs that have more than 50 percent total scale deduction are considered cull. Log diameters are rounded down to the nearest small integer diameter for volume calculation in FPS (foot-pound-second) system, i.e., a log with diameter of 33.5 cm (13.2 in) or 34.54 cm (13.6 in) is rounded to 33 cm (13 in). Log lengths are also rounded to the nearest acceptable grade length plus 7.62 cm trim allowance.

### 3D Bucking Process

The bucking process was implemented via a 3D-based Windows dialog box with four tab controls labeled as stems, defects, shapes, and grades. The stem tab is used to display all stem data saved in the database. A structured query language (SQL) query was employed to view defects, shapes, and grades associated with a selected stem by clicking one of the other three tabs. This program is currently capable of conducting analysis in U.S. customary units of measurements and the images of the program display values in those units. The equivalent metric units are used to show the results of the analysis.

Once a tree stem is selected, its 3D image can then be generated (**Fig. 4a**). The 3D display dialog consists of three major sections: display area (top area), information area (bottom left area), and command area (bottom right area). The display area is for displaying a 3D stem image and viewing bucking results of a selected stem. Text in the upper left corner of the display area

**Table 1.** ~ *Log grading rules.*

| Grade | Minimum diameter | Minimum length | Species | Log position | No. of clearfaces |
|---|---|---|---|---|---|
| | (cm) | (m) | | | |
| Veneer | 41 | 2.44 | White oak, red oak, yellow-poplar | Butt | 4 |
| Prime | 30 | 2.44 | Any | Any | 4 |
| Select | 30 | 2.44 | Any | Any | 3 |
| Common | 30 | 2.44 | Any | Any | 2 |
| Below common | 25 | 2.44 | Any | Any | 1 |

**Table 2.** ~ *Log price matrix by species, grade, and dimension ($/m³).*

| Log grade | Log dimension | | Species | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Diameter | Length | Chestnut oak | White oak | Red oak | Scarlet oak | Black oak | Yellow-poplar |
| | (cm) | (m) | | | | | | |
| Veneer (no defect) | ≥ 41 | 2 to 5 | -- | 240 | 261 | -- | -- | 120 |
| Prime (4 clearfaces) | ≥ 41 | 4 to 5 | 109 | 131 | 196 | 87 | 153 | 87 |
| | | 3 to 4 | 98 | 103 | 174 | 71 | 131 | 87 |
| | ≥ 30 | 3 to 5 | 76 | 82 | 120 | 65 | 87 | 76 |
| | | 2 | 65 | 71 | 98 | 60 | 71 | 76 |
| Select (3 clearfaces) | ≥ 41 | 4 to 5 | 98 | 98 | 174 | 76 | 131 | 54 |
| | | 3 to 4 | 87 | 87 | 136 | 65 | 87 | 54 |
| | ≥ 30 | 3 to 5 | 65 | 65 | 98 | 60 | 65 | 54 |
| | | 2 | 60 | 60 | 76 | 54 | 60 | 54 |
| Common (2 clearfaces) | ≥ 41 | 4 to 5 | 87 | 87 | 120 | 65 | 87 | 44 |
| | | 3 to 4 | 76 | 76 | 98 | 60 | 65 | 44 |
| | ≥ 30 | 3 to 5 | 60 | 60 | 76 | 54 | 60 | 44 |
| | | 2 | 54 | 54 | 54 | 49 | 54 | 44 |
| Below common (1 clearface) | ≥ 41 | 4 to 5 | 76 | 76 | 93 | 60 | 65 | 27 |
| | | 3 to 4 | 65 | 65 | 76 | 54 | 60 | 27 |
| | ≥ 25 | 3 to 5 | 54 | 54 | 54 | 54 | 54 | 27 |
| | | 2 | 49 | 49 | 49 | 49 | 49 | 27 |
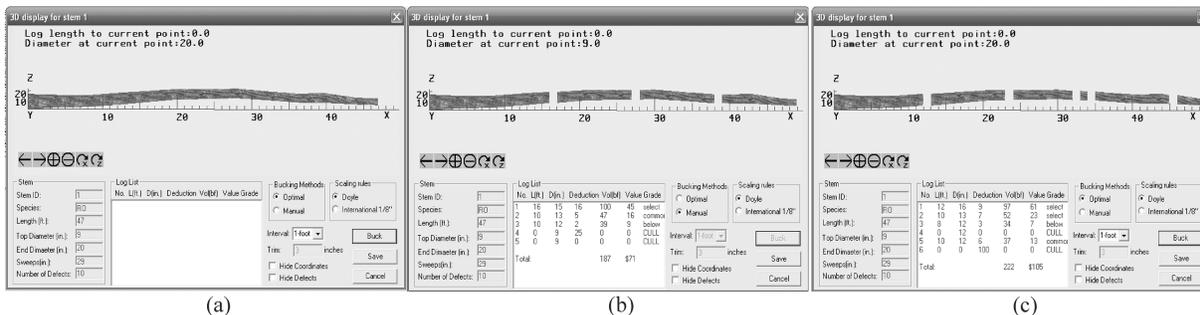
**Figure 4.** ~ *(a) 3D bucking system for a tree-stem with (b) manual bucking solution and (c) optimal solution.*

is used to update inside bark diameter and length from a previous cut to the current cut position. In the currently displayed image case, the saw is at the butt end of the stem and the associated inside bark diameter of this stem is 20 inches (50.8 cm). Six command buttons in the display area (i.e., left move, right move, zoom in, zoom out, rotate along x-axis, and rotate along z-axis) are used for implementing zoom, projection, and perspective view functions, which allows the user to have a better understanding of the stem defects and shape while performing manual bucking. Defects are represented as red rectangles with their actual sizes and locations on the stem, which can be either measured in the field or entered by the user.

The information area shows the basic information for a selected stem and the detailed bucking results. Options are provided to users for log rules and bucking methods in the command area. When the user selects optimal bucking, a stage interval should be chosen from the dropdown list. If manual bucking is selected, this drop list for stage interval selection is disabled. Log volume is calculated based on the selected log rule: Doyle or International 1/4-inch. On the bottom left of the command area, there are two check boxes for displaying or hiding coordinates and defect data. Three command buttons buck, save, and cancel are used for bucking, saving bucking results, and closing the display dialog, respectively.

For example in **Figure 4b**, stem 1 was recorded as red oak in the field and was manually bucked into four logs having lengths of one 16-foot (4.87 m) and three 10-foot (3.05 m) sections. The total log value for stem 1 is $71 and the total volume of logs bucked from stem 1 is 187 board feet (BF) (0.44 m³). The log length for the fourth log in the log list is 0 instead because this log is not a grade log. Accordingly, stem 1 was optimally bucked using a stage interval of 1-foot (0.30 m) (**Fig. 4c**). The optimal bucking yielded a total log value of $105 and total log volume of 222 BF (0.52 m³) for this stem which included four logs with lengths of 12 feet (3.66 m), 10 feet (3.05 m), 8 feet (2.44 m), and 10 feet (3.05 m). The user has the option of saving or performing alternative bucking processes using different methods or stage intervals.

### System Applications

### Sites and Stem Data

Field measurements were conducted to collect stem dimension, shapes, defects, and manual bucking results. A total sample of 264 stems were measured at five sites located throughout West Virginia (Wang et al. in press). Each site had only one working crew performing the operations during the field measurements. Two manual and three mechanized harvesting operations were investigated during the study. Bucking, however, was performed by one bucker per site using a bucksaw. The bucker's experience varied from 14 to 20 years.

All of the stems sampled were measured with diameter calipers and linear tape. Diameters were measured at 1.22-m (4-ft) intervals along a tree stem. Total length and merchantable length were also measured for a stem. Each defect was recorded for type, location, and size. Defect types included bark distortion (BD), bulge (BU), split (SL), stain (ST), and hole (HO). BD, BU, and ST are grading defects, which can cause lower log grades. SL and HO are scaling defects, which can cause volume deductions. To measure sweep, two sticks were nailed on both ends of the stem in the same direction and a string was tightened to these two sticks at the same height from the surface of the stem. This height was called the base height. At each measured interval, distance between the string and the surface of the stem was measured and subtracted from the base height accordingly. These measurements were replicated after turning the string 90° from its previous direction. All data were recorded on spread sheets and were then saved to a database.

Six hardwood species were observed during the field studies. They were black oak (*Quercus velutina*), chestnut oak (*Quercus prinus*), red oak (*Quercus rubra*), white oak (*Quercus alba*), scarlet oak (*Quercus coccinea*), and yellow-poplar (*Liriodendron tulipifera*).

Outside bark diameters were converted into inside bark diameters based on a constant ratio for each species for volume calculation. The ratios used to make these conversions were 0.90 for yellow-poplar, 0.929 for red oak, 0.937 for white oak, 0.925 for black oak, 0.909 for chestnut oak, and 0.939 for scarlet oak (Harrison et al. 1986).

The number of trees measured at each site ranged from 29 to 60. Yellow-poplar accounted for 54.92 percent and the oak species accounted for 45.08 percent of the total trees sampled (**Table 3**). Among these 264 tree stems, diameter at breast height (DBH) varied from 29.97 to 89.66 cm with an average of 45.21 cm. Merchantable height (MHT) ranged from 9.63 to 29.80 m with an average of 17.13 m. The yellow-poplar stems were longer on average compared to the oaks. The sizes of the stems var-

**Table 3.** ~ *Stem size (diameter at breast height [DBH] and merchantable height [MHT]) and defects by species.*

| Species | No. of stems | Stem DBH (cm) | | | | Stem MHT (m) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Standard deviation | Min. | Max. | Mean | Standard deviation | Min. | Max. |
| Yellow-poplar | 145 | 45.97 | 9.40 | 30.32 | 89.66 | 19.45 | 4.15 | 10.55 | 29.87 |
| Oaks | 119 | 44.20 | 8.38 | 29.97 | 67.87 | 14.33 | 2.96 | 9.63 | 20.70 |
| | | No. of stem defects | | | | Size of defects (cm) | | | |
| | | Mean | SD | Min. | Max. | Mean | SD | Min. | Max. |
| Yellow-poplar | 145 | 8.28 | 4.52 | 1 | 27 | 13.87 | 5.05 | 5.08 | 33.02 |
| Oaks | 119 | 8.33 | 3.95 | 1 | 23 | 15.09 | 8.10 | 5.08 | 81.28 |

**Table 4.** ~ *Value and volume gains of optimal bucking compared to manual bucking.*

| Item | Manual bucking | Stage interval for optimal bucking (cm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2.54 | | 10.16 | | 30.48 | | 121.92 | |
| | | Value | % change | Value | % change | Value | % change | Value | % change |
| Value of logs/stem ($) | 69.43 | 95.61 | 37.69 | 95.31 | 37.28 | 94.65 | 36.32 | 91.23 | 31.39 |
| Volume of logs/stem (m$^3$) | 0.475 | 0.551 | 16.03 | 0.553 | 16.24 | 0.554 | 16.6 | 0.552 | 16.13 |
| Value of logs/unit volume ($/m$^3$) | 146.17 | 0.41 | 18.67 | 172.66 | 18.09 | 170.85 | 16.92 | 165.27 | 13.13 |
| Utilization rate (%) | 71.39 | 79.19 | 10.93 | 79.23 | 10.98 | 79.41 | 11.23 | 78.61 | 10.11 |

ied among species. Defects statistics for each species class were very similar (**Table 3**). The oak species, however, had slightly more and slightly larger defects on average.

### System Execution Time

All optimal bucking experiments using this 3D system were performed on a desktop PC built with Pentium IV 3.60 GHz CPU, 1.0 GB RAM, 80 GB hard drive under Microsoft Windows XP platform. The average running time for 121.92 cm, 30.48 cm, 10.16 cm, and 2.54 cm stage intervals were 15.00, 189.00, 1,620.00 and 25,525.23 milliseconds, respectively. The execution time approximated a near to negative exponential relationship to stage interval. When stage interval decreased from 121.92 to 30.48 cm, 10.16 cm, and 2.54 cm, system execution time increased 13, 108, and 1,702 times, respectively. Factors such as species, DBH, MHT, stage interval, number of defects, and size of defect can also influence system execution time. At $\alpha$ = 0.05 level, stage interval ($p < 0.0001$) and number of defects ($p = 0.0081$) had a significant effect on the system execution time.

### Value and Volume of Logs Bucked Per Stem

Logs bucked using different bucking methods were classified into different length and diameter classes based on log grading length and small-end diameter. Logs with 25.4 cm (10 in) or 30.48 cm (12 in) grading diameter accounted for about 30 percent of the total number of logs bucked, respectively, while logs with grading diameter of 35.56 cm (14 in) or 40.64 cm (16 in) accounted for about 20 percent of the total, respectively (**Fig. 5a**).

Optimal bucking with different stage intervals yielded similar log length distributions. Logs of 2.44 m (8 ft) obtained using manual bucking accounted for 26.94 percent of the total logs bucked, while logs with the same length by optimal bucking were

(a)

(b)
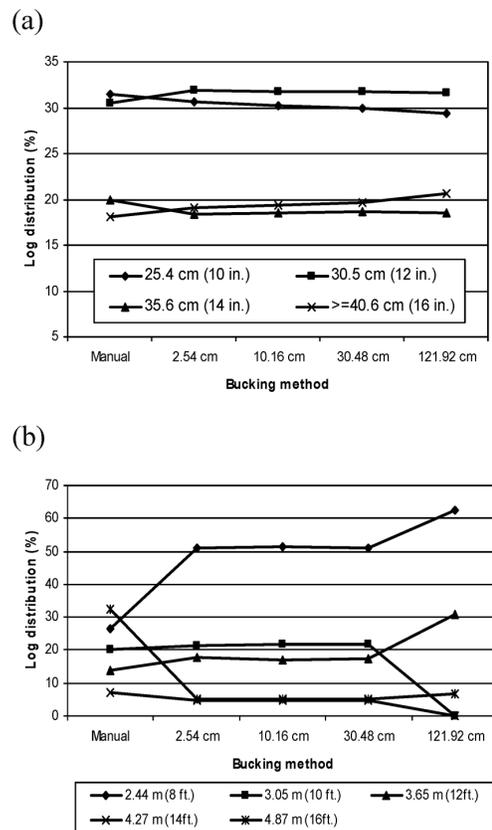
**Figure 5.** ~ *Log distributions as obtained from manual bucking and optimal bucking of different stage intervals shown in percentage by (a) scaling diameter and (b) scaling length.*

between 50.66 percent and 62.60 percent. Logs of 4.87 m (16 ft) logs obtained using manual bucking accounted for 32 percent of the total, while logs of the same length were between 5.18 percent and 6.56 percent by optimal bucking (**Fig. 5b**). Compared to

manual bucking, optimal bucking produced a higher percentage of short logs and a smaller percentage of long logs.

The average value and volume of logs bucked per stem by manual bucking was $69.43 and 0.475 m³ per stem. Optimal bucking generated logs resulting in an increase in the range from 31.39 to 37.69 percent for average stem value compared to manual bucking (**Table 4**). The average volume of logs per stem by optimal bucking ranged from 16.03 to 16.60 percent higher than that by manual bucking. The stem value/m³ from computer-aided optimal bucking with different stage intervals also increased from 13.13 to 18.67 percent in comparison with manual bucking, which simply indicated that optimal bucking could produce higher grade logs than manual bucking. The tree stem utilization rate is defined as the total length of logs bucked from a stem divided by the stem's MHT. For manual bucking, the average utilization rate was 71.39 percent, which was about 8 percent lower than that of optimal bucking. The higher tree stem utilization rates with optimal bucking consequently resulted in the increase of average value and volume of logs bucked per stem compared to manual bucking.

When optimally bucking, value gain of logs bucked per stem generally decreases with the increase of stage interval (**Fig. 6**). In comparisons with manual bucking, the percentage changes of stem value gains were further grouped by DBH classes (38 cm for < 38 cm, 50 for ≥ 38 and < 50 cm, and 63 cm for ≥ 50 cm). The general trend was that the larger DBH a stem has, the higher percentage of value increase is obtained compared to manual bucking (**Fig. 6a**). Optimal bucking yielded a higher percentage of value per stem for stems with DBH less than 38 cm (15 in) because of their lower base value yielded by manual bucking. Similarly, the greater the MHT, the higher value per stem and percentage of value per stem increase could be obtained by optimal bucking. The percentage changes of stem value gains by optimal bucking were classified into four MHT classes: 15 m (< 15 m), 18 m (≥ 15 and < 18 m), 21 m (≥18 and < 21 m), and 24 m (≥ 21 m). For example, when optimally bucking tree stems with MHT more than 21 m (70 ft), the average stem value increase could be more than 40 percent, compared to manual bucking. For tree stems with MHT of 15 m or less, about 30-percent increase of average stem value could be achieved with optimal bucking over manual bucking (**Fig. 6b**).

Stem value increase by optimal bucking also varied by species (**Fig. 6c**). Both oaks and yellow-poplar are the major merchantable species in this region. Oaks are the species with higher per unit volume value and have more defects and irregular shapes in comparison with yellow-poplar. Buckers usually pay more attention when bucking oaks than when bucking less valuable and more uniform yellow-poplar. When comparing



(a)                                        (b)

(c)                                        (d)
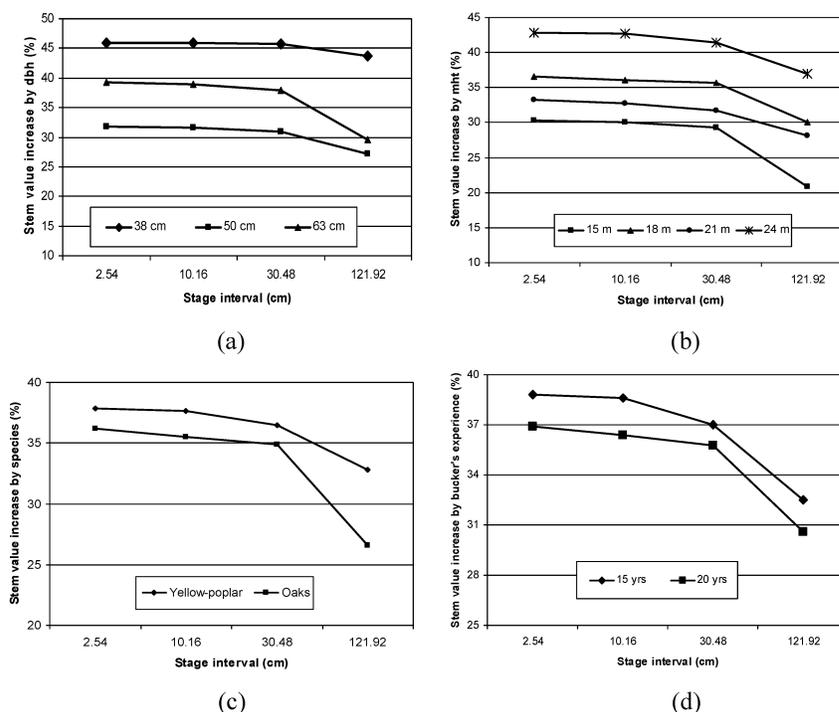
**Figure 6.** ~ *Compared to manual bucking, percentage changes of stem value gains: (a) by diameter (DBH) class; (b) by MHT class; (c) by species; and (d) by buckers' experience as obtained from different stage intervals in optimal bucking.*

optimal bucking with manual bucking based on the experience of the bucker, stem value gain by optimal bucking decreased with the increase of buckers' experience (15 yr for the buckers with ≤ 15 yr of experience, and 20 yr for >15 yr of experience) (**Fig. 6d**). Stem value gains by optimal bucking ranged from 32 to 39 percent for the 15-year group while the stem value gains were between 31 percent and 37 percent for the 20-year group.

One tailed t-test was employed to test whether the bucking results were significantly different between manual bucking and computer optimal bucking. The null hypothesis is that there is no significant difference between computer-aided optimal bucking and manual bucking. The alternative hypothesis is that optimal bucking can significantly increase average stem value, volume of logs per stem, value/m³, or utilization rate. Under equal variance assumption, the results indicated that at $\alpha$ = 0.05 level, optimal bucking could significantly increase the average value, volume of logs bucked per stem, value/m³, and utilization rate compared to manual bucking.

Factors that affect stem value, volume of logs per stem, and value/m³ of manual bucking results include species, DBH, MHT, bucker's experience, number of defects, size of defects, and interactions among species and DBH, species and MHT, species and size of defects, DBH and MHT, and MHT and number of defects. The generic general linear model (GLM) for estimating stem value, stem volume, or value/m³ by manual bucking can be expressed as:

$$V_{ijklmno} = \mu + SP_i + D_j + H_k + BE_l + ND_m + SD_n + SP_i * D_j + SP_i * H_k + SP_i * SD_n + D_j * H_k + H_k * ND_m + \varepsilon_{ijklmno} \quad [\mathbf{3}]$$

where:

$V_{ijklmno}$ = the $o^{th}$ observation of the stem value, volume of logs bucked per stem by manual bucking, or value/m$^3$,

$\mu$ = mean of stem value, stem volume or value/m$^3$,

$SP_i$ = effect of the $i^{th}$ species ($i = 1,2$),

$D_j$ = effect of the $j^{th}$ dbh ($j = 1,2,...,4$),

$H_k$ = represents effect of the $k^{th}$ MHT ($k = 1,2,...,5$),

$BE_l$ = effect of the $l^{th}$ bucker's experience ($l = 1,2$),

$ND_m$ = effect of the $m^{th}$ number of defects ($m = 1,2,...,4$),

$SD_n$ = effect of the $n^{th}$ average size of defects ($n = 1,2,3$), and

$\varepsilon_{ijklmno}$ = an error component that represents random variability.

For manual bucking, value of logs bucked per stem was significantly different among DBH classes (F = 100.26; df = 3,263; $p$ = 0.0001), bucker's experience (F = 24.04; df = 1,263; $p$ = 0.0001), and the interaction among DBH classes and MHT classes (F = 2.56; df = 10,263; $p$ = 0.0060) (**Table 5**). Volume of logs bucked per stem by manual bucking was significantly affected by DBH classes (F = 103.88; df = 3, 263; $p$ = 0.0001), MHT classes (F = 3.12; df = 4, 263; $p$ = 0.0160), bucker's experience (F = 7.88; df = 1, 263; $p$ = 0.0054), and interaction among species and DBH classes (F = 3.05; df = 3, 263; $p$ = 0.0295). Value/m$^3$ per stem by manual bucking also differed significantly between species classes (F = 14.51; df = 1,263; $p$ = 0.0002), among DBH classes (F = 17.56; df = 3,263; $p$ = 0.0001), between bucker's experience (F = 136.54; df = 1,263; $p$ = 0.0001), among number of defects (F = 9.11; df = 3,263; $p$ = 0.0001), and interaction between DBH classes and MHT classes (F = 2.71; df = 10,263; $p$ = 0.0037).

For optimal bucking, value, volume of logs bucked per stem, and value/m$^3$ could be influenced by species, DBH, MHT, stage interval, number of defects, size of defects, and interactions among species and DBH, species and MHT, species and size of defects, DBH and MHT, and MHT and number of defects. The generic GLM for estimating stem value, volume of logs per stem, or value per unit volume by optimal bucking can be expressed as:

$$V_{ijklmno} = \mu + SP_i + D_j + H_k + S_l + ND_m + SD_n + SP_i * D_j + SP_i * H_k + SP_i * SD_n + D_j * H_k + H_k * ND_m + ND_m + \varepsilon_{ijklmno}$$

[**4**]

where:

$V_{ijklmno}$ = the $o^{th}$ observation of stem value, volume of logs bucked per stem, or value/m$^3$,

$\mu$ = mean of stem value, stem volume of value/m$^3$,

$SP_i$ = effect of the $i^{th}$ species ($i = 1,2$),

**Table 5**. ~ *Means and significance levels of bucking results by manual bucking.*[a]

|  | Value/stem | Volume of logs/stem | Value/unit volume |
|---|---|---|---|
|  | ($) | (m$^3$) | ($/m$^3$) |
| DBH (cm) |  |  |  |
| < 38.1 | 14.46 d | 0.15 d | 98.38 c |
| 38.1 to 50.8 | 54.77 c | 0.42 c | 130.08 b |
| 50.8 to 63.5 | 139.25 b | 0.81 b | 172.55 a |
| ≥ 63.5 | 266.01 a | 1.58 a | 168.47 a |
| MHT (m) |  |  |  |
| < 12. 19 | 27.20 d | 0.21 e | 130.75 b |
| 12.19 to 15.24 | 49.31 c | 0.34 d | 145.01 ab |
| 15.24 to 18.29 | 75.30 b | 0.48 c | 157.54 a |
| 18.29 to 21.34 | 81.59 b | 0.56 b | 145.43 ab |
| ≥ 21.34 | 100.70 a | 0.72 a | 139.48 b |
| Species |  |  |  |
| Yellow-poplar | 76.09 a | 0.56 a | 135.39 b |
| Oaks | 61.32 b | 0.37 b | 165.74 a |
| Number of defects |  |  |  |
| < 5 | 78.10 ab | 0.49 b | 159.06 a |
| 5 to 10 | 58.22 c | 0.40 c | 147.39 ab |
| 10 to 15 | 88.70 a | 0.62 a | 142.84 a |
| ≥ 15 | 71.90 bc | 0.56 ab | 129.08 b |
| Size of defects (cm) |  |  |  |
| 12.7 | 37.21 c | 0.32 b | 116.28 b |
| 12.7 to 25.4 | 90.54 b | 0.58 a | 156.10 a |
| ≥ 25.4 | 111.37 a | 0.61 a | 182.27 a |
| Experience (years) |  |  |  |
| 15 | 62.32 b | 0.44 b | 141.96 b |
| 20 | 83.66 a | 0.55 a | 153.50 a |

[a] Means with the same letter in a column of the same group are not significantly different at the 5-percent level with Duncan's Multiple-Range Test.

$D_j$ = effect of the $j^{th}$ DBH class ($j = 1,2,...,4$),

$H_k$ = effect of the $k^{th}$ MHT class ($k = 1,2,...,5$),

$SI_l$ = effect of the $l^{th}$ stage interval ($l = 1,2,...,4$),

$ND_m$ = effect of the $m^{th}$ number of defects ($m = 1,2,...4$),

$SD_n$ = effect of the $n^{th}$ average size of defects ($n = 1,2,3$), and

$\varepsilon_{ijklmno}$ = represents an error component that represents random variability.

Value of bucked logs per stem by optimal bucking was significantly affected by DBH classes (F = 439.51; df = 3,1055; $p$ = 0.0001), MHT classes (F = 7.90; df = 4,1055; $p$ = 0.0001), number of defects (F = 4.79; df = 3,1055; $p$ = 0.0026), and interactions between DBH classes and MHT classes (F = 18.91; df = 10,1055; $p$ = 0.0001), species and size of defects (F = 6.05; df = 2,1055; $p$ = 0.0024), and MHT classes and number of defects (F = 4.89; df = 11,1055; $p$ = 0.0001) (**Table 6**). Volume of bucked logs per stem by optimal bucking was significantly different among DBH classes (F = 446.32; df = 3,1055; $p$ = 0.0001), MHT classes (F = 17.90; df = 4,1055; $p$ = 0.0001), number of defects (F = 7.92; df = 3,1055; $p$ = 0.0001), interactions between DBH classes and MHT

**Table 6.** ~ *Means and significance levels of bucking results by optimal bucking.[a]*

| | Value/stem | Volume of logs/stem | Value/unit volume |
|---|---|---|---|
| | ($) | (m³) | ($/m³) |
| DBH (cm) | | | |
| < 15 | 20.93 d | 0.199 d | 105.41 d |
| 15 to 20 | 71.28 c | 0.492 c | 144.81 c |
| 20 to 25 | 191.36 b | 0.916 b | 208.91 b |
| ≥ 25 | 287.63 a | 1.753 a | 164.09 a |
| MHT (m) | | | |
| < 40 | 34.99 d | 0.244 e | 143.30 c |
| 40 to 50 | 64.11 c | 0.386 d | 166.22 b |
| 50 to 60 | 103.53 b | 0.549 c | 188.48 a |
| 60 to 70 | 108.00 b | 0.650 b | 166.10 b |
| ≥ 70 | 142.81 a | 0.627 a | 227.96 bc |
| Species | | | |
| Yellow-poplar | 103.78 a | 0.663 a | 156.52 b |
| Oaks | 82.53 b | 0.418 b | 197.40 a |
| Number of defects | | | |
| < 5 | 102.00 b | 0.562 c | 181.52 a |
| 5 to 10 | 78.22 c | 0.462 d | 169.31 b |
| 10 to 15 | 124.68 a | 0.722 a | 172.80 a |
| ≥ 15 | 99.09 b | 0.655 b | 151.34 b |
| Size of defects (cm) | | | |
| < 12.7 | 50.65 b | 50.65 b | 0.389 b |
| 12.7 to 25.4 | 123.30 a | 123.30 a | 0.665 a |
| ≥ 25.4 | 141.54 a | 141.54 a | 0.699 a |
| Stage interval (cm) | | | |
| 2.54 | 95.60 a | 0.551 a | 173.51 a |
| 10.16 | 95.32 a | 0.553 a | 172.52 a |
| 30.48 | 94.65 a | 0.554 a | 170.79 a |
| 121.92 | 91.23 a | 0.552 a | 165.26 a |

[a] Means with the same letter in a column of the same group are not significantly different at the 5-percent level with Duncan's Multiple-Range Test.

classes (F = 10.45; df = 10,1055; $p$ = 0.0001), species and DBH classes (F = 10.17; df = 3,1055; $p$ = 0.0001), species and MHT classes (F = 4.96; df = 3,1055; $p$ = 0.0020), and MHT classes and number of defects (F = 7.01; df = 11,1055; $p$ = 0.0001). Value/m³ per stem yielded by optimal bucking was significantly affected by species (F = 35.42; df = 1,1055; $p$ = 0.0001), DBH classes (F = 125.65; df = 3,1055; $p$ = 0.0001), MHT classes (F = 10.90; df = 4,1055; $p$ = 0.0001), number of defects (F = 12.13; df = 3,1055; $p$ = 0.0001), interactions between species and size of defects (F = 4.37; df = 2,1055; $p$ = 0.0129), DBH classes and MHT classes (F = 21.55; df = 10,1055; $p$ = 0.0001), species and DBH classes (F =18.64; df = 3,1105; $p$ = 0.0001), species and MHT classes (F = 4.11; df = 3,1055; $p$ = 0.0066), and MHT classes and number of defects (F = 4.54; df = 11,1055; $p$ = 0.0001). As stage interval decreased from 121.92 cm (4 ft) to 2.54 cm (1 in), value of logs bucked per stem, volume of logs bucked per stem, and value of logs per m³ increased, but these increases were not statistically significant among stage intervals (F = 0.50; df = 3,1055; $p$ = 0.6802, F = 0.01; df = 3,1055; $p$ = 0.9983, and F = 1.49; df = 3,1055; $p$ = 0.2156).

## Discussion and Conclusions

The optimal bucking system developed in this study adopted component object modeling (COM) techniques with objected-oriented programming and 3D graphs. The system can be installed on a handheld field PC or a desktop PC located in a centralized log yard to improve central Appalachian hardwood utilization. It can also be used as a training tool for students or loggers.

A network analysis algorithm was employed to achieve the maximum total log value per stem. The selection of a stage interval is a key factor that could affect the system execution time and final bucking results. The smaller the stage interval, the longer it will take to achieve the optimal bucking solution. Balancing the time needed to find the optimal results using an appropriate stage interval could enhance the application of this bucking system.

Applying this system to a sample of 264 tree stems of six hardwood species and comparing the results with manual bucking, optimal bucking demonstrated that it could increase individual stem value by 31.39 to 37.69 percent. The total volume of logs bucked per stem could be increased by 16.03 to 16.60 percent. Value per unit volume and stem utilization rate were also increased by 13.13 to 18.67 percent and 10.11 to 11.23 percent, respectively. Value and volume of logs bucked per stem by optimal bucking were generally increased as the stage interval decreased. But, they were not significantly affected by the stage interval. System execution time by optimal bucking was significantly affected by stage interval and number of defects. When stage interval decreased from 1.22 m, 0.30 m, 10.16 cm, and 2.54 cm, system execution time increased 13, 108, and 1,702 times, respectively.

Results of t-tests (α = 0.05) indicated that value per stem, volume per stem, and value/m³ or utilization rate were significantly increased by using optimal bucking in comparisons with manual bucking. Increased volume and utilization rate per stem showed that optimal bucking could use tree stems more efficiently. Optimal bucking yielded higher value per unit volume than manual bucking, which indicated that optimal bucking could produce higher grade logs than manual bucking.

Analysis of variance (ANOVA) indicated that manual bucking was significantly affected by the experience of the bucker and stem dimension. The results also indicated that DBH classes, bucker's experience, and interaction among DBH classes and MHT classes have significant effects on the value of bucked logs per stem and value per unit volume. The DBH classes and MHT classes, bucker's experience, and interaction among DBH classes and MHT classes could significantly affect volume of bucked logs per stem. Value/m³ was significantly affected by species, DBH classes, bucker's experience, number of defects, and interaction between DBH classes and MHT classes.

In addition to stem dimension, the number of defects per stem and average size of defects also significantly affected the value of logs bucked per stem, volume per stem, and value/m³ by optimal bucking. This implies that computer-based optimal bucking checks the detailed defects information before yielding

a bucking solution. For example, **Figure 4c** shows a cull chunk between logs 3 and 4 where some defect was bucked out of the stem. When comparing optimal bucking with manual bucking by DBH and MHT classes, it showed that a higher percentage of value increase is achieved for logs with larger DBH and higher MHT. This indicated that optimal bucking could gain more value on a larger tree stem.

Optimal bucking could slightly increase the percentage of stem value when bucking yellow-poplar compared with oaks. This is probably due to the presence of defects and irregularities in the shape of stems of oaks. Additional species, specifically higher value species, should be tested using the system. All of the buckers observed in this study had 14 to 20 years of working experience. Compared to manual bucking results, the percentage of stem value increase by optimal bucking decreased gradually as the buckers' experience increased from 14 to 20 years.

The stem shape data were measured at outside bark diameter. Outside bark diameters are currently converted to inside bark diameter for each species using a constant ratio. More accurate shape estimates should be used in the system to achieve more accurate optimal bucking results. Currently, the shapes and defects data need to be measured manually in the field, which is time-consuming and tedious. Using electronic devices to automatically measure and collect these data will facilitate this optimal bucking system. This system should be utilized in the specific region in which it was developed. It is necessary to collect data for a particular region in order to account for region specific grades, prices, and mill requirements. Mill requirements must be considered when performing bucking operations; however, producing results from an optimal bucking program may help mills in developing their specifications based on the species and regional data.

We used a 3D mathematical programming approach to solve the problem of optimally bucking hardwood tree stems. Although we only considered 264 actual tree stems, contemporary bucking practices from a field investigation of five logging companies, field bucker's experience, contemporary log grades and prices, actual field bucked stems, two log rules, four tree species, and multiple variable interactions, the results should not be inferred generally. But, the results illustrate the benefits of using optimal bucking techniques. The major 3D benefits are that the log defects and sweep can be visualized and bucking can take place to mitigate/minimize the impact of such because field buckers generally do not consider or cannot see all of these defects and sweep.

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