Analysis of Red Oak Timber Defects and Associated Internal Defect Area for the Generation of Simulated Logs

by

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Abstract

Log sawing simulation computer programs can be a valuable tool for training sawyers as well as for testing different sawing patterns. Most available simulation programs rely on databases from which to draw logs and can be very costly and time-consuming to develop. In this study, a computer program was developed that can accurately generate random, artificial logs and serve as an alternative to using a log database. One major advantage of using such a program is that every log generated is unique, whereas a database is finite.

Real log and external defect data was obtained from the Forest Service Northeastern Research Station in Princeton, West Virginia for red oak (*Quercus rubra*, L.) logs. These data were analyzed to determine distributions for log and external defect attributes, and the information was used in the program to assure realistic log generation. An attempt was made to relate the external defect attributes to internal defect characteristics such as volume, depth, and angle. CT scanning was used to obtain internal information for the five most common defect types according to the Princeton log data. Results indicate that external indicators have the potential to be good predictors for internal defect volume. Tests performed to determine whether a significant amount of variation in volume was explained by the predictor variables proved significant for all defect types. Corresponding R^2 values ranged from 0.39 to 0.93. External indicators contributed little to the explanation of variation in the other dependent variables. Additional predictor variables should be tested to determine if further variation could be explained.

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1 Introduction

In the fields of forestry and forest products, information on the external characteristics of logs can be invaluable. Whether for a timber consultant appraising the value of timber, a log buyer estimating the value of logs, or a sawyer bucking hardwood timber, understanding the relationship between log grades and associated defects can greatly improve job performance. For example, a sawyer bucking timber can increase log grade, and ultimately value, by sawing logs that will produce the greatest number of long, clear-face cuttings. If the sawyer knows that the majority of defects on Grade 1 logs are located near the ends, he/she can use this information to more efficiently produce higher-grade logs. Likewise, a log or tree grader can improve speed and accuracy by first understanding the common characteristics shared by logs of the same grade.

Similar to the understanding of external defect characteristics, the ability to predict internal log information could potentially improve forestry and sawmill operations significantly. For example, if a sawmill headrig operator could accurately estimate internal defect information prior to opening the log, he/she could orient the log so as to maximize lumber value. Harless *et al*. (1991) showed that log orientation prior to sawing could have a significant effect on the value of lumber produced. Another area where this information would be invaluable is in the veneer industry. Since the size and depth of internal defects directly affects the volume of clear-face veneer, the veneer log buyer could better assess log value. To date, no research has been published that shows an accurate relationship between the size and shape of external defect indicators and internal defect attributes in red oak logs.

The ultimate goal of this research project was to develop a computer spreadsheet program to accurately generate artificial red oak log data based on the characteristics of real logs. Red oak was chosen for analysis because of its wide distribution in the eastern United States and its use in a variety of products from pallets to furniture. Information obtained from the analysis of external defect and log characteristics as well as significant information on the internal/external defect relationship was incorporated into the program to ensure the validity of generated logs.

The generated log data can be used as input into log-sawing simulation programs that require accurate and detailed log feature information.

2 Objectives

2.1 Determine Relationship Between Log Characteristics and External Defect Characteristics

The ultimate goal of this research project was to develop a program that can accurately generate artificial logs. The first step in reaching this goal was to qualify the characteristics of grade logs. In order to do this, it was necessary to quantify the relationship among defects as well as the relationship between defects and log attributes such as grade, size and position type (butt vs. upper).

2.2 Find Correlation Between External Defect Indicators and Associated Internal Defect Attributes

Since the scope of this research project involved generating external as well as internal features of a log, it was imperative to define the relationship (if any exists) between external indicators and internal defect information. Once the artificial log has been generated and the external defects placed on the log, a simple regression formula can be used to delineate internal defect area.

2.3 Create Spreadsheet Program for Artificial Log Data Generation

Researchers in the Department of Industrial and Manufacturing Systems Engineering at the University of Missouri-Columbia, in collaboration with the Southern Research Station of the U.S. Forest Service, recently developed a hardwood log sawing simulator for use by the hardwood sawmill industry. LogCast (Log Computer Aided Sawyer Trainer) was designed to be used as a training tool for sawyers in primary hardwood processing mills (Occeña *et al*. 2000). The program provides a non-destructive method for sawyers to experiment with different log orientations and sawing patterns and presents the user with yield and value information resulting from sawing decisions. A major advantage of the program is that it incorporates both external and internal defect information.

One major limitation of the program is the small number of logs in the database. Currently, there are only 18 logs available. The external characteristics of the sample logs were modeled from actual red oak logs while the internal defect shape and size was artificially generated using defect information obtained from physically sawn logs. Though the shape and size of the defects proved to be accurate, defect placement and orientation was arbitrary.

Another method that could be used to obtain the internal defect data is to utilize CT imagery. CT scans could be taken along the length of the log and fused together to create an accurate representation of the log and all internal defects. However, there is currently no sawmill-grade scanner available that can provide accurate and inexpensive data.

A more practical method of obtaining log data is to generate both the log and defect attributes using a computer program that takes into account real-log characteristics. Creating a computer-generated log is much faster, easier and less costly than physically modeling a real log. Another advantage of using computer-generated logs is the assurance that every log will be unique. Unlike a database, which is finite, the chance of generating the same log twice is infinitesimal. This would also make the training program more closely related to real-world situations where every log a sawyer encounters is different.

3 Literature Review

3.1 Hardwood Log Grades

Standard hardwood log grades were first proposed by the U.S. Forest Service Forest Products Laboratory in 1949 and adopted as the official Forest Service method of log grading in 1952 (Vaughan *et al*. 1966). Factory lumber log grade specifications were developed by detailed analysis of approximately 11,000 logs sawn at 28 sawmills in the northern, central and southern regions of the U.S. Each log was accurately diagrammed, then sawn into lumber to assess yield. Based on log information and lumber yield, three log grades were developed. The specifications for each log grade (F1, F2 and F3) are shown in **Table 1**. The letter ‘F’ is used in the grading nomenclature to distinguish factory lumber log grades from grades for other log classes such as veneer, construction, and local-use. As the log grade increases, the volume of useable wood decreases.

Table 1. Forest Service standard grades for hardwood factory lumber logs.

Grading Factors		Log Grades							
		F1			F2				F3
Position in tree		Butts only	Butts & Uppers		Butts & Uppers				Butts & Uppers
Scaling diameter, inches		13-15[a]	16-19	20+	11+[b]	12+			8+
Length without trim, feet		10+			10+	8-9	10-11	12+	8+
Required clear cuttings[c] of each 3 best faces[d]	Min. length, feet	7	5	3	3	3	3	3	2
	Max. number	2	2	2	2	2	2	3	No limit
	Min. proportion of log length required in clear cutting	5/6	5/6	5/6	2/3	3/4	2/3	2/3	½
Maximum sweep & crook allowance	For logs with less than ¼ of end in sound defects	15%			30%				50%
	For logs with more than ¼ of end in sound defects	10%			20%				35%
Maximum scaling deduction		40%[e]			50%[f]				50%
End defect:		See Rast *et al*. 1973 (p.18)							

[a] Ash and basswood butts can be 12 inches if they otherwise meet requirements for small F1's.
[b] Ten-inch logs of all species can be F2 if they otherwise meet requirements for small F1's.
[c] A clear cutting is a portion of a face, extending the width of the face, that is free of defects.
[d] A face is ¼ of the surface of the log as divided lengthwise.
[e] Otherwise F1 logs with 41-60% deductions can be F2.
[f] Otherwise F2 logs with 51-60% deductions can be F3.

The first step involved in grading the log is to divide the log into four equal faces so as to maximize the number of good faces. Next, the three best faces are graded on the basis of the clear cutting requirements shown in **Table 1**. The grade of the log is equivalent to the lowest grade of these three faces. The grading face can be thought of as either the 2nd worst face or the 3rd best face of the log.

In order to promote the adoption of the grading rules to industry, as well as provide a field reference for Forest Service personnel, an instructional guide was made available (Rast *et al*. 1973). The guide provides detailed instructions for measuring defects, determining best face, estimating clear cuttings and ultimately assessing log grade.

3.2 Log Quality and Lumber Recovery

If there were no correlation between log defects and value of lumber produced, there would be little justification in describing the defect-log relationship. Log grades would be irrelevant since the whole principle behind grading logs is to assess value. Every log, regardless of defect frequency, size or location, would have the same potential to produce valuable lumber. A study was conducted by Hanks *et al*. (1980) in an effort to determine the relationship between log grades and lumber recovery for factory grade logs. Though multiple species were included in the study, only the results for northern red oak will be discussed.

A sample of 1,316 red oak logs with scaling diameters ranging from 8 to 31 inches were graded and processed into lumber. Each board produced was then graded using the National Hardwood Lumber Association (NHLA) hardwood lumber grading rules, and an average lumber grade yield over all diameters was calculated for each of the three log grades (**Table 2**). If we assume a log has a volume of 100 board feet, the percentage yield values will be equivalent to board foot yield values. By making this assumption, the average value by log grade can be calculated. The results indicate that on average, higher log grades produce more valuable lumber. Value of lumber produced from grade 1, 2 and 3 logs is $78.35, $60.68 and $49.38 respectively. Therefore, we can make the assumption that lumber value is directly related to log grade. Since we know that log grade is directly related to defect type, frequency, size and location, we can also conclude that log defect information contributes to the value of lumber produced.

Table 2. Value of lumber produced from Grade F1, F2 and F3 red oak logs.

Lumber Grade[a]	% of Lumber by Log Grade Grade F1	Grade F2	Grade F3	Lumber Value/BF[b]	Value of Lumber by Log Grade ($) Grade 1	Grade 2	Grade 3
FAS	31.9	10.8	2.6	1.110	35.41	11.99	2.89
F1F	14.2	8.8	3.4	1.100	15.62	9.68	3.74
SEL	2.9	2.4	1.0	1.000	2.90	2.40	1.00
1C	28.3	34.5	22.3	0.500	14.15	17.25	11.15
2C	14.6	25.3	34.4	0.485	7.08	12.27	16.68
3A	6.1	13.0	24.2	0.425	2.59	5.53	10.29
3B	2.0	5.2	12.1	0.300	0.60	1.56	3.63
Total	100.0	100.0	100.0	--	78.35	60.68	49.38

[a] Definitions of lumber grades can be obtained from *Rules for the Measurement and Inspection of Hardwood and Cypress*, National Hardwood Lumber Association, Memphis, TN, 1994.
[b] Lumber values were estimated from *The Weekly Hardwood Review* (Vol. 18, Issue 17, 2002) and represent green Appalachian red oak lumber prices.

3.3 Distribution of Mill-Run Logs

One desired aspect of the log-generating program included in this study is that the characteristics of the logs generated be similar to logs found at sawmills. Therefore, it would be beneficial to know the distribution of red oak logs by scaling diameter, length and grade. Goho and Wysor (1970) summarized these characteristics for hardwood logs delivered to Appalachian sawmills. The red oak logs sampled ranged in diameter from 8 to 27 inches, 50% of which were 11 to 14 inches. The grade distribution for factory grade 1, 2 and 3 logs was 21.2%, 41.4% and 37.4% respectively. The nominal log length distribution was also given and showed a somewhat normal distribution with 12 foot logs being the most common, accounting for 27% of all logs.

3.4 Hardwood Log Defects

For the past 50 years or so, there has been an increased effort in forestry research to define and describe external defects in hardwood trees and logs. The earliest comprehensive study describing external defects was published by Lockard *et al*. (1950 and 1963) and later revised and expanded by Carpenter *et al*. (1989). These papers looked at all major scalable and grade defects occurring on the surface and ends of hardwood logs. Information such as cause, susceptible species and significance was presented for each defect type. Also, photographs of internal and external defects accompanied many of the defect explanations. In 1967, Carpenter conducted a similar study that instead examined the major defect types in southern hardwood veneer logs. Though the defect types found were similar, the adverse effects that these defects had in producing quality veneer was the main focus of the article. Finally, Shigo (1983) published a photo guide of external and internal defect information similar to the Lockard publications but instead focused on the internal decay associated with various defect types.

A more species-specific photo investigation was performed by Frederick, *et al*. (1973). The study looked at two major defect types in black cherry (*Prunus serotina* Ehrh.): open and overgrown branch stubs, and bark distortions. Where previous studies showed only one internal defect photo, scientists in this study dissected and photographed the defective log area in 5/8-inch increments from the external-most to the internal-most portion of the defect. For the first time, a visual representation of a defect's transformation while approaching the pith was available. Since the main purpose of the study was to relate certain defects to site quality and not to relate internal and external defect information, photos from only four defects of the 28 bolts sawn were published. However, the door was opened for future photographic investigations of internal defects.

From 1982 to 1991, Rast *et al*. published a series of Forest Service research papers illustrating the internal defects associated with several of the more common external defect indicators. Each paper focused on one of the following northeastern hardwood tree species: northern red oak, black cherry, white oak (*Quercus alba*, L.), black walnut (*Juglans nigra*, L.), sugar maple (*Acer saccharum*, Marsh.), yellow-poplar (*Liriodendron tulipifera*, L.) and yellow birch (*Betula alleghaniensis*, Britt.). Logs that contained a variety of defect types and sizes were selected at veneer mills, and photographs were then taken of each external defect prior to log processing. Each log was sawn into flitches and subsequently sliced into veneer. After drying the veneer, photographs were taken of all internal defects corresponding to the defects photographed before processing. Pictures of each defect were taken from the first indication of the defect below the surface to the last slice of veneer or the last indication of the defect. One set of photographs was published for each defect type and includes the photograph of the external indicator and several photographs of the internal defect as it progressed through the flitch. Though these publications allow the reader to better visualize the attributes of internal defects associated with external indicators, no attempt was made to explain the correlation.

The first study that explored the relationship between external indicators and internal defects was conducted by Stayton *et al*. (1970) on sugar maple. The goal of the study was to determine the percentage of external defect indicators that had associated internal defects within the quality zone of hardwood stems. Quality zone is defined as the portion of the bole that lies outside the central core area, the diameter of which is equal to one-half of the stem diameter at that point. An attempt was then made to find a correlation between internal defect frequency for each indicator type and size of the indicator, its height above the stump, DBH, tree age and growth rate.

Results showed that internal defects contained in the quality zone were found with 100% of the sound and unsound knots; 83-96% of the surface rises; bumps; and overgrown knots; 66% of the over-grown seams and bark distortions; 58% of the epicormic branches; and 49% of flutes. Using linear and multiple regression analysis, the only defects to show a significant relationship between defect indicator size and presence of internal defect were flutes. As flute length increased, the percentage of associated internal defect increased as well. A significant relationship was also found between the percentage of bark distortions and surface rises that had associated internal defect, and the height of the indicator above the ground. With increased height above the stump, internal defects were more prevalent and occurred closer to the bark. When analyzing the effect of tree age on interior defect occurrence, researchers found a significant relationship with bark distortions, flutes and overgrown seams. Bark distortions and flutes both exhibited positive correlations while those of overgrown seams were negative. Finally, tree age and growth rate and frequency of bark distortions, flutes, epicormic branches, surface rises and overgrown seams were also found to be statistically significant. Frequency of bark distortions and flutes both increased with tree growth rate. Epicormic branches and surface rises decreased with tree age while the number of overgrown seams per tree increased.

3.5 Log Modeling and Sawing Simulation

As the interest in internal defect characteristics increased and the capabilities of computers improved, researchers began attempting the arduous task of log and defect modeling. The advantage of modeling is that it allows simulation of sawmill processes such as log sawing and provides a nondestructive method for training sawyers. Since knots are a major grade defect in timber and appeared to be a good candidate for modeling, most early studies focused their attention here. One of the earliest of such studies simulated knots and other defects as rectangular solids, with dimensions generated from a log grade-specific exponential distribution (Pnevmaticos *et al*. 1974). All defect types were lumped together and defect representations were crude. A more realistic model was produced by Richards *et al*. (1979) while exploring the development of a hardwood log sawing simulation program. Knots were simulated as cones beginning at the pith and projecting outward in a direction perpendicular to the log axis. Knots were terminated, either inside the log or outside, by a spherical surface with a radius equal to the length of the knot. Though this was a good start at describing knot structure, the use of the modeled defects was limited since it did not take into account many of the true characteristics of knots such as projection angle and the variability in knot shape.

One of the first endeavors to accurately describe knots inside logs using modeling procedures was by Samson (1993) using Scots pine (*Pinus sylvestris* L.). A Cartesian coordinate system was used to describe the knot position on the stem with the z-axis being the pith and the x-y plane resting perpendicular at the butt end of the log. Each knot was represented as an elliptical cone, characterized by a vertex that falls on the z-axis and a termination point that lies somewhere between the pith and the bark. Seven parameters related to defect shape and position along the stem were used to define each knot:

1. Distance of knot vertex from the origin along the z-axis.
2. Angle of knot axis relative to the z-axis.
3. Angle of the knot axis relative to the x-axis.
4. Distance from pith to end of knot.
5. Vertical semi-vertex angle measured in the vertical plane of the knot.
6. Horizontal semi-vertex angle measured in the horizontal plane of the knot.
7. Distance from the end of a pruned stem to point of overgrowth.

To test the validity of the model, several pieces of 3” thick Scots pine lumber were selected which exhibited knot characteristics typical in this species. Defect measurements were taken on all exposed surfaces to estimate model input. The model was then used to generate defect boundary lines on planes corresponding to the surfaces of the test block. Visual comparison of the generated knots and actual knots indicates that the model could accurately reproduce knot shape on all surfaces. The test was also conducted on several log cross sections and generated the same results. Though the parameters used were derived from direct defect measurement, the model appears to have great potential for use in random knot generation as well.

Randomized log and defect generation has become increasingly important due to the scarcity of real-log data and the costly and time-consuming task of physical data collection. One of the difficulties encountered by researchers while attempting to accomplish this task, however, is the extreme variability in shape among logs and defects. Past modeling studies assumed that log cross sections were circular in shape. However, because of environmental factors such as wind, this is rarely the case. Also, previous log representations were conical in shape, even though most logs exhibit some form of sweep or crook. Defect attributes, similarly, rarely take on simple geometric form. A method was therefore proposed for generating realistic synthesized log and knot defect shape attributes.

Using information from 12 red oak log samples, a three-step process was developed for log simulation (Chen and Occeña 1996). First, a series of circular log cross sections was generated whose centroids fell in a straight line. Second, the size of each cross section was manipulated to account for tree taper and interslice dependencies. Finally, the centroids of the cross sections were shifted to account for the vertical variation in the stem. Mode analysis was then performed on Fourier descriptors of cross sectional contour information to obtain the shape of each cross section. The result is an artificially generated log whose shape elements fall within the range of the sample data. A similar procedure using knot cross sectional information was used for generating knot shape attributes.

Since the ultimate goal of this research project was to provide log and defect input into the LogCast sawing simulation program, it is pertinent to discuss the history of its development. In 1988, Occeña and Tanchoco first presented information on their version of a log-sawing simulator simply termed GSS (Graphic Sawing Simulator) (1988b). All log and defect information used in the model was obtained by physically measuring the external features of the logs, sawing the logs into lumber, measuring the surface defects on the lumber, and fusing the defect information together to obtain a 3-dimensional representation of the logs. Once the real-log data was collected, the spatial information was imported into a CAD-based graphic simulator where the log and associated defects were displayed as closed polyhedra made up of polygon patches. This method of visual representation provides a more realistic log and simplifies computations.

The user of the sawing simulator is first presented with 4 views of the log: front, top, side and isometric. Images can then be rotated around the log axis until the desired orientation to the simulated saw line is obtained. The saw line can also be moved from side to side to the preferred sawing location. When instructed to saw lumber, the program performs Boolean operations to subtract the flitch and saw kerf from the remaining log section. Residual log information is then displayed, ready for the user to make the next cut. All lumber is automatically edged and trimmed by the program then graded using the NHLA grading rules for hardwood lumber. Lumber yield and value information can then be obtained and used to evaluate different sawing patterns of the same log.

Researchers involved in the simulator's development anticipated that input data would eventually come from computed axial tomographic (CT) imaging and that physical measurements of log and defect characteristics would no longer be necessary. Though this would drastically reduce collection time, one drawback of this method is the large size of the resulting data set. It is estimated that the dataset size for a single log is in the order of 7-10 megabytes (Occeña *et al*. 1995). To simplify computations and increase processing time, a means was developed to reduce the data while maintaining the integrity of the model representation. Since defect data is measured on a smaller scale, any reduction in data compromises the accuracy of defect dimensions. Therefore, only log profile data is condensed.

The initial process in data reduction involves examination of centroidal variation among CT slices. The first step of the procedure is to calculate the centroid of each CT slice. Any slice containing a centroid with the maximum displacement from a reference line and exceeding a specified threshold value is deemed significant and retained. The log is then divided at the point of maximum significant variation and the process is repeated on the remaining sections until the entire log has been analyzed.

The second data reduction process uses a similar procedure but instead deals with cross-sectional area variation. Any slices that exhibit significant variation in area are retained in the model as well. An example of a log before and after data reduction is shown in **Figure 1**.

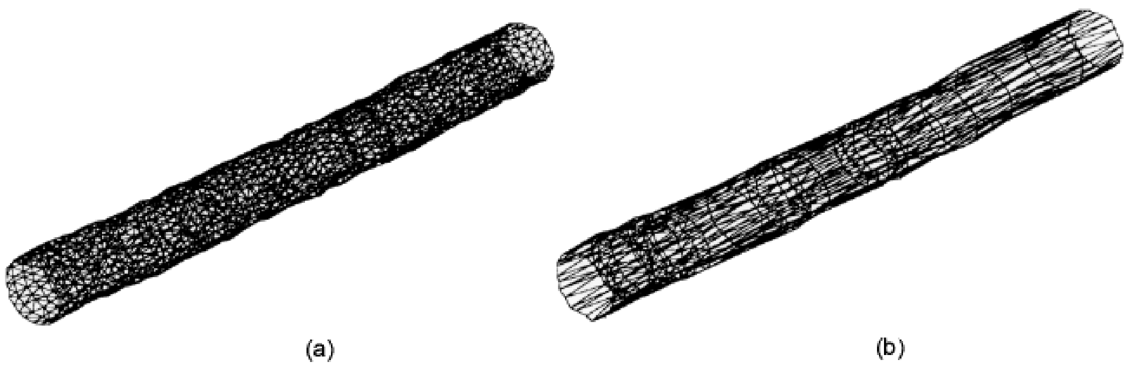


Figure 1. Log representation (a) before and (b) after data reduction.

In 1996, Occeña and Schmoldt introduced GRASP (GRAphic Sawing Program), a much-improved version of the earlier GSS program. Unlike GSS which ran on a minicomputer platform, GRASP functioned on a microcomputer platform, making the program accessible to a larger group of people. The newer version now had the capability to model a much larger range of sawing operations. Some examples include stem bucking and topping, log breakdown, quartering, veneering, lumber edging and trimming, secondary processing and even production of furniture components. Essentially, wood products at any stage of the wood processing operation can be modeled as long as the product can be represented as a closed polyhedral solid. Another advantage of GRASP is that it allows more options for visual representation of the object. The object can be displayed as a see-through wire-frame image, as a solid, or as a more realistic-looking shaded object.

The current version of the sawyer trainer (LogCAST) was first introduced at the 28th Annual Hardwood Symposium (Occeña *et al*. 2000). LogCAST incorporates many of the features of GRASP with a new user-friendly environment and additional processing and display options. The trainer itself is built on top of a CAD-based program developed by the Schroff Development Corporation called SilverScreen. Within the program, six main menu items are presented to the user: sawing simulation, user profile, high score, picture gallery, assistance and clean-up.

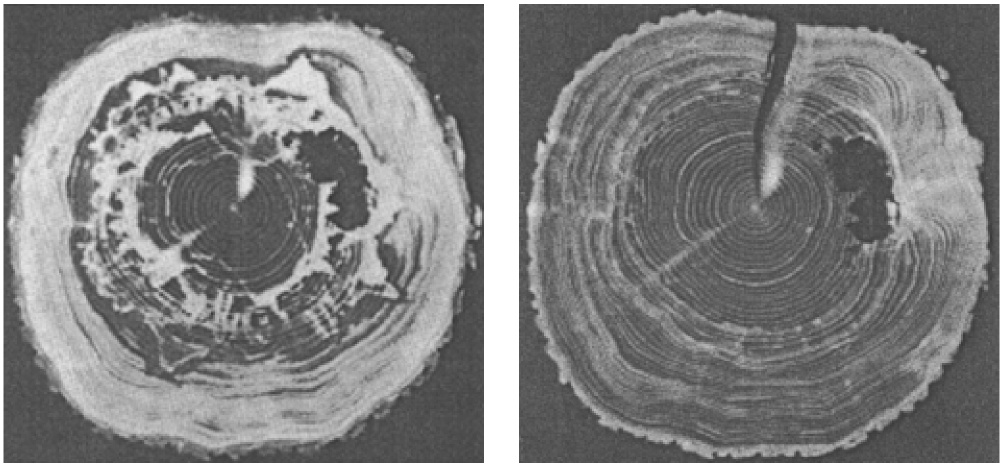
After the user begins the *sawing simulation*, a choice of logs is offered. Currently the database consists of 18 red oak logs (six for each Forest Service log grade). Descriptions of each log are given as well. After choosing a log, the user can specify saw type (band or circular) and default board thickness. Next, the trainee can begin processing the log into lumber. Before each cut, the user has the option of rotating the log or flitch to the desired orientation. Once the last cut is made, the lumber is automatically edged and graded and the resulting grade and value of the lumber is presented. Information on each sawing attempt is stored in the *user profile*. The highest lumber value obtained for each log is shown under *high score*. The user can view all previous sawing patterns in the *picture gallery* and purge any unwanted profiles with the *clean-up* feature. Finally, the *assistance* tool displays a sample high-scoring sawing pattern for each log in the library.

3.6 Defect Detection Using Computed Tomography

Computed tomography (CT) scanners were introduced commercially in the early 1970's to provide medical professionals with a means of viewing high-resolution 3-dimensional imagery of their patients. Most current scanners utilize a technique where the patient lies still inside a stationary ring of detectors while a gamma ray or x-ray source is rotated around them (Hopkins *et al*. 1982). A flat fan of rays is passed through the patient to the detectors where information is then sent to a computer for processing. Software is used to analyze the data and produce a cross-sectional image of the subject at the point of scanning. Information from longitudinally adjacent scans can be used to generate 3-dimensional models of scanned features.

Since the inception of the scanners, researchers in various fields have explored the possibilities of using CT scanning techniques for purposes other than medical applications. Taylor *et al*. (1984) looked at the feasibility of using computed tomography to locate internal knots in logs. Four loblolly pine log sections and one red oak log section were scanned at 16 cross-sectional planes with 1 centimeter between slices. The resulting scan images were processed using a simple image analysis program to extract perimeter information from the log and associated knots. Each log section was then physically sawn at the point of each scan and all slices were photographed. Finally, photographs were compared to image interpretations to assess reliability. Results indicated that log and defect boundaries obtained through image analysis compared favorably to those of the actual log slices. It was therefore concluded that the potential exists to use CT scanning techniques in a wood-processing environment.

Since mill-run logs are generally green, any industrial-type CT scanning system would need to have the capability of collecting and analyzing data from wet logs. For this reason, all scanning for this project was performed while the log sections are still green. This would appear to pose a problem due to the fact that water appears as a high-density area in the CT image and certain defects such as knots have a similar representation. Funt and Bryant (1987) demonstrated that this was indeed the case (**Figure 2**). However, they also showed that by incorporating a defect-specific shape test within the image interpretation algorithm, the adverse effect of moisture content could be minimized.



(a) (b)

Figure 2. CT scan of same hemlock log section while (a) green and (b) dry.

In the race to develop an accurate labeling technique for the internal features of logs, researchers have experimented with many different algorithms to extract defect information from CT images. Some of the earlier approaches utilized rule-based pixel analysis (Zhu *et al*. 1991) and texture modeling (Zhu and Beex 1994). Most recent methods, however, incorporate these techniques as well as neural net classifiers for defect extraction (Schmoldt *et al*. 1995, 1996a, 1996b, 2000; Li *et al*. 1996a; Sarigul *et al*. 2000, 2001). To account for the variability of defects between species groups, experiments using species-specific neural net classifiers were also performed (Li *et al*. 1996b; Schmoldt *et al*. 1998). Each of these techniques proved to be accurate enough for use in a sawmill environment.

4 Methods

4.1 Characterizing the Log-Defect Relationship

During the early 1960's, the Forest Service collected extensive hardwood log data throughout the northeastern U.S. Only recently, however, the data was entered into a computer database by the Forest Service Northeastern Research Station in Princeton, West Virginia, thereby making the information much more readily available. The data consists of over 1,700 log samples encompassing five of the major hardwood species in the northeast: red oak (270), white oak (560), maple (330), yellow-poplar (430), and cherry (200). For simplification, only red oak was used in the current study. Pertinent log attributes in the dataset include species, position in tree (butt or upper), length, sweep, crook, small and large end inside bark diameter, and grade. Important defect attributes include type, location (both end and surface), length, width and height. A key to the defect codes used, as well as defect definitions, can be found in **Appendix A**. In order to determine if any relationships exist between logs and associated defect attributes, various aspects of the dataset were examined. An attempt was also made to characterize the relationship between defects of different types as well as any correlation among similar defect types.

4.1.1 Frequency of Defect Occurrence

Within each log grade, the mean and standard deviation of defect occurrence by type of defect was calculated. In order to account for the variability in log sizes, defect occurrence was expressed as the number of defects per square foot of log surface area. The formula for the lateral surface area of a cone frustum was used to estimate the surface area of each log. **Equation 1** shows the formula used to calculate the number of defects per square foot of log surface area.

$$N = \frac{2n}{\pi L(d + D)} \quad \textbf{(1)}$$

where N = Number of defects per ft^2 of log surface area
n = Number of defects per log
L = Slant length of log
d = Log small end diameter
D = Log large end diameter

The raw data was then subdivided by log type (butt or upper) and the same calculations were performed.

The defect frequency values for all logs were then used to measure the correlation between occurrences of all possible pairs of defect types. The objective of the analysis was to determine if the presence of one defect type is related to the occurrence of another defect type. At first glance, it would seem appropriate to measure correlation by calculating the product-moment correlation coefficient for all defect pairs. However, since all defect data distributions are non-Gaussian and hypothesis testing on correlation coefficients requires that data be Gaussian distributed, an alternative measure of correlation was chosen. First, two-way contingency tables were constructed for each defect pair. The format of the contingency tables is shown in **Figure 3**. A chi-square test of independence was then performed on each pair of defect types to determine if the occurrences of the two defects are dependent upon one another. For all defect pairs that exhibited dependency, the adjusted contingency coefficient was calculated as a measure of the strength of the relationship. The coefficient ranges from 0 (no correlation) to 1 (perfect correlation). The nature of the relationship between dependent variables (positive or negative) was also determined by comparing the sums of the diagonals within each contingency table. A positive relationship indicates that one type of defect is present when the other type is present, and a negative relationship indicates that one defect type is absent when the other is present.

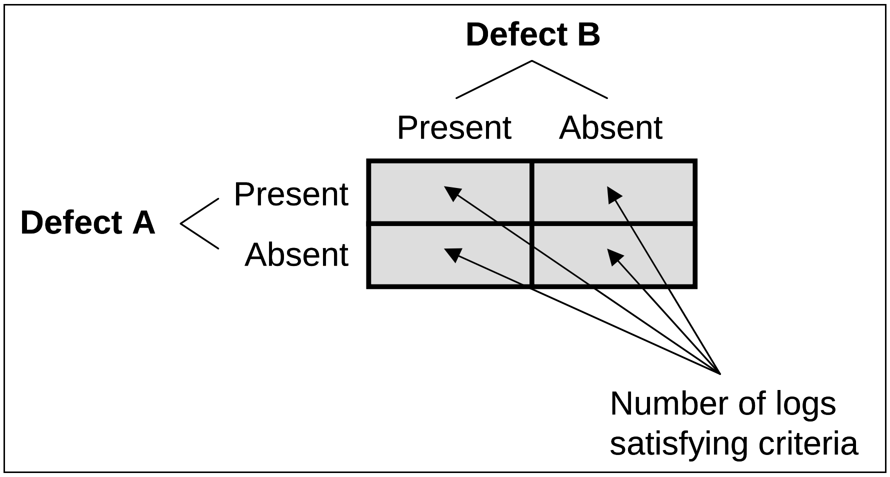


Figure 3. Two-way contingency table format used in assessing the dependency between occurrences of different defect types.

4.1.2 Defect Size

In order to assess the role that defect size plays on log grade, the mean and standard deviation of defect basal area was calculated for each defect type within each log grade. Assuming that the defects were oval in shape, basal area was calculated using the area formula for an ellipse. To see if the position of the log in the tree has an effect on defect size, the same calculations were performed for each log type. Also, mean surface area measurements were examined within each 2-inch diameter class in order to determine if defect size is related to log diameter. Log diameter at the midpoint of each defect was determined using the small- and large-end diameters and the distance of the defect from the large end. Simple linear regression was then used to assess the relationship between defect size and diameter. Using a 5% level of significance, a *t*-test was performed on each regression to test the null hypothesis that the slope equals zero. By rejecting the null hypothesis, we can assume that log diameter is useful in predicting defect basal area. Additional values that were calculated include R-square values, standard errors, and the nature of the relationship (positive or negative).

4.1.3 Defect Location

Defect location along the length of the log plays an important role in log grade determination. A log bucked so that the majority of defects are near the ends has a better chance of obtaining a higher grade than a log with defects located near the center. A single defect within one foot of either log end will result in a grade F1 face while the same defect located in the center of the log will reduce the face grade to F3. To better understand the relationship between log grade and defect locations, a within-grade frequency distribution was generated for all defects based on the distance of the defect from the large end of the log. Defect distances were expressed as percentages of total log length to account for the variability in log sizes. Similar distributions were generated based on log type as well. Even though information was collected on the radial location of each defect and radial location relative to other defects plays an important role in grade determination, the information from log to log is not comparable. The reason is that the 0° line placed along the length of the log from which all defects were measured was positioned arbitrarily.

4.1.4 Sweep and Crook

In addition to surface defects, sweep or crook in a log can be significant degraders as well. An excessive amount of sweep or crook in a log results in a scaling deduction, or a reduction in the volume of sound wood. Each grade has a maximum sweep and crook scaling deduction allowance. For grade F1, F2 and F3 logs, the maximum allowances are 15%, 30% and 50% respectively. The formulas used to calculate sweep and crook are shown in **Equations 2** and **3**.

$$S = \frac{s - (L/8)}{d} * 100 \qquad (\mathbf{2})$$

where $S =$ Sweep deduction
$s =$ Amount of sweep in inches
$L =$ Nominal log length in feet
$d =$ Scaling diameter in inches

$$C = \left(\frac{c}{d}\right)\left(\frac{l}{L}\right) * 100 \qquad \textbf{(3)}$$

where $C =$ Crook deduction
$c =$ Amount of crook deviation in inches
$d =$ Scaling diameter in inches
$l =$ Length of crook in feet
$L =$ Nominal log length in feet

The percentage of logs within each grade that contained sweep or crook was calculated from the log data set. Average scaling deductions were also determined for each log grade. Once again, the calculations performed within grades were also performed for each log type.

4.1.5 Defect Clustering

Mean distance analysis was performed on defect location data in order to determine the relative location of one defect type with respect to defects of the same type as well as defects of different types. The goal of the analysis is to determine whether or not certain defect types tend to cluster with similar or different defect types. For each log, x-y coordinates were first assigned to each defect center based on the radial location and the distance of the defect from the large end of the log. The distance along the log surface between each defect and all other defects was then determined by calculating the x and y differences between defects and using the Pythagorean Theorem to calculate the diagonal distance. For each defect pair combination, the mean distance over all logs was determined but was only reported for samples of thirty and greater.

4.2 Correlation Between External Indicators and Internal Defects

4.2.1 Data Collection

In order to assess the relationship between external and corresponding internal defects, it was necessary to collect samples of green red oak log sections that contained the various defect types. Determining the necessary sample size is a difficult task since there is no standard procedure available. The ideal method for determining sample size is to conduct a small pilot study and perform a power analysis on the results. For this study, however, this was not a viable option. While taking into account cost and time constraints, it was decided that the approximate sample size would be equal to 10× the number of predictor variables in the multiple regression equation used to predict the internal defect attributes. Considering that we have a maximum of five predictor variables, roughly 50 samples are needed for each defect type. Again due to time and cost constraints, it was not feasible to collect 50 samples of every defect type. Therefore, the Princeton log data were analyzed in order to determine the five external defect types that occur most frequently in red oak. During the evaluation, no distinction was made between defects with callous growth and similar defects without callous growth. For example, overgrown knots and overgrown knots containing callous tissue were combined into one defect type. There was also no distinction made between light, medium, and heavy bark distortions, and clusters of individual defects were not considered in the analysis. The results indicate that the most common defect types in red oak are overgrown knots, adventitious knots, sound knots, unsound knots, and bark distortions.

Six sawtimber-size northern red oaks trees and two scarlet oaks (*Quercus coccinea*, Muenchh.) were felled in Montgomery County, Virginia. Log sections from 11 to 30 inches long that contained defects of interest were bucked from the tree. Sections were collected up to an 8-inch small-end diameter. A total of 115 log sections were obtained from the 8 sample trees. Each section was labeled on the small-end with the tree number and log number starting at the butt end of the tree. An arbitrary reference point was also marked on the log ends to serve as the zero degree point when recording the radial location of defects. In order to assure that the log sections are as green as possible when scanning, an end coating was applied to all logs to help prevent moisture loss.

8 digital photos were taken of each log section at 45° increments around the circumference of the log. Log attributes consisting of small- and large-end diameters, section length, and the number of small-end annual rings were then recorded. The type

and location of all external surface defects were then identified and measured. The length and width of each defect was measured at its base and height was measured as the maximum perpendicular distance from the normal tree form. The setup used for photographing the log sections and taking measurements is shown in **Figure 4** and consists of a height-adjustable lazy Susan apparatus mounted to a stationary platform.

Figure 4. Setup for photographing and measuring sample log sections.

After quantifying the external features of each log, select log sections were put through a CT scanner to obtain internal defect information. Due to the high cost associated with CT scanning, the logs were prioritized so as to obtain the necessary number of defect samples with as few scans as possible. 95 of the 115 log sections were scanned. 53 of the logs were scanned at the Virginia-Maryland Regional College of Veterinary Medicine Small Animal Clinic in Blacksburg, Virginia, and the remaining logs were scanned at Forintek Canada Corporation in Quebec City, Quebec. At the veterinary college, logs were scanned with a Picker IQ-Xtra CT scanner using a modified liver protocol, 130 kVp tube voltage, 125 mA tube current, and an image size of 480. No filtering was performed on the images. At the Forintek lab, a Siemens Somatom Plus 4 Volume Zoom CT scanner was used with the same settings except for the use of a modified pelvis protocol and a tube voltage of 140 kVp. Also, the images were post-processed using a medium-sharp filter.

All logs were oriented with the reference point facing up and the butt-end of the log toward the scanner to assist in later matching the internal defects with the associated external indicators (**Figure 5**). Taking into account the fact that a larger scan thickness usually provides better contrast, a scanning width of 10 mm per slice was considered sufficient to delineate defects. Also, a distance of 10 mm between slices was maintained in order to assure full coverage of the desired scanning area. In order to minimize the costly procedure of CT data collection, an attempt was made to scan only that area which includes defects of interest. An example of a partial CT image sequence for an overgrown knot is shown in **Figure 6**.

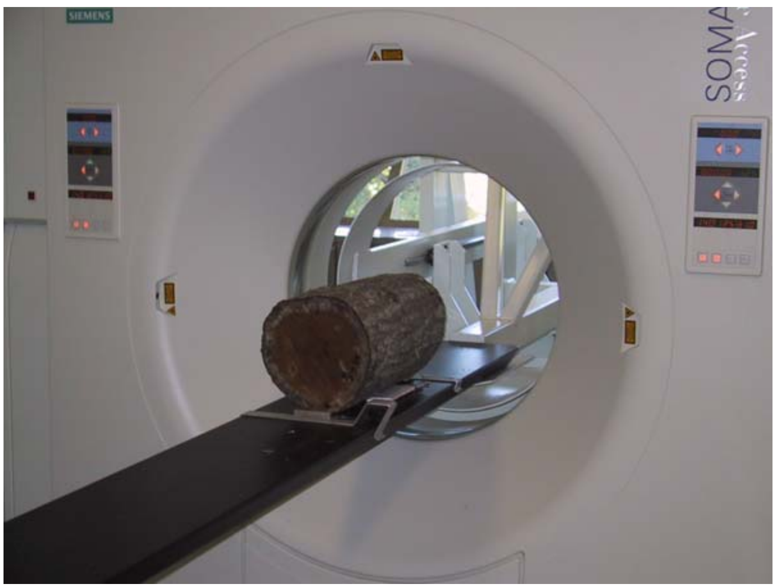


Figure 5. Example CT scanning setup for log section samples.

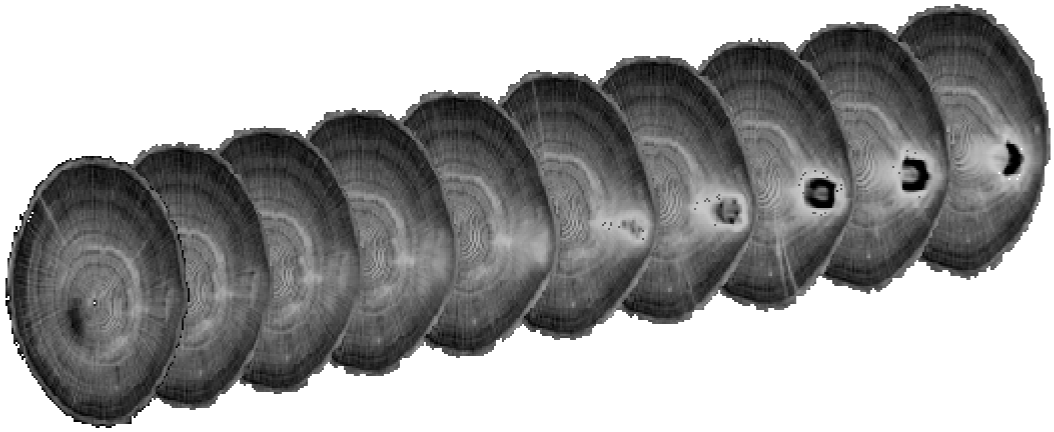


Figure 6. Partial CT image sequence for an overgrown knot.

4.2.2 Defect Labeling

Once the CT images were collected, the data was stored to disk and moved to a PC for analysis. *Scion Image* (version 4.0.1), a multifunctional image analysis program developed by the Scion Corporation, was used to examine the CT slices. The software was chosen for its ability to manipulate image parameters, provide length and area estimates, and record x-y coordinates of locations within the image. Another nice feature of the program is that it allows consecutive CT slices to be stored as a single stacked TIFF file. Users can easily scroll through images of a log section to better visualize a defect's progression through the log.

In order provide sufficient information for calculating the desired defect parameters, five measurements were taken on each image (**Figure 7**):

(a) x-y coordinates of the pith
(b) length of defect (in line with pith)
(c) width of defect (perpendicular to pith)
(d) x-y coordinates of defect center
(e) minimum depth of defect from cambium

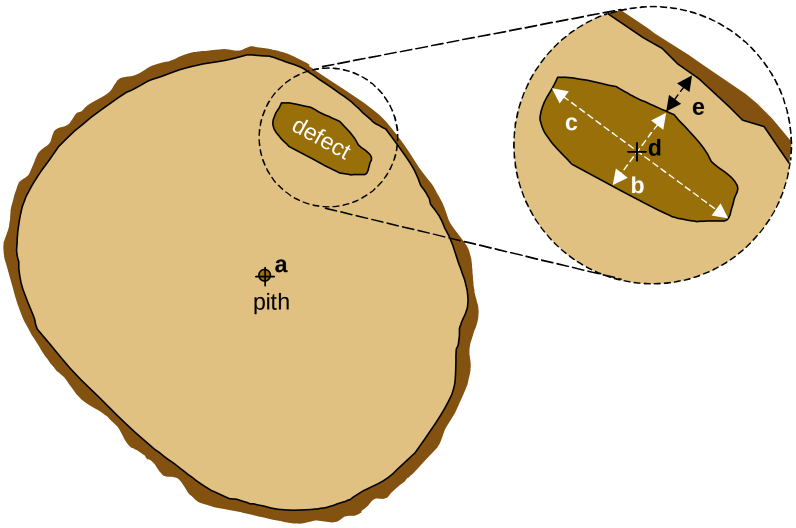


Figure 7. Measurement locations for each CT slice of a red oak log section.

Log and defect information obtained from each CT slice was used to calculate three defect parameters. First, the defect volume was estimated by summing among all slices the products of the defect area and scan thickness (10 mm). When calculating area, the defect was assumed to be elliptical in shape. Second, the minimum distance of the defect from the cambium was determined. Finally, the third parameter that was calculated is the angle (θ) of the defect with respect to the pith (**Figure 8**). For each log section, the pith was assumed to be straight. The distance d_n from the pith to the defect center was then calculated for each slice. Next, a line was generated that minimized the sum of the squared distances from itself to the center of each defect slice. The angle was measured at the intersection of this line and the pith.

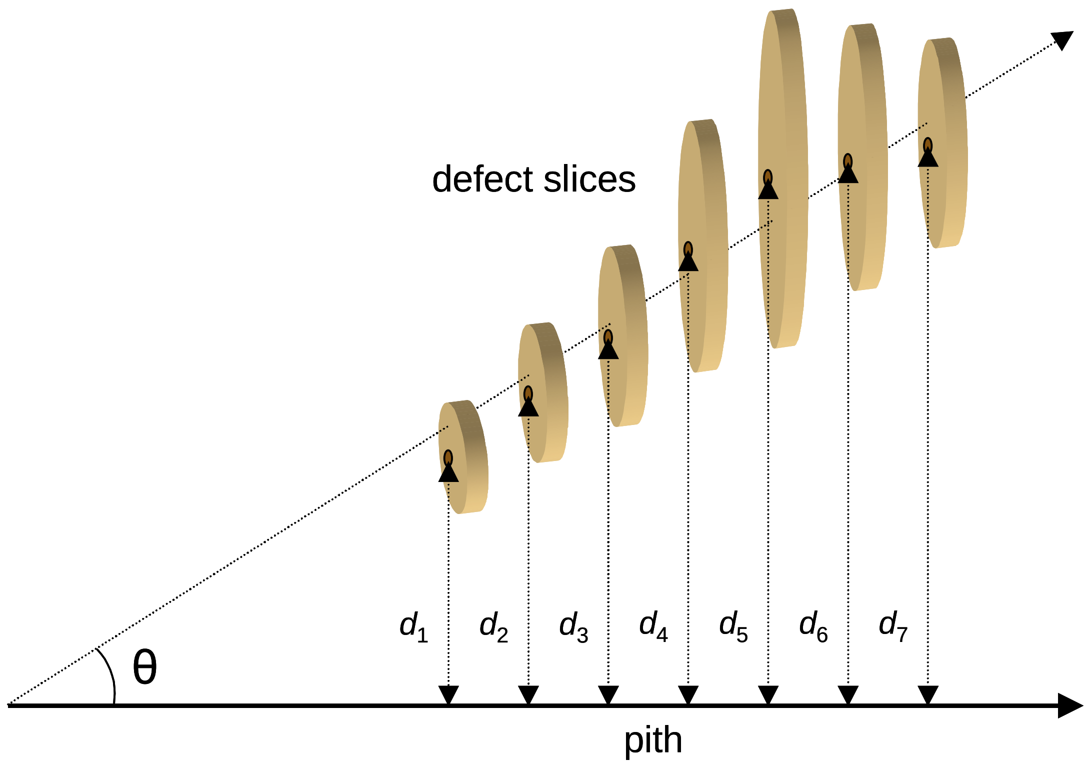


Figure 8. Defect angle (θ) measured at the intersection of the pith and a reference line that minimizes the squared deviation from defect slice centers.

4.2.3 Regression Analysis

Multiple linear regression analysis was performed on the data in an attempt to find significant predictor variables for internal defect volume, defect angle relative to the pith, and the minimum depth of the defect below the cambium. Predictor variables that were used include log diameter and external indicator length, width, height, and the length-width product. Two transformations of the predictor variables were also considered: the natural log and the square. In order to determine the best fitting of the three predictor variable varieties, each was plotted separately against the dependent variables for each defect type. The form of the predictor variable that illustrated the greatest R^2 value was the one chosen for regression analysis (**Table 3**). Adventitious knot angle was omitted from any regression analysis since it usually only occurred in one or two CT slices, making the angle calculation unreliable. It should be noted, however, that adventitious knots generally grow perpendicular to the pith. Depth measurements for sound and unsound knots were also omitted since they always appear above the log surface.

Table 3. Predictor variable used in regression analysis for each defect type and dependent variable.

		Predictor Variable Used in Regression Analysis				
Defect Type	Dependent Variable	Defect Length	Defect Width	Defect Height	Defect Length*Width	Log Diameter
Adventitious Knot	Angle	--	--	--	--	--
	Volume	ln(x)	x^2	x^2	ln(x)	ln(x)
	Depth	ln(x)	ln(x)	x	ln(x)	x^2
Distortion	Angle	ln(x)	ln(x)	x	ln(x)	ln(x)
	Volume	x	x^2	x	x	x^2
	Depth	x	x	x	x	x^2
Overgrown Knot	Angle	x^2	x^2	x^2	x^2	ln(x)
	Volume	x^2	x^2	x	x	x^2
	Depth	x^2	x^2	x	x	ln(x)
Sound Knot	Angle	ln(x)	ln(x)	ln(x)	ln(x)	ln(x)
	Volume	x	x^2	x	x	ln(x)
	Depth	--	--	--	--	--
Unsound Knot	Angle	ln(x)	ln(x)	x^2	ln(x)	x^2
	Volume	x	x	x	x	ln(x)
	Depth	--	--	--	--	--

Though many different methods are available for choosing the independent variables to include in the regression model, the PRESS procedure (Predicted Residual Sum of Squares) was chosen since it favors small datasets and provides a balance of over- and under-fitting of the model. The PRESS statistic is computed by removing the i^{th} observation from the data set, computing the regression equation without this observation, predicting that dependent variable based on the regression equation, then computing the residual. The process is repeated *n*-1 times, where *n* is the number of observations. The calculation for the PRESS statistic is shown in **Equation 4**. For each defect type and dependent variable, the model that produced the smallest PRESS statistic was chosen as the best-fitting model.

$$PRESS = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \quad (4)$$

where y_i = Actual value of observation i

$\hat{y}_i$ = Predicted value of observation i

After determining the best model, variance analysis was performed in SAS to determine if there was a significant linear relationship between the dependent variable and predictor variables. All tests were conducted at the 5% level of significance. Parameter estimates and R^2 values were also obtained for each regression equation.

4.3 Artificial Log and Defect Generation

4.3.1 Data Organization

The majority of log and defect data used in the artificial log generator was extracted from the Princeton database. Before analyzing the red oak data, it was subdivided into 6 data sets (one for each grade/position combination). Any logs that exhibited out of the ordinary characteristics or that appeared to contain errors were then removed to prevent later problems when developing modeling criteria.

4.3.2 Program Overview

Microsoft® Excel was chosen as the platform for the artificial log generator (ALOG) because of its ability to organize data and perform complex data calculations and manipulations using macros. The Excel program utilizes information in the Princeton log database, the log data published by Goho and Wysor, and external/internal defect relationships to generate artificial log and defect characteristics. ALOG allows the user to specify log type and grade or have them drawn at random from known distributions. Once the input parameters have been specified, the user can click a button to generate the artificial log attributes. Macros are used within the Excel spreadsheet to perform calculations and display results. Log parameters included in the output are type, grade, length, small- and large-end inside-bark diameters, sweep depth and orientation, and crook length, depth and orientation. External defect attributes include type, length, width, height, distance from large end of log, and radial orientation. Internal defect information consists of the minimum depth of the defect from the cambium, volume, and the defect angle relative to the pith. A summary of the steps involved in the log and defect generation is shown in **Figure 9**.

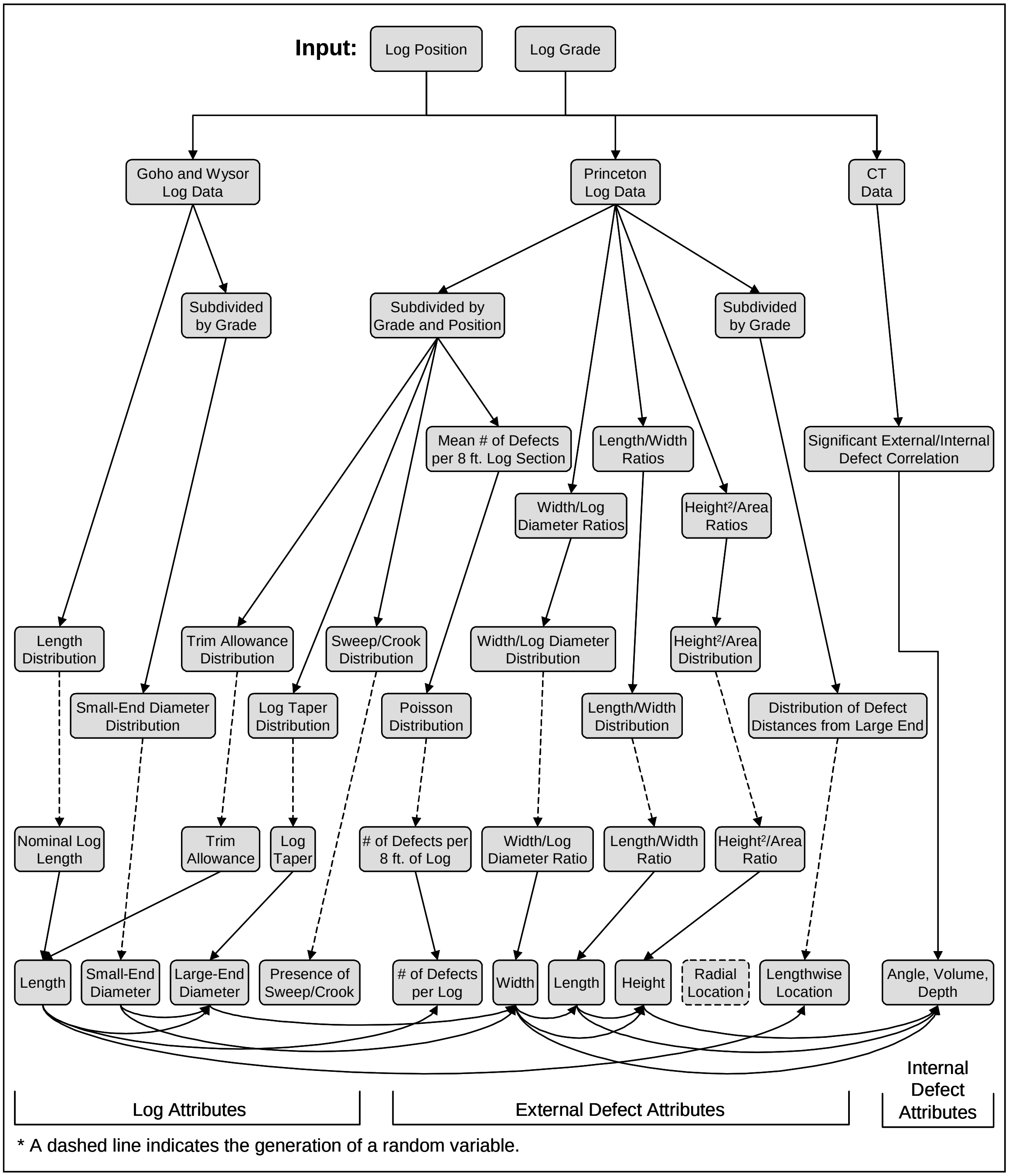


Figure 9. Diagram showing the steps involved in the log and defect data generation using ALOG.

Due to the many random variables used in the artificial log and defect generation, the grade of the generated log may not correspond to the specified grade. Therefore, a grading algorithm is incorporated into the ALOG program, allowing the user to verify the grade of the generated log.

4.3.3 Generation of Log Attributes

Goho and Wysor (1970) published length, scaling diameter and grade distributions for factory-grade hardwood logs delivered to Appalachian sawmills. Included in the study were 958 red oak logs. The red oak information is used in the program to derive several of the artificial log characteristics. Nominal 2-foot log length is calculated by random drawing from the given distribution. A random trim allowance is then added to the nominal log length using the following formula:

$$T = \bar{t} + (s_t * r) \qquad \textbf{(5)}$$

where T = Trim allowance for artificial log (in.)
$\bar{t}$ = Mean trim allowance from Princeton log data for specified log type and grade (in.)
s_t = Standard deviation trim allowance from Princeton log data for specified log type and grade (in.)
r = Random number from a standardized normal distribution

Scaling diameter (small-end) is also derived from the distribution developed by Goho and Wysor. The diameter distribution is subdivided by grade, so a random number is drawn from the distribution that corresponds to the grade specified. The same method used in **Equation 6** is used to generate a random log taper from the Princeton data. Large-end diameter is then calculated as

$$D_{LE} = (P * L) + D_{SE} \qquad \textbf{(6)}$$

where D_{SE} = Small-end diameter (in.)
P = Log taper (in./ft.)
L = Log length (ft.)

In order to assign sweep or crook to the generated logs, the percentage of logs containing these features was first calculated within each of the six data sets. Next, a random number is generated between 0 and 1. If the random number falls within the percentage of logs with sweep/crook, the generated log is given sweep/crook. The program is also configured to allow sweep *or* crook but not *both*. The method for determining the amount of sweep or crook to be assigned is explained in the following section on external defect generation.

4.3.4 Generation of External Defects

Now that the artificial log has been generated, the next step is to place external defects on the log. For all logs within each of the six datasets, the frequency of each defect type is first calculated. To account for the variations in log length, the resulting value is multiplied by eight and divided by the nominal log length to give the number of defects per 8 ft. log section. For each dataset, the mean number of defects of each type per 8 ft. log section is calculated. A random number is then generated from a Poisson distribution with the frequency mean as the input parameter. A Poisson distribution is ideal for count data since it will always return an integer greater than or equal to zero. Finally, the random number is multiplied by the ratio of generated log length to eight and rounded to the nearest whole number. The values from the dataset corresponding to the artificial log grade and type represent the number of defects of each type placed on the generated log.

Once the quantity of each defect type has been determined, it is necessary to generate the external defect parameters of length, width and height. Since the values are based on the distributions of the sample defects, there must be enough samples to generate a reasonable distribution. Therefore, due to the scarcity of defects of the same type within an individual dataset, all datasets were combined for this analysis.

For each defect in the sample data, ratios were first calculated for defect width to log diameter, defect length to width, and defect height-squared to area. Using ratios allows correlation information among defect parameters to be maintained. Frequency histograms were developed for each defect type, omitting any defects in the array that contained extreme outliers (more than three times the inter-quartile range). *PopTools* (version 2.3), an Excel add-in available for free download from http://www.cse.csiro.au/CDG/poptools/, was used to develop the histograms.

Next, a random integer is generated for each defect type between one and the total number of defect occurrences. That number is then compared to the cumulative frequency distribution to determine an attributes range. Finally, a random real number is drawn from whichever range is selected. This is the ratio value used in determining the defect parameters.

As an example, suppose we have 15 occurrences of *heavy bark distortions* in our sample data. The attributes for our hypothetical defects are shown in the first three columns of **Table 4**. The calculated ratio values are shown in the last three columns. Now suppose we want to calculate a length/width ratio for a *heavy bark distortion* to be placed on our artificial log. First, we determine the inter-quartile range (IQR) for the length/width ratio data and multiply by three. Then we determine our upper and lower limits by subtracting 3×IQR from the first quartile (lower limit) and adding 3×IQR to the third quartile (upper limit). In this example, the IQR is 0.23 and the lower and upper limits are 0.08 and 1.69 respectively. Since the last two entries in the table have values outside of this range (3.25 and 5.14 are both greater than 1.69), they are omitted when developing the histogram for the length/width ratio.

Table 4. Sample external defect data and ratio values for hypothetical heavy bark distortions.

Length (in)	Width (in)	Height (in)	Log Diameter (in)	Width/Diameter Ratio	Length/Width Ratio	$Height^2$/Area Ratio
1	1	0	12.5	0.08	1	0
2	8	0	25.7	0.31	0.25	0
2	2	0	21.6	0.09	1	0
2	5	0	19.5	0.26	0.4	0
3	3	0	20.1	0.15	1	0
3	3	0	10.2	0.29	1	0
3	3	1	10.9	0.28	1	0.14
5	6	0	15.5	0.39	0.83	0
5	7	0	27.3	0.26	0.71	0
5	5	0	26.9	0.19	1	0
6	9	0	21.2	0.42	0.67	0
6	6	0	19.9	0.30	1	0
8	6	0	22.2	0.27	1.33	0
13	4	0	23.4	0.17	3.25	0
36	7	0	22.7	0.31	5.14	0

Next, the *Summary Stats* option in PopTools is used to develop a histogram for length/width ratios of the remaining defects. Information from the histogram generated from the sample data is shown in **Table 5**. A random number is then generated between 1 and 13 (the number of defects in the sample) and compared to the cumulative distribution values in the table. If our random number is 8, we then find the first row in the table with a cumulative frequency greater than 8. In the table, the selected row is shown circled. We then pick a random real number between the lower and upper limits for that row (0.88 and 1.02 respectively). Let's say that the random number generated is 0.91. This is the length/width ratio for the defect. This same procedure is used to find values for the width/diameter and height^2/area ratios, then the whole process is repeated for each defect to be placed on the artificial log.

Table 5. Frequency distribution data for length/width ratios of hypothetical defects.

Lower Limit	Upper Limit	Frequency	Cumulative Frequency
0.25	0.40	2	2
0.41	0.56	0	2
0.57	0.71	2	4
0.72	0.87	1	5
0.88	1.02	7	12
1.03	1.18	0	12
1.19	1.33	1	13

Once we have the ratio values for each defect, the defect parameters are calculated as follows:

- Width = Width/Diameter Ratio × Log Diameter
- Length = Length/Width Ratio × Width
- Height = $\sqrt{\text{Height}^2/\text{Area Ratio} \times \text{Area}}$

Up to this point, we have generated the artificial log, determined the number of each type of defect to include on the log, and generated the external attributes of each defect. The final step in developing the external features of the log is defect placement. Each defect is arranged radially around the log from a specified point by generating a random degree between 0 and 360. Position along the length of the log is given as a percentage of log length from the large end and is calculated in the same manner as the defect size attributes. The only difference is that the distribution will be derived from *all* defects within a grade. This is mainly for grading purposes since defect location is an important grading factor but defect type is not.

4.3.5 Generation of Internal Defects

Internal defect information is also incorporated into ALOG for those defect types that were included in the CT study. If a significant relationship was found between external and internal defect characteristics, the regression equations were used to predict internal defect attributes.

4.3.6 Grading the Artificial Log

Since many random variables were used in the log and defect generation, it is possible that the grade of the generated log does not correspond to the specified grade. Therefore, a grading algorithm is incorporated into the program to verify the log grade. Using an increment of 5º, the grade for all possible faces (72 total) is first determined using the Forest Service log grading rules (Rast *et al*. 1973). For each 4-face group, the second lowest grade is determined. The highest of these grades over all groups is the log grade.

5 Results and Discussion

5.1 Log-Defect Relationship

An understanding of the relationships between logs and associated defects can be a valuable tool in log assessment. Knowing the nature of defects as they relate to log attributes such as size, type, and grade can improve the speed and accuracy of log evaluation. Defect attributes can be used as predictor variables for log attributes such as grade, and log attributes can be used as indicators of associated defect characteristics such as type and frequency. Likewise, an understanding of the correlations between similar and different defect types can be invaluable in predicting one defect attribute based on another.

One thing to consider when discussing the summary results of the Princeton data, particularly the data summarized by log grade, is that the results reflect stipulations in the grading rules. Log and defect summary values, by definition, must fall within the allowable limits of each log grade. For example, the average scaling deduction for sweep must be less than 15% for grade 1 logs.

5.1.1 Defect Frequency

Using the log data obtained from the Forest Service, the frequency of surface defect occurrences was calculated for each log grade and type. **Table 6** shows the average number of defects per square foot of log surface area for each log grade as well as its standard deviation. As would be expected, the total number of defects increases as log grade decreases. The most common defect type regardless of log grade is overgrown knots, followed by individual adventitious knots, light bark distortions, adventitious knot clusters, and sound knots. Overgrown knots also dominate grade F2 and F3 logs but place second behind light bark distortions on grade F1 logs. However, since light bark distortions are not considered a grading defect for factory-lumber grade logs, overgrown knots are the most common degrading defects for each individual log grade.

Table 6. Number of defects by log grade per square foot of log surface area.

Defect Type[a]	Number of Defects per Square Foot of Log Surface Area							
	Mean				Standard Deviation			
	Grade 1	Grade 2	Grade 3	All Grades	Grade 1	Grade 2	Grade 3	All Grades
OK	0.0170	0.0581	0.0773	0.0539	0.0290	0.0551	0.0695	0.0602
AK	0.0117	0.0556	0.0639	0.0467	0.0261	0.0734	0.1057	0.0812
LD	0.0277	0.0271	0.0265	0.0270	0.0301	0.0321	0.0424	0.0354
AC	0.0027	0.0338	0.0365	0.0263	0.0075	0.0572	0.0615	0.0524
SK	0.0016	0.0152	0.0271	0.0158	0.0050	0.0225	0.0371	0.0280
OKC	0.0045	0.0132	0.0232	0.0145	0.0094	0.0320	0.0617	0.0425
AD	0.0010	0.0127	0.0185	0.0116	0.0040	0.0281	0.0367	0.0286
SKC	0.0016	0.0096	0.0190	0.0108	0.0050	0.0165	0.0303	0.0219
UK	0.0013	0.0055	0.0212	0.0101	0.0042	0.0141	0.0444	0.0292
UKC	0.0019	0.0056	0.0198	0.0097	0.0050	0.0150	0.0419	0.0279
MD	0.0068	0.0121	0.0089	0.0095	0.0135	0.0261	0.0131	0.0189
GD	0.0000	0.0064	0.0156	0.0080	0.0000	0.0255	0.0444	0.0313
RK	0.0008	0.0061	0.0104	0.0062	0.0031	0.0119	0.0212	0.0151
RKC	0.0000	0.0057	0.0086	0.0052	0.0000	0.0119	0.0227	0.0157
DK	0.0005	0.0041	0.0036	0.0030	0.0027	0.0103	0.0109	0.0092
OBPk	0.0006	0.0042	0.0014	0.0022	0.0034	0.0265	0.0088	0.0168
Op	0.0006	0.0020	0.0034	0.0021	0.0034	0.0065	0.0131	0.0090
GSS	0.0014	0.0030	0.0016	0.0021	0.0043	0.0117	0.0080	0.0088
OKCl	0.0009	0.0018	0.0025	0.0018	0.0036	0.0049	0.0072	0.0055
HD	0.0006	0.0016	0.0027	0.0017	0.0034	0.0050	0.0069	0.0055
B	0.0004	0.0017	0.0020	0.0015	0.0021	0.0064	0.0083	0.0064
KCl	0.0006	0.0029	0.0006	0.0014	0.0031	0.0129	0.0027	0.0081
OSS	0.0000	0.0024	0.0015	0.0014	0.0000	0.0055	0.0054	0.0047
DKC	0.0005	0.0027	0.0005	0.0013	0.0027	0.0084	0.0029	0.0056
CBPk	0.0000	0.0014	0.0022	0.0013	0.0000	0.0060	0.0062	0.0053
CL	0.0014	0.0007	0.0016	0.0012	0.0059	0.0045	0.0056	0.0053
SW	0.0000	0.0019	0.0011	0.0011	0.0000	0.0098	0.0067	0.0071
Bu	0.0000	0.0002	0.0020	0.0008	0.0000	0.0016	0.0080	0.0049
GSU	0.0000	0.0008	0.0013	0.0008	0.0000	0.0037	0.0041	0.0034
SR	0.0000	0.0000	0.0020	0.0007	0.0000	0.0000	0.0099	0.0060
Fla	0.0005	0.0000	0.0016	0.0007	0.0026	0.0000	0.0100	0.0062
Flu	0.0000	0.0014	0.0000	0.0005	0.0000	0.0089	0.0000	0.0053
SH	0.0000	0.0009	0.0000	0.0003	0.0000	0.0057	0.0000	0.0035
BS	0.0000	0.0000	0.0007	0.0003	0.0000	0.0000	0.0034	0.0021
R	0.0005	0.0000	0.0003	0.0002	0.0030	0.0000	0.0018	0.0019
OSU	0.0000	0.0000	0.0004	0.0002	0.0000	0.0000	0.0028	0.0017
Co	0.0000	0.0000	0.0003	0.0001	0.0000	0.0000	0.0019	0.0011
MH	0.0004	0.0000	0.0000	0.0001	0.0021	0.0000	0.0000	0.0011
GBS	0.0004	0.0000	0.0000	0.0001	0.0020	0.0000	0.0000	0.0010
All Defects	0.0878	0.3007	0.4098	0.2823	0.0539	0.1400	0.2509	0.2164

[a] Key to defect types found in **Appendix A**.

Table 7 shows the same data summarized by the position of the log in the tree. The most common defects in butt logs are adventitious knots followed by adventitious knot clusters and overgrown knots. In logs from the upper portion of the stem, overgrown knots dominate while adventitious knots and light bark distortions follow close behind. Overall, upper logs contain 69% more defects than butt logs.

Table 7. Number of defects by log type per square foot of log surface area.

Defect Type[a]	Number of Defects per Square Foot of Log Surface Area: Mean, Butt	Mean, Upper	Mean, All Types	Standard Deviation, Butt	Standard Deviation, Upper	Standard Deviation, All Types
OK	0.0300	0.0654	0.0539	0.0459	0.0631	0.0602
AK	0.0528	0.0437	0.0467	0.0766	0.0836	0.0812
LD	0.0173	0.0318	0.0270	0.0224	0.0395	0.0354
AC	0.0426	0.0183	0.0263	0.0650	0.0434	0.0524
SK	0.0014	0.0228	0.0158	0.0063	0.0316	0.0280
OKC	0.0028	0.0202	0.0145	0.0067	0.0508	0.0425
AD	0.0105	0.0122	0.0116	0.0241	0.0307	0.0286
SKC	0.0007	0.0158	0.0108	0.0028	0.0252	0.0219
UK	0.0006	0.0147	0.0101	0.0025	0.0347	0.0292
UKC	0.0006	0.0142	0.0097	0.0025	0.0331	0.0279
MD	0.0053	0.0115	0.0095	0.0112	0.0215	0.0189
GD	0.0025	0.0107	0.0080	0.0100	0.0373	0.0313
RK	0.0006	0.0089	0.0062	0.0026	0.0177	0.0151
RKC	0.0010	0.0072	0.0052	0.0045	0.0186	0.0157
DK	0.0004	0.0042	0.0030	0.0025	0.0109	0.0092
OBPk	0.0000	0.0033	0.0022	0.0000	0.0205	0.0168
Op	0.0014	0.0025	0.0021	0.0048	0.0105	0.0090
GSS	0.0033	0.0015	0.0021	0.0092	0.0086	0.0088
OKCl	0.0018	0.0018	0.0018	0.0053	0.0057	0.0055
HD	0.0015	0.0019	0.0017	0.0055	0.0055	0.0055
B	0.0000	0.0022	0.0015	0.0000	0.0077	0.0064
KCl	0.0003	0.0020	0.0014	0.0020	0.0098	0.0081
OSS	0.0043	0.0000	0.0014	0.0075	0.0000	0.0047
DKC	0.0004	0.0017	0.0013	0.0025	0.0066	0.0056
CBPk	0.0019	0.0010	0.0013	0.0057	0.0050	0.0053
CL	0.0008	0.0014	0.0012	0.0036	0.0059	0.0053
SW	0.0017	0.0008	0.0011	0.0100	0.0053	0.0071
Bu	0.0003	0.0011	0.0008	0.0017	0.0059	0.0049
GSU	0.0019	0.0002	0.0008	0.0050	0.0020	0.0034
SR	0.0016	0.0003	0.0007	0.0099	0.0026	0.0060
Fla	0.0004	0.0009	0.0007	0.0024	0.0074	0.0062
Flu	0.0000	0.0008	0.0005	0.0000	0.0065	0.0053
SH	0.0000	0.0005	0.0003	0.0000	0.0042	0.0035
BS	0.0008	0.0000	0.0003	0.0036	0.0000	0.0021
R	0.0000	0.0004	0.0002	0.0000	0.0023	0.0019
OSU	0.0005	0.0000	0.0002	0.0029	0.0000	0.0017
Co	0.0003	0.0000	0.0001	0.0020	0.0000	0.0011
MH	0.0000	0.0002	0.0001	0.0000	0.0014	0.0011
GBS	0.0003	0.0000	0.0001	0.0018	0.0000	0.0010
All Defects	0.1928	0.3259	0.2823	0.1457	0.2321	0.2164

[a] Key to defect types found in **Appendix A**.

5.1.2 Dependencies between Different Defect Types

Based on the presence or absence of defect types on sample logs, all defect pairs that were considered dependent upon one another after performing the chi-square test of independence are shown in **Table 8**. Also displayed in the table are the adjusted contingency coefficients of each defect pair and the nature of the relationship (positive or negative). The defect pairs consisting of the following defects and similar defects with callous growth had the highest adjusted contingency coefficients: unsound knots, rotten knots, sound knots, and dead knots. The high contingency coefficients indicate that these defects exhibited the strongest dependency upon one another. All four of the relationships were positive, meaning that if one defect type is present, the other is likely to be present as well. In fact, all defect pairs showing dependency exhibited positive relationships except for the pairs consisting of ant damage/light bark distortions, closed lesions/rotten knots, and overgrown bark seams/light bark distortions. The results indicate that within each of these defect pairs, if one is present the other is likely to be absent. However, with contingency coefficients less than 0.44, the dependencies between these defects are relatively weak.

Table 8. Strength and nature of relationship of dependent defect pairs.

Defect 1[a]	Defect 2[a]	C_{adj}	Relationship	Defect 1[a]	Defect 2[a]	C_{adj}	Relationship
UK	UKC	0.92	POSITIVE	AD	DK	0.33	POSITIVE
RK	RKC	0.88	POSITIVE	GSS	GSU	0.33	POSITIVE
SK	SKC	0.79	POSITIVE	OK	RK	0.33	POSITIVE
DK	DKC	0.72	POSITIVE	SKC	UK	0.33	POSITIVE
Bu	GD	0.55	POSITIVE	CBPk	Oss	0.32	POSITIVE
HD	MD	0.54	POSITIVE	CBPK	SW	0.32	POSITIVE
AC	AK	0.52	POSITIVE	CL	SW	0.32	POSITIVE
AC	AD	0.46	POSITIVE	GD	SKC	0.32	POSITIVE
GSU	Oss	0.46	POSITIVE	AD	AK	0.31	POSITIVE
AD	LD	0.43	NEGATIVE	AD	Bu	0.31	POSITIVE
GSS	KCl	0.43	POSITIVE	AD	GD	0.31	POSITIVE
DK	SKC	0.42	POSITIVE	AD	HD	0.31	POSITIVE
DKC	SKC	0.42	POSITIVE	CL	OK	0.30	NEGATIVE
BS	CL	0.40	POSITIVE	OBPk	RK	0.30	POSITIVE
B	OKCl	0.39	POSITIVE	OKC	RKC	0.30	POSITIVE
GD	R	0.39	POSITIVE	OKCl	RKC	0.30	POSITIVE
B	MD	0.38	POSITIVE	RK	SKC	0.30	POSITIVE
CBPk	Op	0.37	POSITIVE	GBS	LD	0.29	NEGATIVE
DKC	SK	0.37	POSITIVE	AD	OKC	0.28	POSITIVE
B	SK	0.36	POSITIVE	AD	UK	0.28	POSITIVE
B	SW	0.36	POSITIVE	GD	OK	0.28	POSITIVE
Bu	SW	0.36	POSITIVE	MH	OKCl	0.28	POSITIVE
GBS	KCl	0.36	POSITIVE	OK	RKC	0.28	POSITIVE
SK	UK	0.36	POSITIVE	AD	DKC	0.27	POSITIVE
OBPk	RKC	0.35	POSITIVE	GSS	SKC	0.27	POSITIVE
RK	SK	0.35	POSITIVE	RKC	SK	0.27	POSITIVE
SKC	UKC	0.35	POSITIVE	RKC	SKC	0.27	POSITIVE
DK	SK	0.34	POSITIVE	RKC	UKC	0.27	POSITIVE
OK	SK	0.34	POSITIVE	DKC	MD	0.26	POSITIVE
OK	SKC	0.34	POSITIVE				

[a] Key to defect types found in **Appendix A**.

One possible source of error in the test for dependency is that the number of defect occurrences per log was not taken into account. Comparisons were made between defect types based on their occurrence or absence, regardless of how many times they occurred. An alternative method of testing for dependency would be to expand each contingency table to include all possible values of defect occurrences. Employing this method, however, would result in an enormous increase in calculations if done for all possible defect pairs. Another possible source of error is that the variability in log size was not taken into account. A more appropriate measure of defect occurrence would be per unit surface area of the log. This method also would require expanding the contingency table and again would drastically increase the necessary calculations.

5.1.3 Defect Size

The average surface area occupied by each defect type for each log grade is shown in **Table 9**. Overall, the average defect size for all log grades is 16.23 square inches, and there does not appear to be any correlation between log grade and average defect size. This would indicate that the frequency and location of the defects have the most influence on log grade. On average, the largest defects regardless of log grade are operational defects, closed bird peck, overgrown unsound seams, overgrown knot clusters, and butt scars. The top two defects with respect to size also have the highest standard deviations, which indicates that there is a large amount of variability in size among defects of these types. The largest defects within each log grade class are unsound knots with callous growth, operational defects, and closed bird peck for F1, F2, and F3 logs respectively.

Table 9. Average log surface area occupied by defects for different log grades.

Defect Type[a]	Defect Area (in^2)							
	Mean				Standard Deviation			
	Grade 1	Grade 2	Grade 3	All Grades	Grade 1	Grade 2	Grade 3	All Grades
Op		374.40	7.85	202.34		786.64	3.33	517.36
CBPk		6.02	257.35	173.57		2.97	590.85	483.72
GSU		135.87	105.64	115.72		52.20	64.88	57.57
OKCl	49.09	76.34	97.68	84.09	30.54	28.96	148.51	107.87
BS			80.11	80.11			26.66	26.66
GSS	58.51	78.54	68.80	70.17	64.21	96.65	98.83	84.38
SKC	105.24	73.93	49.63	60.42	63.28	69.82	46.22	57.06
B		35.05	14.63	56.90		20.96	13.34	97.91
SR			46.97	46.97			36.50	36.50
KCl		39.27	67.15	46.77		46.57	5.00	38.82
Bu			31.02	45.24			25.04	38.48
OSS		52.73	24.82	41.10		38.13	8.63	32.04
UKC	127.63	55.84	24.36	40.18	139.40	43.67	20.71	53.71
SK	41.23	16.21	46.38	35.85	32.07	37.04	162.08	130.40
Flu		34.56		34.56		31.10		31.10
DKC		37.14		32.86		24.09		22.21
HD	34.95	16.65	42.52	32.20	10.55	15.36	69.80	49.82
RKC		40.04	23.82	31.60		29.57	20.84	26.20
SW		34.28	9.42	28.75		11.22	0.00	14.65
R				25.92				3.33
Fla			21.99	21.99			0.00	0.00
OKC	38.78	17.59	18.69	21.36	27.10	11.46	11.53	16.40
RK	63.62	2.72	20.69	16.63	43.32	2.28	42.21	35.58
MD	11.33	11.98	21.64	15.35	6.23	9.86	25.10	17.15
UK	8.90	29.00	9.59	13.59	3.17	70.05	33.00	42.33
OK	3.26	4.90	10.28	7.50	4.41	12.95	21.35	17.56
LD	7.56	7.93	6.81	7.44	8.07	6.72	8.01	7.60
CL	4.58		5.01	4.52	1.38		3.44	2.54
GD		1.62	4.77	4.02		1.84	6.37	5.77
AD	6.28	4.25	3.56	3.89	6.66	6.59	12.14	10.23
AC	11.09	3.83	3.40	3.83	22.29	11.53	4.80	9.38
DK		2.99	1.47	2.24		2.67	1.23	2.08
OBPk		0.20	1.18	0.51		0.00	0.56	0.68
AK	0.22	0.48	0.32	0.39	0.11	0.60	0.62	0.59
SH		0.12		0.12		0.10		0.10
All Defects	19.67	14.58	16.85	16.23	54.53	72.33	70.99	70.03

[a] Key to defect types found in **Appendix A**.

Table 10 shows the same data summarized by the position of the log in the tree. The largest defects on average for butt logs are operational defects while the greatest area occupying defect type for upper logs are overgrown knot clusters. Again, there is a great deal of variability in defect sizes for the top ranking defect types.

Table 10. Average log surface area occupied by defects for different log types.

Defect Type[a]	Defect Area (in^2)					
	Mean			Standard Deviation		
	Butt	Upper	All Types	Butt	Upper	All Types
Op	772.83	12.17	202.34	905.81	13.21	517.36
CBPk	257.87	4.97	173.57	590.58	2.52	483.72
GSU	104.30		115.72	56.27		57.57
OKCl	39.43	106.42	84.09	31.45	126.48	107.87
BS	80.11		80.11	26.66		26.66
GSS	61.92	88.75	70.17	77.60	108.44	84.38
SKC	40.45	61.06	60.42	40.54	57.63	57.06
B		56.90	56.90		97.91	97.91
SR	59.43	28.27	46.97	45.53	4.44	36.50
KCl		44.67	46.77		40.95	38.82
Bu		31.02	45.24		25.04	38.48
OSS	41.10		41.10	32.04		32.04
UKC	15.71	41.30	40.18	4.44	54.67	53.71
SK	0.88	37.37	35.85	0.65	133.02	130.40
Flu		34.56	34.56		31.10	31.10
DKC		33.63	32.86		23.87	22.21
HD	58.90	21.52	32.20	93.00	16.05	49.82
RKC	57.60	28.06	31.60	43.26	22.29	26.20
SW	35.80	14.66	28.75	11.47	9.07	14.65
R		25.92	25.92		3.33	3.33
Fla		21.99	21.99		0.00	0.00
OKC	19.47	21.58	21.36	26.14	15.16	16.40
RK	22.38	16.25	16.63	21.66	36.54	35.58
MD	22.19	13.17	15.35	29.45	10.22	17.15
UK	3.93	14.01	13.59	4.44	43.21	42.33
OK	7.84	7.37	7.50	14.37	18.68	17.56
LD	6.63	7.75	7.44	6.81	7.88	7.60
CL	7.66	3.47	4.52	2.50	1.58	2.54
GD	2.64	4.19	4.02	2.22	6.06	5.77
AD	5.66	2.88	3.89	15.76	4.87	10.23
AC	3.06	5.02	3.83	5.79	13.08	9.38
DK		2.19	2.24		2.13	2.08
OBPk		0.51	0.51		0.68	0.68
AK	0.39	0.38	0.39	0.43	0.72	0.59
SH		0.12	0.12		0.10	0.10
All Defects	16.34	16.18	16.23	101.97	49.01	70.03

[a] Key to defect types found in **Appendix A**.

To assess the relationship between log diameter and defect size, simple linear regression analysis was performed on 2-inch log diameter classes (independent variable) and mean defect surface area (dependent variable). The results are shown in **Table 11**. Since the null hypothesis for a slope value of zero was rejected for the combined defect values, we can generalize that log diameter is a good predictor of mean defect surface area over all defect types. The regression for the combined defect category produced a R-square value of 0.55 and a standard error of 3.309 $in.^2$. A scatter plot of the combined mean surface areas is shown in **Figure 10** along with the corresponding regression line. Of the individual defect types found to have slope values other than zero, sound wounds have the highest R-square value followed by operational defects, open sound seams, and rotten knots. Several other defects (bulges and adventitious bud clusters) have relatively high R-square values but failed the zero slope test. Among the defects with non-zero slope values, 80% showed a positive relationship, meaning that as log diameter increases, the average defect surface area increases also.

Table 11. Results of simple linear regression analysis with log diameter class as the independent variable and defect surface area as the dependent variable.

Defect Type[a]	R^2	Standard Error	Relationship	Regression Coefficients β_1	β_0	H_0: β_1=0
SW	0.96	8.598	Positive	3.5056	-51.211	Reject
Op	0.62	126.230	Positive	54.5470	-725.920	Reject
OSS	0.42	9.148	Negative	-2.5902	103.790	Reject
RK	0.30	14.319	Positive	4.3123	-43.292	Reject
SKC	0.25	7.902	Positive	1.8382	27.201	Reject
UKC	0.19	32.593	Positive	6.8204	-47.541	Reject
SK	0.17	12.206	Positive	2.3474	-12.488	Reject
GSU	0.16	24.967	Negative	-4.7434	233.140	Reject
CBPk	0.13	241.162	Positive	29.4440	-311.660	Reject
HD	0.13	14.302	Positive	1.9032	5.036	Reject
B	0.12	41.591	Positive	7.4641	-65.322	Reject
RKC	0.10	7.249	Positive	1.3513	10.371	Reject
GSS	0.09	29.385	Negative	-3.3811	145.330	Reject
UK	0.03	11.477	Positive	0.8988	8.021	Reject
OKCl	0.02	29.422	Positive	2.0468	37.999	Reject
Bu	0.68	27.384	Positive	5.1477	-46.174	Fail to Reject
AC	0.49	0.751	Positive	0.2620	-1.325	Fail to Reject
LD	0.25	0.878	Positive	0.2286	4.216	Fail to Reject
OKC	0.22	2.126	Positive	0.4873	13.440	Fail to Reject
CL	0.17	1.368	Negative	-0.2462	8.527	Fail to Reject
DKC	0.13	6.324	Positive	1.2534	11.698	Fail to Reject
OK	0.11	1.398	Positive	0.2268	3.029	Fail to Reject
MD	0.10	2.362	Negative	-0.3761	21.232	Fail to Reject
GD	0.09	0.926	Negative	-0.1982	7.291	Fail to Reject
AD	0.08	1.776	Negative	-0.2256	10.222	Fail to Reject
KCl	0.07	12.480	Positive	1.5338	23.385	Fail to Reject
AK	0.01	0.056	Positive	0.0024	0.364	Fail to Reject
DK	0.01	0.525	Negative	-0.0405	2.958	Fail to Reject
All Defects	0.55	3.309	Positive	1.0682	-1.801	Reject

[a] Key to defect types found in **Appendix A**.

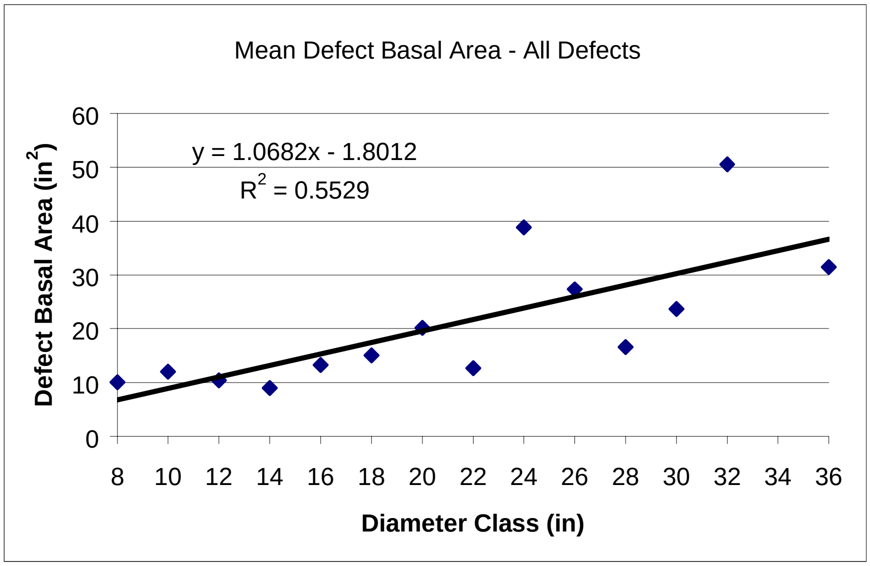


Figure 10. Scatter plot and corresponding regression line of mean defect basal area over all defect types by 2-inch diameter class.

5.1.4 Defect Location

The lengthwise location of all defects with respect to the percentage of total log length from the large end was determined for each log in the dataset. Findings were then summarized by log grade and log type to determine if any correlation exists. The results within each grade as well as the results for all grades combined are shown in **Figures 11-14**. In all figures, the percentage values of the total number of defects cover all defect types. In all cases, the majority of the defects are located toward the small end of the log but are more evident in the grade F1 and F2 logs. There is also more variability in the grade F1 and F2 distributions. However, if we divide each distribution into quarters and compare the quantity of defects in the outer two quarters to the quantity of defects in the inner two quarters, there is no significant difference. The proportion of defects in the center of the log is nearly equal to the proportion of defects on the log ends.

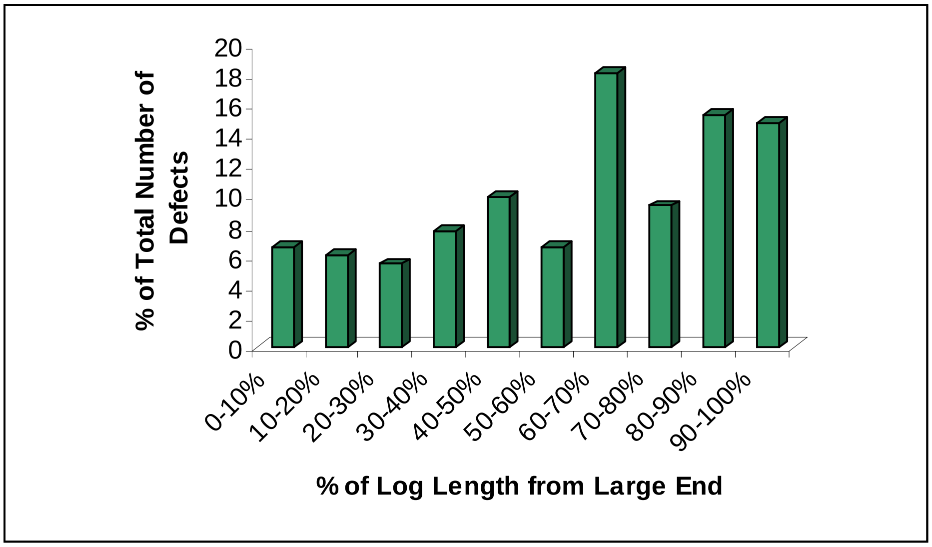


Figure 11. Grade F1 defect location distributions based on the percentage of total log length from the large end.

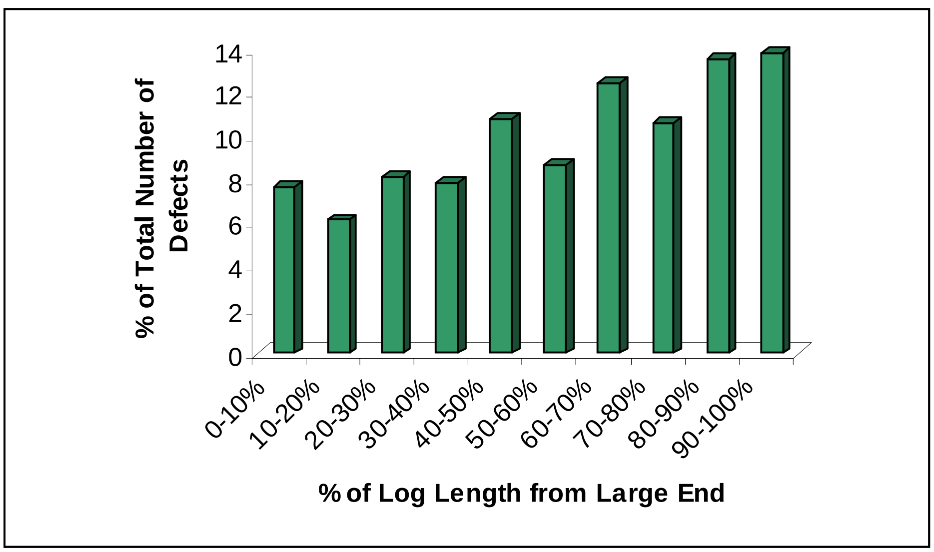


Figure 12. Grade F2 defect location distributions based on the percentage of total log length from the large end.

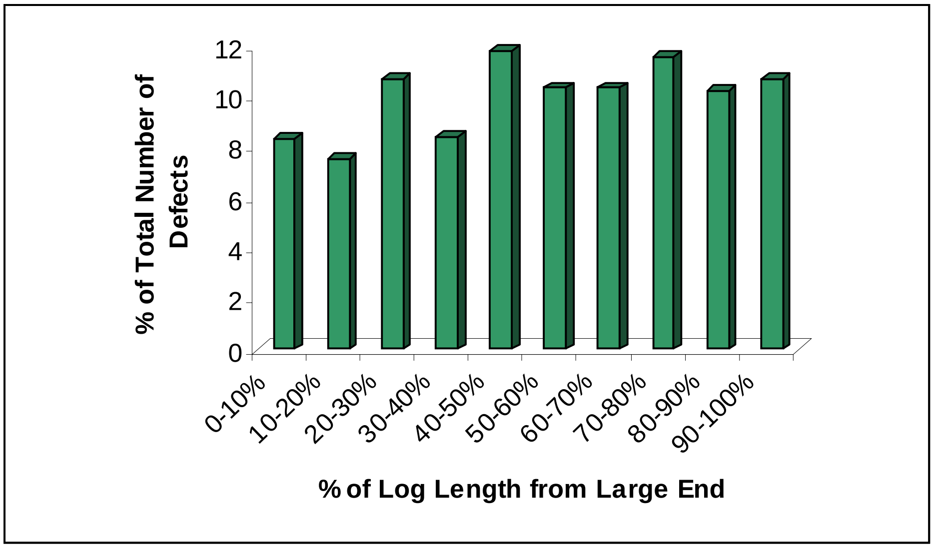


Figure 13. Grade F3 defect location distributions based on the percentage of total log length from the large end.

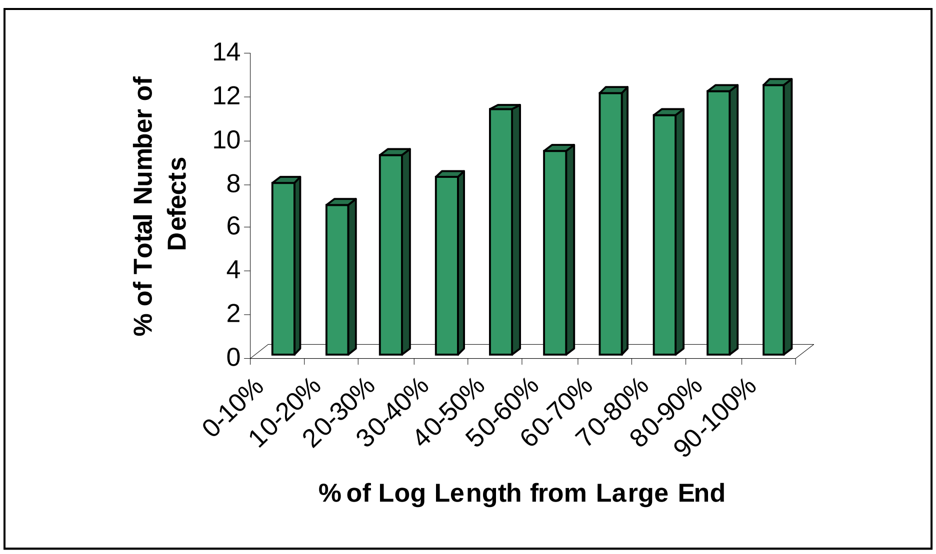


Figure 14. Defect location distributions for all log grades and types based on the percentage of total log length from the large end.

Figures 15-16 show the results of summarizing the defect location information by butt logs and upper logs respectively. Within the butt log category, 116% more defects are located toward the small end of the log, compared to only 6% for upper logs. If we compare the log ends to the log centers for both log types, there again is no significant difference in defect frequency.

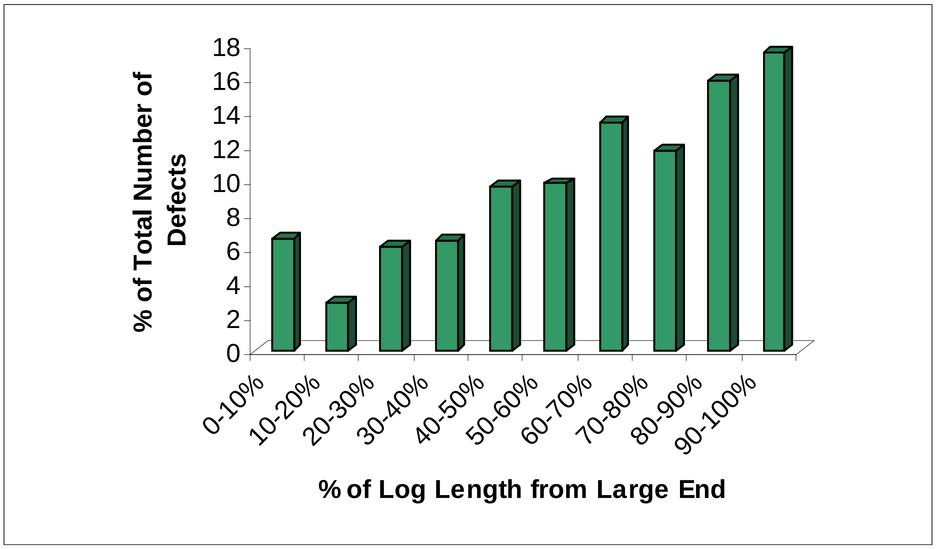


Figure 15. Butt log defect location distributions based on the percentage of total log length from the large end.

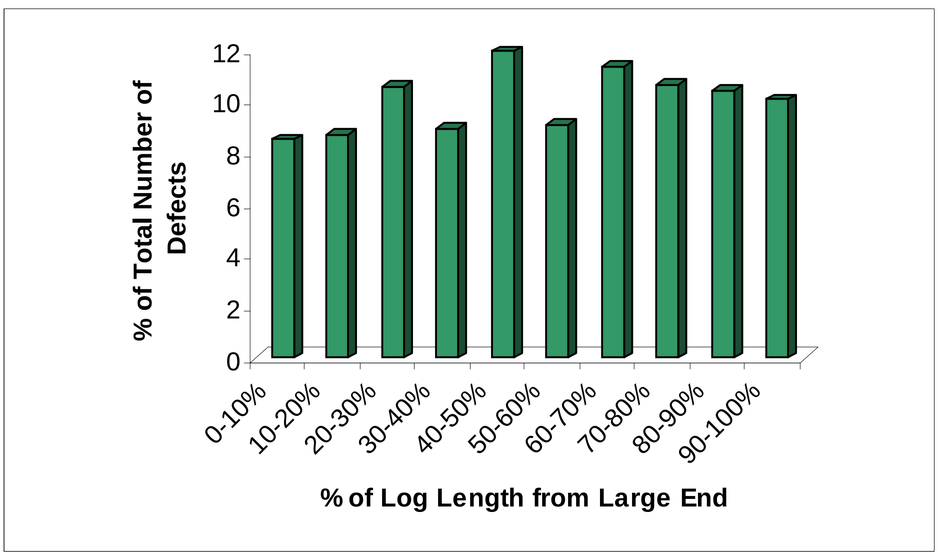


Figure 16. Upper log defect location distributions based on the percentage of total log length from the large end.

5.1.5 Sweep and Crook

Of the 110 logs sampled, 16.4% contained sweep and 11.8% contained crook (**Table 12**). Grade F1, F2 and F3 logs had 33.3%, 12.5% and 7.5% sweep respectively, while crook percentages were 26.7%, 10.0% and 2.5% respectively. The results indicate that the majority of sweep and crook occurs in grade F1 logs. However, since the maximum sweep/crook scaling deduction for grade F1 logs is 15%, we can assume that the severity of the defects are minimal. The results also show that sweep is found in 19.4% of the butt logs and 14.9% of the upper logs. Crook percentages for butt and upper logs are 13.9% and 10.8% respectively. By combining the results from the log grade and type analysis, we can hypothesize that grade F1 butt logs have the highest probability of containing sweep or crook.

Table 12. Percentage of total sample logs containing sweep or crook by log grade and type.

	Percent of Logs Containing Sweep/Crook					
Defect	Grade F1	Grade F2	Grade F3	Butt	Upper	All Logs
Sweep	33.3	12.5	7.5	19.4	14.9	16.4
Crook	26.7	10.0	2.5	13.9	10.8	11.8

Table 13 shows the mean scaling deductions due to sweep and crook for each log grade and type. The average scaling deduction for all occurrences of sweep is 11.4% and the average crook deduction is 7.9%. Scaling deductions due to sweep are 11.3%, 9.3% and 15.4% for grades F1, F2 and F3 logs respectively. Deductions due to crook are 8.4%, 6.3% and 10.8% respectively. Since all deductions are near or below 15%, it does not appear from the results that sweep and crook are significant log degraders. However, a larger sample of logs with sweep and crook would be necessary to better explain the relationship between scaling deductions and log grade. The current sample only contains 31 logs with either defect. When comparing mean scaling deductions by log type, butt logs have higher deductions than upper logs for both sweep and crook. Again, all averages are less than the maximum allowable grade F1 deduction of 15%.

Table 13. Average scaling deductions due to sweep and crook for each log grade and type.

	Mean Scaling Deduction (%)					
Defect	Grade F1	Grade F2	Grade F3	Butt	Upper	All Logs
Sweep	11.3	9.3	15.4	13.2	10.3	11.4
Crook	8.4	6.3	10.8	11.3	5.8	7.9

5.1.6 Defect Clustering

The mean surface distances between defect centers can be used as a measure of the amount of clustering between two defect types or defects of the same type. **Figure 17** shows several hypothetical defect arrangements for eight defects with various degrees of clustering. All defect arrangements that exhibit clustering have lower mean distances than the arrangement with no clustering. Also, as the number of defects within each cluster increases and the distance between clusters decreases, the mean distance decreases.

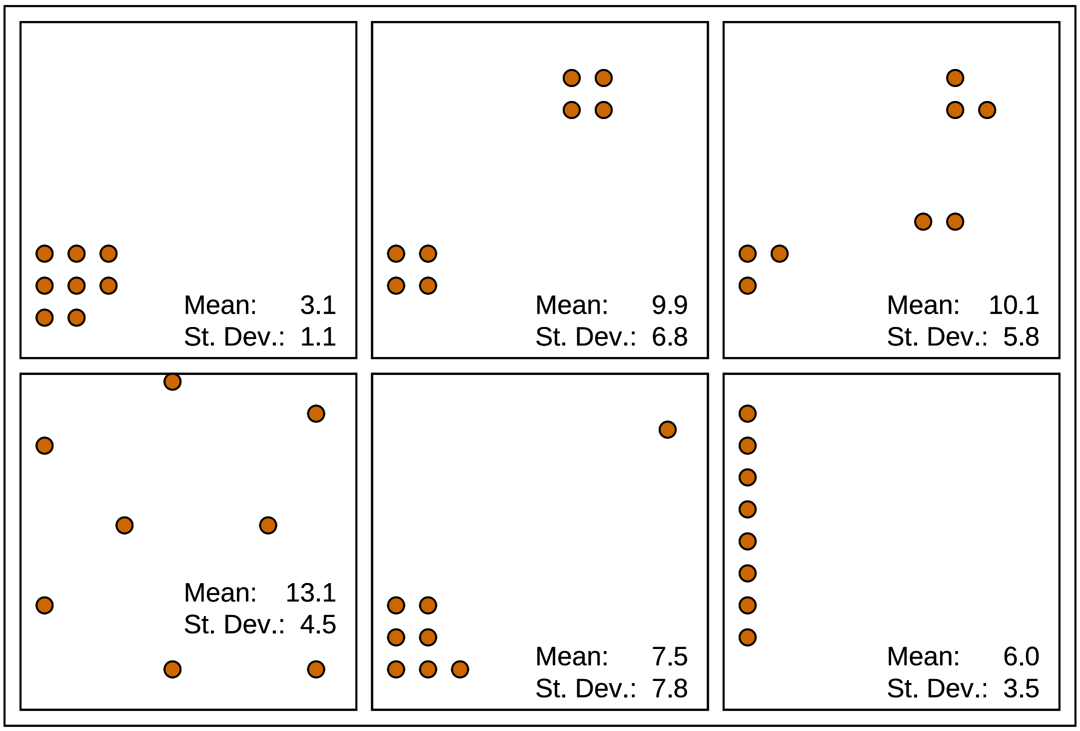


Figure 17. Mean distances and standard deviations for hypothetical defect arrangements.

For each log in the sample data, the distance from each defect center to all other defect centers was first determined. Results were then averaged over all logs for each defect pair combination. **Table 14** shows the mean distance between defects for all defect pairs that had 30 or more occurrences. Table entries are sorted by distance in ascending order. Theoretically, defect pairs with smaller mean distances should be more prone to clustering. Of course, the idea of clustering is subjective, since a minimum distance between defects first needs to be established before deciding if multiple defects are arranged in a cluster. The five defect pairs with the smallest mean distances are; rotten knots with callous growth and rotten knots; unsound knots with callous growth and unsound knots; closed bird peck and adventitious knots; sound wounds and adventitious knots; and rotten knots with callous growth and overgrown knots with callous growth.

Table 14. Mean surface distance between defect centers by defect type.

Defect Type[a]			Mean	Defect Type[a]			Mean	Defect Type[a]			Mean
Def 1	Def 2	n	Dist. (in)	Def 1	Def 2	n	Dist. (in)	Def 1	Def 2	n	Dist. (in)
RKC	RK	40	23.68	UK	AC	102	53.05	OK	GD	146	59.55
UKC	UK	158	37.49	GD	AK	92	53.23	SK	OKC	68	59.57
CBPk	AK	46	41.97	AD	AC	169	53.58	RK	LD	62	59.65
SW	AK	34	42.02	LD	LD	222	53.80	MD	AC	135	59.66
RKC	OKC	52	44.25	HD	AK	35	54.24	OCKl	OK	75	59.69
SK	RKC	33	44.54	AC	AC	851	54.41	CL	AK	27	59.88
SKC	SK	230	44.74	OKC	LD	112	54.63	SKC	SKC	77	59.95
RKC	AK	64	45.14	LD	AC	292	55.15	OK	LD	572	60.03
OKC	OK	292	45.38	UK	RK	38	55.17	SK	GD	45	60.16
RKC	OK	108	46.33	GD	GD	276	55.27	SKC	LD	71	60.23
AD	AD	161	46.83	OBPk	LD	32	55.51	SKC	AK	116	60.89
OKC	AK	167	47.32	OK	DK	71	55.53	LD	GD	34	61.23
RK	OKC	43	47.37	OK	AC	801	55.60	OKCl	AK	58	61.41
OKC	OKC	98	47.38	OK	HD	44	55.66	OK	KCl	30	61.54
HD	AC	46	47.82	AK	AC	1625	55.77	SKC	AD	152	61.77
HD	AD	32	48.09	OK	OBPk	111	56.05	MD	AK	171	61.85
OKC	OBPk	60	48.10	UKC	OK	220	56.15	Op	AK	94	63.21
RKC	LD	49	48.89	UK	SKC	36	56.33	SK	LD	91	63.27
UK	UK	60	49.16	UKC	SKC	42	56.35	OKCl	AC	73	63.77
UKC	AK	207	49.42	SK	SK	133	56.41	GD	AC	56	64.82
SK	RK	46	49.57	SKC	OKC	57	56.47	Op	AC	53	65.02
UK	AK	207	50.02	UK	OK	214	57.22	SKC	AC	89	66.16
UKC	OKC	63	50.44	OK	CL	50	57.41	OK	MD	210	66.80
GD	AD	91	50.49	SK	AC	103	57.51	MD	AD	72	67.03
UK	OKC	63	50.49	UKC	SK	43	57.73	SK	DK	41	67.56
UKC	UKC	56	50.78	OBPk	AK	38	57.79	SKC	DK	36	67.93
DK	AK	44	51.28	SK	OK	412	57.83	DK	AD	30	68.35
LD	AD	35	51.48	UK	SK	45	57.94	LD	DK	32	70.09
SKC	RK	34	51.55	OK	AD	316	58.06	SW	OK	70	70.36
RK	AK	81	51.61	MD	MD	47	58.07	Op	OK	38	71.64
AK	AD	185	51.64	SK	AK	165	58.18	UK	MD	34	72.51
RK	OK	156	51.70	SK	AD	179	58.45	SK	MD	34	73.64
OBPk	OBPk	46	51.95	UKC	LD	129	58.61	SKC	MD	30	74.66
MD	LD	110	52.42	UK	LD	128	58.65	OK	GSS	46	81.39
RK	AC	33	52.47	OK	AK	1188	58.68	OSS	OK	52	89.93
CBPk	AC	41	52.71	OK	B	35	58.89	OSS	AC	62	96.19
UKC	AC	91	52.79	SKC	OK	278	58.97	OSS	AK	92	111.07
UKC	RK	36	52.85	MD	GD	65	59.08				
LD	AK	472	53.03	UK	GD	33	59.45				

[a] Key to defect types found in **Appendix A**.

5.2 External and Internal Defect Correlation

Examples of each of the five external defect types and associated internal defects are shown in **Figure 18**. Note that while the entire external defect is visible, the CT image only represents one image slice through the defect.

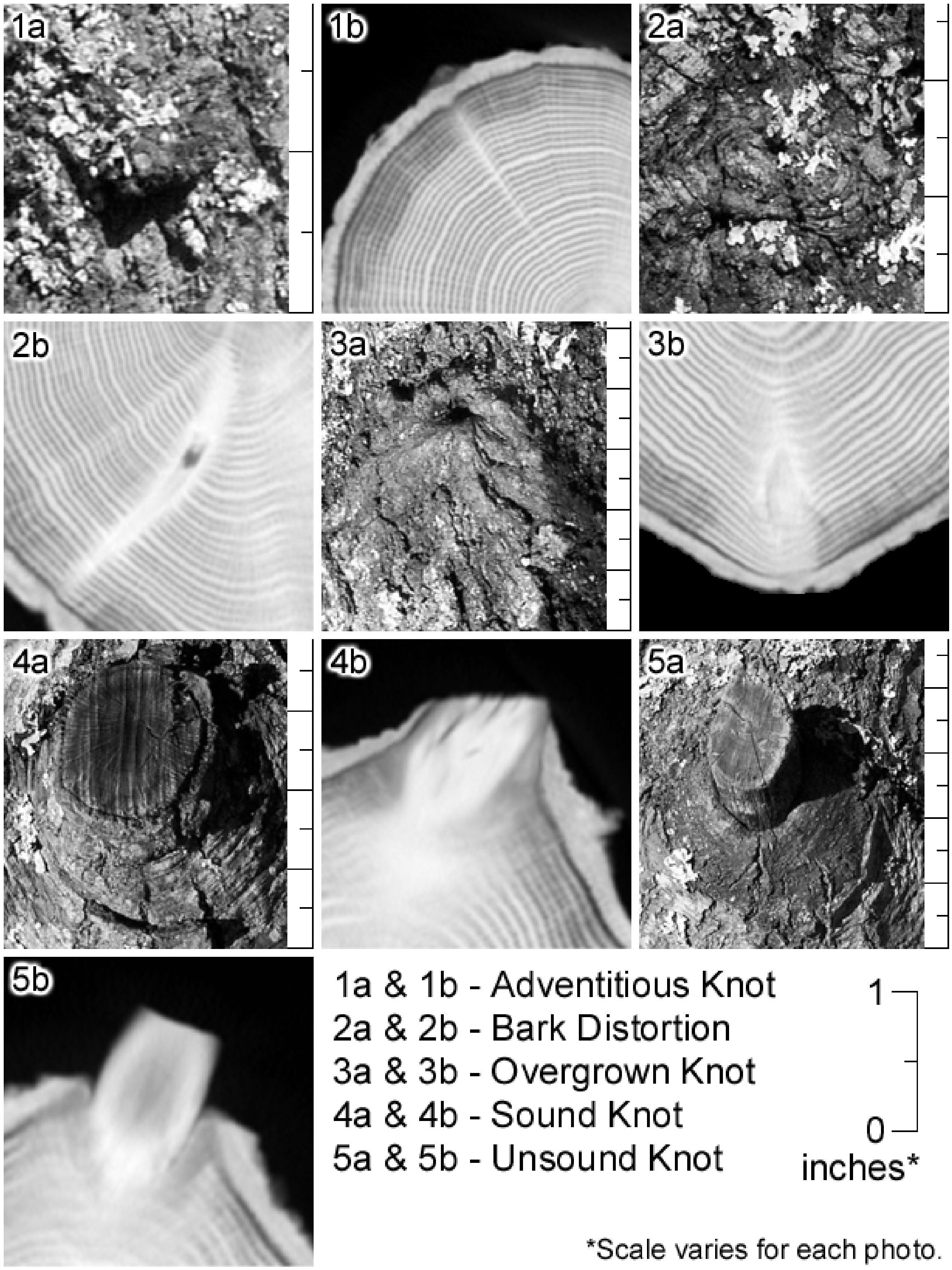


Figure 18. External defect indicators (a) and associated internal defects (b) for five red oak defect types.

5.2.1 Sample Logs

Of the 95 log sections sampled, 70 were northern red oak and 25 were scarlet oak, both of which are in the larger red oak group. The small-end outside bark diameters of the logs averaged 10.7 inches and ranged from 7.6 – 13.1 inches. Average log length was 20 inches and ranged from 11.5 – 30 inches. The number of small-diameter rings was also counted for each log and averaged 54.3 years. This corresponds to an average growth rate of approximately 0.2 inches/year (assuming a bark thickness of 0.5 inches). Individual log attributes are listed in **Appendix B**.

5.2.2 External Defect Indicators

An attribute summary of the sampled external defects is shown in **Appendix C**. The sample sizes of the five chosen defect types (adventitious knots, bark distortions, overgrown knots, sound knots, and unsound knots) are 50, 50, 52, 45, and 50 respectively. The average respective length, width and height measurements and standard deviations (in parentheses) are; 0.44(0.15), 0.57(0.21), 0.24(0.12) for adventitious knots; 1.56(0.51), 1.76(0.46), 0.01(0.05) for bark distortions; 2.54(0.88), 2.57(0.76), 0.72(0.27) for overgrown knots; 2.31(2.68), 1.91(1.49), 1.38(1.01) for sound knots; and 1.03(0.82), 0.91(0.65), 0.86(1.04) for unsound knots. The coefficient of variation values for all measurements are fairly high, averaging 88.04%. However, this is to be expected due to the wide variation in other factors such as log diameter and growth rate. Also, height measurements for sound and unsound knots were dependent upon where the sawyer delimbed the branches. Any meaningful variation analysis would need to take these factors into account.

5.2.3 Internal Defects

Internal defect information obtained from the CT data is also listed in **Appendix C** and contains defect volume, the minimum distance from the defect to the cambium, and the angle of the defect with respect to the pith. Adventitious knots have an average volume of 0.20 in^3 and an average depth of 0.15 inches. Angle measurements were not obtained for adventitious knots but it can be assumed that the defect grows near perpendicular to the pith. Internal defects associated with bark distortions have an average volume, depth, and angle of 35.24, 3.62, and 0.79 respectively. Overgrown knots have values of 38.56, 7.36, and 0.04 respectively. The average angle measurement for sound knots is 25.05 and the average volume is 19.38. Unsound knots have average angle and volume measurements of 41.34 and 11.38 respectively. The depth measurement for all sound and unsound knots equals zero since, by definition, these knots always extend beyond the normal surface of the log.

Note that defects appearing on less than five CT slices do not have associated angle values. Angle estimates for these defects were considered to be unreliable due to the small sample size. Another important thing to note from the data is that there are a few negative angle measurements. This implies that the defect gets closer to the pith as you move up the tree. This most likely occurred on defects that were adventitious in origin, where the defect centers did not change much from slice to slice. In actuality, the defect is probably perpendicular to the pith, but because of the subjectivity involved in delineating the defects on the CT images, the measurements produced a slightly negative slope. Accuracy of the CT measurements could possibly be improved by first incorporating a filtering algorithm to distinguish the defect from clear wood. This would remove any subjectivity involved in manual defect delineation.

5.2.4 Internal/External Defect Correlation

For each defect type and internal attribute, the model chosen using the PRESS method was tested to determine if a significant amount of variation in the dependent variables was explained by the predictor variables. All tests were performed at the 5% significance level and the summarized results are shown in **Table 15**. Complete SAS output for the regression analysis is listed in **Appendix D**. Significance was found in the volume variable for all defect types and has R^2 values ranging from 0.39 (adventitious knots) to 0.93 (sound knots). It appears from the results for all defects except adventitious knots that as the time since branch death increases, the certainty in predicting internal defect volume decreases. On the log surface, knots begin as sound (live) defects. Once they die, the external defect progresses to unsound, overgrown, and finally a bark distortion. Significance was also found for overgrown knot depth and sound knot angle. R^2 values are 0.27 and 0.32 respectively, lower than those obtained from the volume tests. All other tests proved to be insignificant. The final regression models for all dependent variables that tested significant are also shown in the table.

Table 15. Significance test results, R^2 values, and regression models for dependent variables of each defect type.

Defect Type	Dependent Variable	Significant Variation Explained?[a]	R^2	Regression Model[b]
Adventitious Knot	Angle	--	--	--
	Volume	Yes	0.3893	0.20365 + 0.0855×ln(length) + 0.92617×height²
	Depth	No	0.1049	--
Bark Distortion	Angle	No	0.1051	--
	Volume	Yes	0.5080	2.98786 - 13.93413×height - 0.02412×diameter² + 1.26960×lw
	Depth	No	0.0411	--
Overgrown Knot	Angle	No	0.0931	--
	Volume	Yes	0.6044	-0.83092 + 0.01521×diameter² + 0.8677×lw
	Depth	Yes	0.2742	0.06214 + 0.01217×width² - 0.14899×height
Sound Knot	Angle	Yes	0.3235	21.30083 - 44.68715×ln(length) + 58.77868×ln(width)
	Volume	Yes	0.9253	-15.35176 + 9.65642×length + 9.00918×height
	Depth	--	--	--
Unsound Knot	Angle	No	0.1253	--
	Volume	Yes	0.7920	-24.39964 + 13.32873×length + 8.92737×ln(diameter)
	Depth	--	--	--

[a] All tests were performed at the 5% level of significance.
[b] Insignificant models are not shown.

Even though several models were found to be significant, the R^2 values in general were fairly low. Since the R^2 values measure how well the model fits the data, there is a significant amount of variation not explained by the models. One way to improve the models would be to test different predictor variables. It seems reasonable that tree growth rate has the potential to be a significant predictor variable and could explain additional variation in the dependent variables. However, the intent of this study was to use predictor variables that were easily obtainable by visual inspection of the log surface.

Due to the limited data, it was not feasible to test the predictive ability of the models. Therefore, it is recommended that additional data be collected in order to test how well the models predict. Analysis of the residuals will show how applicable the models are to additional data.

5.3 ALOG

A screen capture of the ALOG program is shown in **Figure 19**. First, the user selects the desired attributes for the generated log, including the log position in the tree (butt or upper) and the Forest Service log grade. The program can also choose the attributes at random if preferred. Next, the *Generate Log* button is clicked and the log and defect data is calculated for the specified log type. In the example below, a grade 1, upper log was generated with a length of 10.24 feet and end diameters of 22.76 and 24.77 inches. Also shown is the length, depth, and radial location of crook associated with the log. In the *Defect Attributes* portion of the screen, all generated defects are listed along with the associated size and location values. Notice that internal information is also included for defect types that were found to have significant external/internal defect correlation.

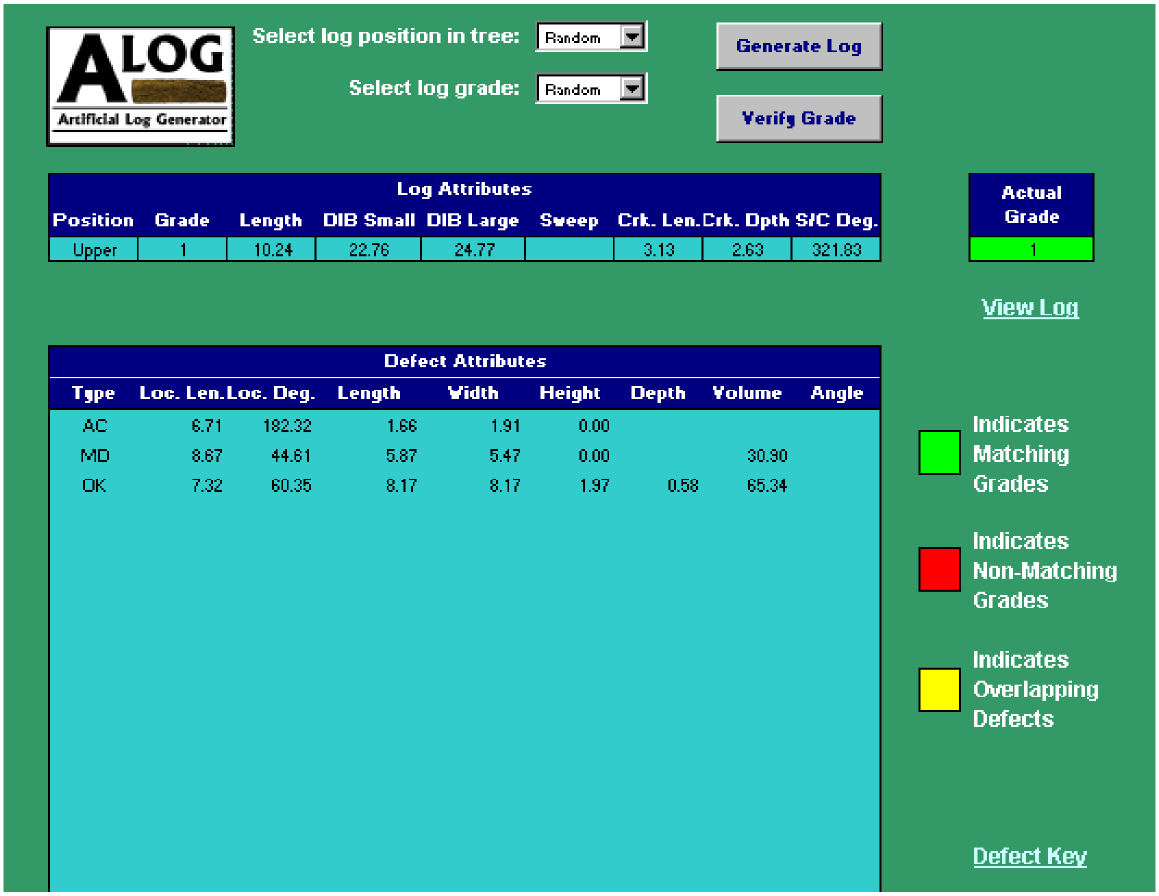


Figure 19. Screen capture of the ALOG program.

Once the log data has been generated, the user can click the *Verify Grade* button to calculate the actual grade of the log. In this case, the specified grade and the generated grade were the same. However, because of the randomness associated with the log and defect generation, this is not always the case. It should be noted though that the log generated is still a reasonable sample, it just has a grade different than that specified. If the grades match, the cell containing the actual grade appears green. Otherwise it appears red. Since no testing was done to assess the accuracy of the grading program, it would be advantageous to input manually graded log data into the program and compare grade results.

Another minor problem caused by the use of random values is that occasionally defects will overlap. If this happens, the defects and their attributes appear highlighted in yellow. As the program is now, the user has to generate another log until one with non-overlapping defects is created. In the future, an algorithm can be incorporated into the program to prevent overlapping defects or automatically generate another log when overlapping defects are detected.

Additional features of the ALOG program include a key to the defects and a rudimentary image of the generated log surface. The defect key is similar to that shown in **Appendix A** and includes descriptions of all defect types used in the program. The log image (**Figure 20**) represents an unrolled view of the log surface. Defects are shown in red and the grading face that was determined is shown in blue. There may be several grading faces but the program only displays the first one when moving from the top to the bottom of the image.

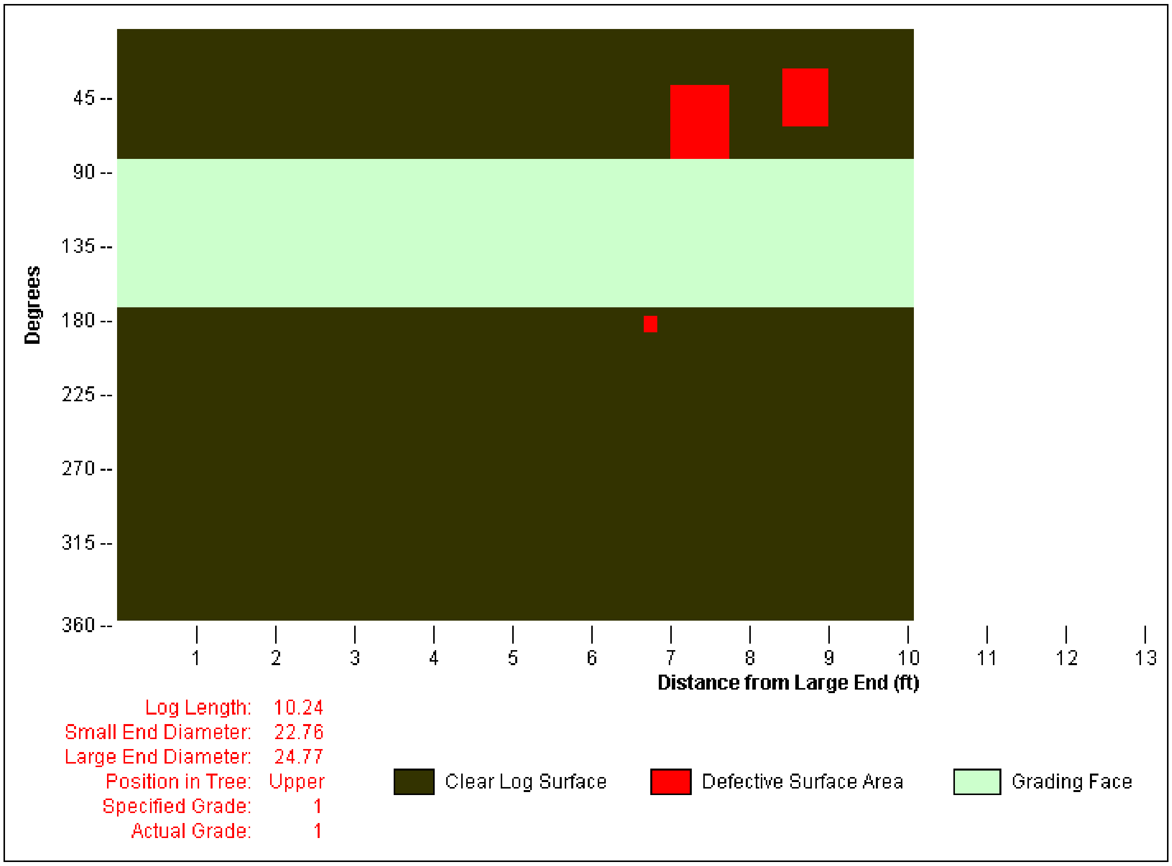


Figure 20. Screen capture of a sample log surface generated in ALOG.

One last thing to consider is that the program currently does not support log end defects. Since end defects are also considered when determining log grade, it would be beneficial to include them in the program in the future.

6 Conclusion

Sawing simulation computer programs can be an invaluable tool for training sawyers as well as for obtaining value-yield information for different sawing patterns. A major limitation of such programs, however, is that true log data (internal and external) can be difficult and costly to obtain. Also, most sawing simulation programs input log data via a database, which limits the number of logs that can be tested. ALOG, an artificial log generation program, can be a valuable alternative to using log databases. This Microsoft® Excel program can quickly generate simulated log and defect data. Also, since the program relies on drawing random values from known log data distributions, the number of unique logs that can be generated is infinite. This relates more closely to what one might find in a sawmill or logyard, where every log is different. Since the generated data is based on real log data, the simulated logs should be representative of possible log and defect configurations.

Though the external data generated by the program should be reliable, the internal defect information generated may not be so. Internal information, including defect volume, depth, and angle, was predicted using regression models based on external defect characteristics. Since only five defect types were tested and not all showed significance, the internal defect information in ALOG is incomplete. Also, the models that did show significance had relatively low R^2 values, indicating that the models did not explain a large amount of the variation. One solution to this problem might be to test other predictor variables for significance and see if a considerably larger amount of variation is explained. If not, it may be more feasible to simply pull internal defect attributes from known distributions, as was done with the external defect characteristics.

Future work on the ALOG program should focus on improving the accuracy of the internal defect information, adding end defects, improving upon the generated log image, and adding additional log species. In addition to the red oak log information, the Princeton log data also includes samples of white oak, maple, yellow-poplar and cherry. Therefore, it would be reasonable to assume that these species can be added to the program without much difficulty. Future work should also include additional testing of the program to assure accuracy in the generated log and defect data as well as accuracy in the grading portion of the program.

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8 Appendix A – Key to Defect Codes and Defect Definitions

Defect Code	Defect Type	Defect Description*
AC	Adventitious Bud Cluster	A localized group of adventitious buds, often originating from wounding or bruising of the cambium. Adventitious bud clusters often develop into clusters of short-lived fine twigs; when this happens, a bump usually develops that contains small bark pockets along with the twig knots.
AD	Ant or Bark Scarrer Damage	If a hole has remained open for a period of time, decay fungi can enter. Carpenter ants will then excavate the rotten wood and enlarge the galleries to make their nest cavities. Recent fresh attacks by the bark scarrer appear as open holes about one-quarter inch or less in diameter. They are identified by their round, irregular outline and by their nonpenetration of the wood. The work of the bark scarrer and borers results in a frothy exudation, which turns a dirty brown. Bark scarrer attacks can result in an overgrowth, appearing as a vertical slit with callus area on both sides.
AK	Individual Adventitious Bud	Subnormal buds found at points along the stem. They arise from latent or dormant buds in the leaf axils of the young stem and persist for an indefinite number of years within the cortical-cambial zone. These buds can be activated at any time during the life of the tree in response to various stimuli, leading to the development of an epicormic branch.
B	Bump	A protuberance on the tree or log surface that is overgrown with bark. It may be abrupt with steep surfaces, or it may be a smooth undulation that tapers gradually in all directions to the normal contour of the log. The majority of bumps cover projecting sound or rotten limb stubs, a cluster of adventitious buds, or a concentration of ingrown bark over a scar.
BS	Butt scar	Generally a triangular-shaped break in the bark or wood at the butt end of the first log caused by fire, logging, or other means.
Bu	Bulge	A general enlargement of the stem of a tree or log—a barreling effect—often without an evident cause such as a knot or callus formation. It may be near a branch stub, rotten knot, knothole, wound, or other point of entry for fungi that can cause rot. It usually suggests a cull section, the extent of the rot indicated by the farthest limits of the deformation.

CBPk	Closed Bird Peck	Occluded holes caused by bird attacks that are filled with callus tissue. Holes can appear singularly, linearly, or in groups. Damage usually extends into the wood in the form of bark flecks, callus pockets, and stain spots.
CL	Closed Lesion	A relatively localized, spindle-shaped necrotic canker consisting primarily of bark and cambium. A lesion starts as a small area of dead bark resulting from a wound caused by cambium-mining insects, mechanical wounding, fungal diseases, or gnawing of the bark by red squirrels. A spot of gum then appears, and gum continues to ooze through the bark down the trunk, where it hardens and darkens. Healing of the crack results in coarse vertical folds of ingrown bark. A closed lesion shows a prominent rib of callus, folded bark, and abnormal wood projections of the surface of the log.
DK	Dead Knot	Remnant of a branch consisting of all or a part of the stub. The knot consists of dead tissue but shows no presence of decay and may be as hard as the surrounding wood.
DKC	Dead Knot w/ Callous Growth	Remnant of a branch consisting of all or a part of the stub. The knot consists of dead tissue but shows no presence of decay and is covered or surrounded either partially or wholly with callous growth.
Fla	Flange	Triangular, buttress- or wing-like formations projecting from the base of the butt log. Exaggerated projections of the normal stump flare sometimes extend 7 or 8 feet and seem to be related to wetness and softness of site. Flanges occur outside the milling frustrum of the log but have no relation to blemishes in the underlying wood.
Flu	Flute	Folds or convolutions in the surface of a tree, extending upward from the base. They generally are accompanied by more than normal butt flare and usually include ingrown bark. If flutes do not extend deeply into the small end of the log and the ingrown bark does not extend into the right cylinder, they are disregarded as grading defects.
GBS	Overgrown Bark Seam	A seam that has healed to the point where a patch of bark is partially or wholly enclosed in the wood.
GD	Grub Damage	A scar in the bark resulting from grub work. Usually a sharp pucker consisting of a pitted core, not over 1/4 inch in diameter, surrounded by callous tissue and distorted bark over an area 3/4 inch to 2 inches in diameter. In severe cases a round "plaster" of callous tissue as large as 3 inches in diameter may occur.
GSS	Overgrown Sound Seam	Longitudinal radial separation of the fibers in a log overgrown with callous tissue and showing no signs of decay. They are usually caused by wind, frost, or lightening.

GSU	Overgrown Unsound Seam	Longitudinal radial separation of the fibers in a log overgrown with callous tissue but has decay beneath and possibly to the sides of the callous. They are usually caused by wind, frost, or lightening.
HD	Heavy Bark Distortion	An indicator of an overgrown knot identified by the characteristic pattern of concentric circles encompassing the defect indicator. Bark distortions differ from "overgrown knots" in that there is no height associated with the indicator.
KCl	Knot Cluster	Two or more knots or branches growing in a more or less inseparable group and usually elevated above the normal surface.
LD	Light Bark Distortion	An indicator of an overgrown knot identified by the characteristic pattern of concentric circles encompassing the defect indicator. Light distortions show only a slight amount of curvature in the surrounding bark plates, and the bark pattern shows only slight variance from normal. Since the internal knots associated with light bark distortions are usually buried deep within the log, it is not considered a grading defect in factory-grade logs. Bark distortions differ from "overgrown knots" in that there is no height associated with the indicator.
MD	Medium Bark Distortion	An indicator of an overgrown knot identified by the characteristic pattern of concentric circles encompassing the defect indicator. Medium distortions show signs of the concentric circles, but the circles are broken in several areas by the normal bark pattern starting to reform. Bark distortions differ from "overgrown knots" in that there is no height associated with the indicator.
MH	Medium Hole	Unoccluded openings in the bark, 3/16 to 1/2 inch in diameter, which sometimes penetrate into the wood beneath. They include entrance and emergence holes of wood-boring insects, increment-borer and tap holes, and openings made by sapsuckers.
OBPk	Open Bird Peck	Unoccluded openings in the bark caused by bird attacks. Generally, the holes show no signs of callus tissue formation. Open bird peck is an indication of a recent attack and usually doesn't affect the underlying wood.
OK	Overgrown Knot	A knot that has been completely overgrown but is clearly outlined by circular or other configurations in the bark. Overgrown knots differ from bark distortions in that there is an obvious height attribute of the defect when compared to the normal log surface.
OKC	Overgrown Knot w/ Callous Growth	A knot that has been completely overgrown but is clearly outlined by circular or other configurations in the bark. The knot is covered or surrounded either partially or wholly with callous growth.

OKCl	Overgrown Knot Cluster	Two or more overgrown knots growing in a more or less inseparable group.
Op	Operational Defect	Cracks, splits, brooming, splinter pull, "barber chair", holes, etc., that result from felling, skidding, or loading.
Oss	Open sound Seam	Longitudinal radial separation of the fibers in a log with no evidence of callous tissue or decay. They are usually caused by wind, frost, or lightening.
R	Rot	Advanced decay, not identifiable with a knot or branch.
RK	Rotten Knot	A knot where advanced decay is present and extends beyond the area of the limb stub.
RKC	Rotten Knot w/ Callous Growth	A rotten knot covered or surrounded either partially or wholly with callous growth. Advanced decay is present and extends beyond the area of the limb stub.
SH	Small Hole	Unoccluded openings less than three-tenths of an inch (0.8 cm) in diameter leading into the wood. The holes are often caused by insects of several genera of beetles, especially the ambrosia beetles. Small holes on the log surface are often accompanied by other features such as wounds or sap rot.
SK	Sound Knot	Remnant of a branch consisting of all or a part of the stub. The knot shows no indication of decay and is as hard as the surrounding wood.
SKC	Sound Knot w/ Callous Growth	Sound knot covered or surrounded either partially or wholly with callous growth. The knot shows no indication of decay and is as hard as the surrounding wood.
SR	Surface Rise	A smooth undulation in the surface of the log that gradually tapers back in all directions to the normal contour. When the taper of the rise is steeper than 1 to 6, it is classified as a bump. A surface rise usually results from a small limb stub, a cluster of adventitious buds, or a deeply buried knot or wound. Sometimes it reflects an earlier crook in the stem. Since the associated internal defect is buried deeply within the log, a surface rise is disregarded as a log grade defect.
SW	Sound Wound	Damage to the stem due to natural causes such as a limb falling against another tree or from logging. The wood underneath is sound and callous overgrowth may be open or closed or any degree of coverage of the wound.
UK	Unsound Knot	Remnant of a branch consisting of all or a part of the stub. The knot shows presence of decay and is not as hard as the surrounding wood. The amount of decay is normally confined to the limb stub.

UKC	Unsound Knot w/ Callous Growth	Unsound knot covered or surrounded either partially or wholly with callous growth. The knot shows presence of decay and is not as hard as the surrounding wood. The amount of decay is normally confined to the limb stub.

*Defect descriptions taken from; Carpenter, R., D. Sonderman, E. Rast and M. Jones. 1989. Defects in hardwood timber. USDA Forest Service Agriculture Handbook No. 678, Washington, DC.; Rast, E. 1982. Photographic guide of selected external defect indicators and associated internal defects in northern red oak. USDA Forest Service Research Paper NE-511, Broomall, PA.; and Bulgrin, E. Circa 1960. Manual of standard procedures for diagramming hardwood trees and primary products. USDA Forest Service Internal Document.

9 Appendix B – Scanned Log Attributes

			DOB (in)		Section	Sm. Diam.
Tree #	Log #	Species	Small	Large	Length (in)	Rings
1	1	Red Oak	13.1	13.5	17.75	71
1	2	Red Oak	12.7	13.0	18.00	71
1	4	Red Oak	12.1	12.4	21.00	68
1	5	Red Oak	11.8	11.8	20.00	65
1	6	Red Oak	11.7	11.5	17.75	64
1	8	Red Oak	11.0	11.4	22.00	63
1	9	Red Oak	10.6	11.1	29.00	34
1	10	Red Oak	10.1	10.4	18.50	33
1	11	Red Oak	9.5	10.2	22.00	31
1	12	Red Oak	9.4	9.3	20.50	28
1	13	Red Oak	8.7	9.1	17.75	28
2	1	Red Oak	13.0	14.3	22.25	42
2	2	Red Oak	12.4	13.0	21.00	39
2	3	Red Oak	11.7	12.1	22.00	36
2	5	Red Oak	11.5	11.5	24.00	34
2	7	Red Oak	11.1	11.3	20.00	32
2	9	Red Oak	10.8	10.6	24.00	31
2	11	Red Oak	7.8	8.3	20.00	27
3	1	Red Oak	13.0	14.0	16.00	37
3	3	Red Oak	12.0	12.2	16.00	36
3	6	Red Oak	11.1	11.5	15.25	33
3	7	Red Oak	11.5	11.8	18.50	32
3	8	Red Oak	10.9	11.1	19.00	32
3	10	Red Oak	11.0	11.5	25.00	28
3	12	Red Oak	9.8	11.2	20.50	26
4	1	Red Oak	11.9	12.6	21.00	60
4	2	Red Oak	11.1	11.2	19.50	58
4	3	Red Oak	11.2	11.1	18.50	58
4	4	Red Oak	10.8	11.2	22.25	57
4	5	Red Oak	10.3	10.7	19.00	56
4	6	Red Oak	10.3	10.3	18.50	54
4	7	Red Oak	10.1	10.3	18.00	51
4	8	Red Oak	9.6	9.8	18.00	48
4	9	Red Oak	10.0	9.8	17.50	48
4	11	Red Oak	9.4	9.4	25.50	46
4	12	Red Oak	8.9	9.3	13.50	45
4	15	Red Oak	8.5	8.1	20.00	41
4	16	Red Oak	8.1	8.4	14.00	37
4	17	Red Oak	8.3	8.1	22.00	33
5	2	Scarlet Oak	12.8	13.0	22.25	54
5	3	Scarlet Oak	12.4	12.7	12.00	53
5	4	Scarlet Oak	12.5	12.3	16.50	52
5	5	Scarlet Oak	12.5	12.5	19.00	52
5	6	Scarlet Oak	11.8	12.3	16.00	51
5	7	Scarlet Oak	11.9	11.8	16.00	50
5	9	Scarlet Oak	11.8	11.5	18.50	48
5	10	Scarlet Oak	11.3	11.5	19.00	48
5	11	Scarlet Oak	11.3	11.2	18.50	47
5	12	Scarlet Oak	10.7	11.4	30.00	45
5	13	Scarlet Oak	10.0	10.4	14.25	44
5	14	Scarlet Oak	9.9	10.0	25.50	40
5	16	Scarlet Oak	8.9	9.2	18.25	39
5	17	Scarlet Oak	9.0	8.9	17.00	39
5	19	Scarlet Oak	8.7	9.1	16.75	35
6	1	Red Oak	11.8	12.2	18.25	83
6	2	Red Oak	11.5	11.7	13.00	82
6	3	Red Oak	11.5	11.5	19.75	78
6	4	Red Oak	11.2	11.4	22.25	77

			DOB (in)		Section	Sm. Diam.
Tree #	Log #	Species	Small	Large	Length (in)	Rings
6	5	Red Oak	11.0	11.3	21.50	76
6	6	Red Oak	11.4	11.0	11.50	70
6	7	Red Oak	11.0	11.6	20.25	67
6	8	Red Oak	11.1	11.0	17.75	64
6	9	Red Oak	10.6	11.0	14.25	61
6	10	Red Oak	10.4	10.6	19.50	57
6	11	Red Oak	10.4	10.5	21.25	51
6	12	Red Oak	10.3	10.6	22.00	45
6	13	Red Oak	9.8	10.4	24.25	40
6	14	Red Oak	9.5	9.7	21.00	38
6	15	Red Oak	9.3	9.5	26.25	34
6	16	Red Oak	8.7	9.4	24.75	31
6	17	Red Oak	8.3	8.6	22.00	29
6	18	Red Oak	7.6	8.3	24.25	28
7	1	Scarlet Oak	12.0	12.4	15.00	80
7	2	Scarlet Oak	11.9	12.0	16.50	79
7	3	Scarlet Oak	12.0	11.9	25.50	78
7	4	Scarlet Oak	11.7	12.0	28.50	77
7	5	Scarlet Oak	11.5	11.5	18.75	76
7	6	Scarlet Oak	11.1	11.4	12.25	75
7	7	Scarlet Oak	11.0	11.2	26.50	72
7	8	Scarlet Oak	10.6	10.7	21.25	70
7	9	Scarlet Oak	10.4	10.6	27.50	68
7	10	Scarlet Oak	10.2	10.5	28.50	67
8	1	Red Oak	12.3	12.7	17.00	97
8	2	Red Oak	12.0	12.2	21.00	90
8	3	Red Oak	11.6	11.8	21.00	86
8	4	Red Oak	11.6	11.7	14.25	82
8	5	Red Oak	11.2	11.5	24.75	80
8	6	Red Oak	11.1	11.3	15.25	79
8	7	Red Oak	11.3	11.3	25.75	78
8	8	Red Oak	10.6	11.4	26.50	74
8	9	Red Oak	10.2	10.5	18.25	71
8	10	Red Oak	10.0	10.2	22.50	69
8	12	Red Oak	9.6	10.0	23.00	65
8	13	Red Oak	9.6	9.6	19.00	65
8	14	Red Oak	9.9	9.6	14.00	63

10 Appendix C – Internal and External Defect Attributes

		Defect	Defect Location		Defect Size			DOB	Angle	Volume	Minimum
Tree #	Log #	Type[a]	Angle[b]	Dist. From LE (in)	Length	Width	Height	at Defect	Rel. to Pith[c]	(in^3)	Depth
1	1	OK	12	9.50	2.50	3.00	0.50	13.27	48.84	7.78	0.00
1	2	D	4	15.50	1.25	1.75	0.00	12.75	23.47	3.76	0.00
1	2	UK	2	13.00	0.25	0.25	0.00	12.78	43.36	2.54	0.00
1	4	OK	12	6.25	3.00	3.50	0.75	12.35	25.44	5.75	0.22
1	4	OK	8	18.25	3.00	3.00	0.50	12.17	55.25	3.61	0.20
1	5	D	2	9.00	1.50	2.00	0.00	11.81	51.69	1.77	1.31
1	5	OK	4	16.50	2.00	2.50	0.50	11.81	36.32	6.83	0.00
1	5	UK	5	14.50	0.50	0.50	0.00	11.81	32.31	4.54	0.00
1	6	SK	12	7.50	2.25	2.25	0.75	11.59	--	16.45	0.00
1	6	SK	12	14.25	0.50	0.50	0.50	11.50	--	1.92	0.00
1	8	D	9	7.75	1.50	1.50	0.00	11.28	50.85	2.18	0.41
1	8	D	1	8.75	1.25	2.00	0.00	11.26	--	0.31	1.28
1	8	UK	12	16.00	2.00	1.50	0.75	11.13	--	14.59	0.00
1	9	SK	4	9.50	1.75	1.50	0.75	10.93	--	12.11	0.00
1	9	UK	7	24.50	1.25	1.00	0.00	10.67	6.11	3.48	0.00
1	9	UK	6	24.75	2.00	1.50	1.25	10.67	50.15	19.97	0.00
1	10	SK	12	15.00	1.25	1.50	0.50	10.15	43.46	7.66	0.00
1	10	SK	12	16.00	0.50	0.50	0.75	10.13	--	0.24	0.00
1	11	SK	12	18.00	2.00	2.00	1.25	9.64	45.26	10.96	0.00
1	12	SK	8	18.75	0.25	0.25	0.75	9.30	--	0.96	0.00
1	12	UK	12	17.25	1.00	1.00	0.50	9.32	50.04	7.29	0.00
1	13	AK	6	12.00	0.25	0.50	0.25	8.87	--	0.16	0.00
1	13	SK	12	11.25	2.75	2.50	1.50	8.88	42.82	16.68	0.00
2	1	OK	12	19.00	3.00	2.50	1.00	13.15	50.53	4.08	0.00
2	2	OK	3	13.75	4.00	4.25	2.00	12.62	24.56	23.72	0.00
2	2	OK	11	12.00	3.00	3.00	1.00	12.67	41.54	8.71	0.00
2	2	OK	2	10.50	4.00	3.00	1.00	12.72	46.01	6.11	0.00
2	2	UK	12	16.25	1.00	0.50	0.00	12.54	28.94	14.47	0.00
2	3	D	12	13.00	1.50	2.00	0.00	11.87	--	0.63	0.81
2	3	OK	12	18.50	3.00	3.25	0.75	11.76	41.30	5.15	0.00
2	3	OK	6	16.00	3.00	2.75	0.50	11.81	50.95	4.63	0.00
2	5	D	7	19.75	1.00	1.25	0.00	11.46	-3.52	2.72	0.59
2	5	D	8	15.25	1.00	1.00	0.00	11.47	-1.62	1.81	0.47
2	5	OK	8	8.00	2.75	2.00	0.50	11.48	34.77	5.00	0.00
2	5	UK	12	20.25	1.50	1.25	1.50	11.46	24.87	24.31	0.00
2	5	UK	12	18.75	0.75	0.75	0.50	11.47	--	0.56	0.00
2	7	OK	4	3.50	1.75	2.25	0.50	11.30	50.66	1.74	0.17
2	7	UK	4	15.50	1.25	1.25	1.25	11.19	36.64	12.32	0.00
2	7	UK	1	5.00	0.75	0.75	1.00	11.29	58.79	7.76	0.00
2	9	D	2	12.25	1.25	1.25	0.00	10.73	45.06	0.83	2.41
2	9	OK	9	20.25	1.50	2.00	0.50	10.66	38.28	3.45	0.00
2	9	UK	7	15.75	1.25	1.25	1.50	10.70	41.30	19.59	0.00
2	11	AK	5	12.00	0.50	1.00	0.25	8.00	--	0.11	0.41
2	11	UK	12	10.00	1.00	1.00	1.50	8.05	41.55	8.66	0.00
3	1	D	12	9.50	2.00	2.50	0.00	13.41	44.36	5.95	0.18
3	3	D	10	8.00	2.25	2.50	0.00	12.11	49.04	3.64	0.38
3	3	OK	12	14.25	2.75	2.50	0.75	12.06	23.02	11.44	0.00
3	6	UK	9	10.00	0.50	0.50	0.00	11.25	38.19	5.10	0.00
3	6	UK	10	9.75	0.50	0.50	0.00	11.26	46.38	3.12	0.00
3	7	AK	12	3.50	0.50	0.50	0.00	11.76	--	0.14	0.79
3	7	D	4	5.50	1.50	1.25	0.00	11.73	43.04	3.07	0.90
3	7	D	10	4.50	1.25	2.00	0.00	11.74	49.80	3.01	0.51
3	7	UK	6	12.75	0.50	0.75	0.50	11.62	47.42	4.64	0.00
3	8	D	12	12.50	1.25	1.75	0.00	10.95	49.74	3.80	0.48
3	10	UK	12	16.50	4.00	3.25	3.50	11.16	44.95	39.21	0.00
3	12	AK	5	5.00	0.50	0.50	0.00	10.87	--	0.07	0.55
3	12	SK	12	14.75	7.00	4.50	2.00	10.17	25.63	94.12	0.00

Tree #	Log #	Defect Type[a]	Defect Location Angle[b]	Defect Location Dist. From LE (in)	Defect Size Length	Defect Size Width	Defect Size Height	DOB at Defect	Angle Rel. to Pith[c]	Volume (in^3)	Minimum Depth
4	1	D	2	4.50	1.25	1.25	0.00	12.45	40.09	3.33	0.63
4	1	D	9	18.25	1.00	1.00	0.00	11.98	58.81	3.16	0.00
4	2	AK	10	7.50	0.50	0.50	0.25	11.16	--	0.13	0.27
4	3	AK	12	6.50	0.75	0.75	0.00	11.19	--	0.05	0.52
4	3	OK	6	14.00	1.50	1.50	1.00	11.16	34.33	6.61	0.00
4	3	UK	8	8.75	0.25	0.25	0.00	11.18	50.35	3.01	0.00
4	4	D	6	10.50	1.50	1.25	0.00	11.03	49.25	2.55	1.14
4	5	OK	12	13.75	1.50	1.25	0.50	10.41	34.13	6.03	0.00
4	6	D	7	14.75	1.75	1.75	0.00	10.28	35.95	4.42	0.58
4	6	D	1	11.00	1.25	1.50	0.00	10.29	49.73	1.95	1.37
4	7	D	5	13.50	2.00	1.75	0.00	10.17	28.90	8.27	0.32
4	8	AK	11	16.00	0.50	0.75	0.25	9.67	--	0.03	0.00
4	9	D	7	8.25	1.75	1.50	0.00	9.89	32.76	3.36	0.70
4	11	OK	12	21.25	2.75	3.50	0.75	9.38	9.23	13.04	0.00
4	11	UK	9	12.75	0.25	0.25	0.00	9.39	39.92	1.75	0.00
4	12	D	7	5.75	1.25	1.50	0.25	9.08	45.57	1.46	0.08
4	15	AK	1	3.50	0.50	0.50	0.00	8.44	--	0.06	0.60
4	15	D	7	9.50	1.25	1.25	0.00	8.34	--	0.74	1.23
4	15	UK	1	8.75	0.25	0.25	0.00	8.35	44.83	2.75	0.00
4	15	UK	5	5.00	0.50	0.50	0.00	8.42	47.33	3.21	0.00
4	15	UK	12	17.75	1.50	1.25	5.00	8.19	48.55	12.50	0.00
4	16	SK	12	6.00	3.00	2.75	1.25	8.29	38.87	14.36	0.00
4	17	D	7	14.00	2.00	2.00	0.00	8.14	13.14	9.13	0.00
4	17	UK	12	11.50	2.00	1.50	1.00	8.16	32.87	15.01	0.00
5	2	OK	7	11.25	2.50	2.25	0.75	12.87	40.09	6.30	0.00
5	2	OK	3	11.00	1.75	3.00	0.50	12.88	47.67	7.23	0.00
5	3	AK	2	7.00	0.50	0.50	0.25	12.53	--	0.27	0.00
5	3	AK	6	5.25	0.50	0.50	0.25	12.58	--	0.29	0.00
5	4	OK	2	11.50	1.50	2.00	0.75	12.34	46.84	4.15	0.00
5	5	D	3	10.25	1.50	2.00	0.00	12.48	36.61	3.08	0.00
5	5	UK	12	11.00	0.50	0.50	0.50	12.48	53.87	12.00	0.00
5	5	UK	7	10.25	0.25	0.25	0.00	12.48	--	1.69	0.00
5	6	D	10	5.25	2.00	2.00	0.00	12.14	49.45	2.35	0.44
5	6	OK	7	9.25	1.50	1.75	0.50	12.00	26.75	9.16	0.00
5	6	UK	12	3.25	0.75	0.75	1.25	12.21	--	4.98	0.00
5	7	OK	10	6.50	2.00	2.50	0.50	11.83	48.99	3.80	0.00
5	7	UK	9	7.00	0.50	0.50	0.75	11.83	--	0.38	0.00
5	9	AK	5	17.00	0.50	0.50	0.25	11.52	--	0.21	0.55
5	9	UK	7	13.00	1.25	1.00	0.00	11.59	41.69	21.54	0.00
5	9	UK	10	15.50	1.00	1.00	1.50	11.55	54.19	12.76	0.00
5	10	AK	6	2.25	0.50	0.50	0.00	11.47	--	0.10	0.00
5	10	OK	4	7.50	3.00	2.75	0.75	11.40	42.60	17.36	0.00
5	10	UK	1	12.50	0.50	0.50	0.75	11.34	40.16	9.14	0.00
5	11	AK	1	5.25	1.00	1.00	0.25	11.28	--	0.10	0.00
5	11	AK	9	10.25	0.50	0.50	0.25	11.26	--	0.06	0.30
5	12	AK	6	17.25	0.50	0.50	0.25	10.99	--	0.10	0.00
5	12	SK	12	22.50	17.00	8.00	2.00	10.88	10.64	170.37	0.00
5	12	UK	1	5.00	1.50	1.25	2.00	11.27	47.79	14.09	0.00
5	12	UK	9	20.00	1.75	1.50	4.00	10.93	53.19	21.09	0.00
5	12	UK	8	18.50	0.50	0.50	1.00	10.97	--	0.27	0.00
5	13	AK	9	6.25	0.50	0.50	0.25	10.22	--	0.28	0.00
5	13	AK	11	10.75	0.50	0.50	0.00	10.10	--	0.19	0.00
5	13	AK	4	5.50	0.50	0.75	0.25	10.24	--	0.18	0.00
5	13	UK	2	10.50	0.75	0.75	1.50	10.10	-1.65	3.78	0.00
5	14	AK	9	19.75	0.50	0.50	0.25	9.92	--	0.25	0.00
5	14	UK	3	23.75	3.75	2.50	1.00	9.89	34.33	54.12	0.00
5	14	UK	11	19.50	1.50	1.25	0.50	9.92	37.61	17.45	0.00
5	16	AK	9	16.25	0.50	0.50	0.25	8.93	--	0.29	0.00
5	16	SK	2	2.75	0.50	0.50	1.00	9.17	-12.49	1.60	0.00
5	17	D	9	13.00	1.50	1.50	0.00	8.92	32.40	1.71	0.92
5	19	AK	3	8.75	0.50	0.50	0.25	8.87	--	0.15	0.00
6	1	D	8	10.75	1.25	2.00	0.00	11.97	--	2.62	0.63

		Defect	Defect Location		Defect Size			DOB	Angle	Volume	Minimum
Tree #	Log #	Type[a]	Angle[b]	Dist. From LE (in)	Length	Width	Height	at Defect	Rel. to Pith[c]	(in^3)	Depth
6	2	D	2	8.00	1.50	1.50	0.00	11.60	--	0.75	2.38
6	2	OK	12	5.75	1.50	2.00	0.75	11.62	11.74	4.54	0.00
6	3	D	1	17.75	1.50	1.50	0.00	11.50	52.39	2.06	0.69
6	3	D	3	16.25	1.50	2.25	0.00	11.50	47.43	1.13	2.32
6	3	OK	9	15.50	1.75	2.50	0.50	11.50	54.74	4.34	0.00
6	3	OK	2	16.75	1.75	1.75	0.50	11.50	--	1.79	0.00
6	4	D	9	16.50	2.50	2.25	0.25	11.27	39.25	2.01	0.39
6	4	OK	12	7.25	1.00	1.25	1.00	11.35	--	2.51	0.00
6	4	SK	8	11.25	1.00	1.00	1.50	11.32	--	5.35	0.00
6	4	UK	4	11.75	0.25	0.25	0.00	11.31	48.85	7.60	0.00
6	4	UK	5	6.00	0.50	0.50	0.00	11.36	--	4.51	0.00
6	5	OK	11	4.25	2.50	2.50	1.00	11.21	2.74	6.85	0.00
6	5	UK	12	17.75	0.50	0.50	0.00	11.06	47.50	7.61	0.00
6	6	AK	12	8.25	0.50	1.00	0.50	11.11	--	0.31	0.00
6	6	OK	9	9.50	1.75	2.25	0.50	11.06	55.55	2.57	0.00
6	6	OK	3	4.00	2.50	2.00	0.50	11.27	56.19	4.18	0.00
6	7	SK	5	19.00	1.00	1.00	1.25	11.06	41.61	4.91	0.00
6	7	SK	8	14.50	1.00	0.75	1.25	11.19	--	3.66	0.00
6	7	UK	12	10.00	3.00	3.00	2.00	11.32	45.11	66.16	0.00
6	8	D	7	15.25	1.00	1.75	0.00	11.03	--	1.41	0.16
6	9	AK	11	10.50	0.50	0.50	0.25	10.70	--	0.35	0.00
6	9	SK	5	5.00	1.00	1.00	1.25	10.87	--	7.69	0.00
6	10	AK	6	4.50	0.50	1.00	0.50	10.52	--	0.43	0.00
6	10	AK	4	4.25	0.50	0.50	0.25	10.53	--	0.42	0.00
6	10	OK	9	5.50	2.50	2.50	0.75	10.52	-7.98	5.18	0.00
6	10	UK	4	16.50	0.50	0.50	1.00	10.45	45.54	6.94	0.00
6	11	SK	12	12.25	0.50	0.50	0.75	10.40	--	1.90	0.00
6	11	SK	11	13.00	1.00	0.75	0.75	10.40	--	2.00	0.00
6	11	UK	6	7.25	1.50	1.50	1.25	10.43	48.35	25.08	0.00
6	12	AK	3	17.00	0.50	0.75	0.25	10.39	--	0.21	0.00
6	12	AK	3	17.75	0.50	0.75	0.25	10.38	--	0.05	0.22
6	12	AK	5	17.50	0.25	0.25	0.25	10.38	--	0.05	0.00
6	13	AK	11	4.00	0.50	0.75	0.25	10.33	--	0.23	0.00
6	13	AK	2	18.00	0.50	0.75	0.25	9.97	--	0.37	0.00
6	13	D	5	17.00	1.00	1.50	0.00	9.99	18.40	1.66	1.83
6	13	UK	8	6.50	0.75	0.75	0.50	10.26	39.29	8.42	0.00
6	14	AK	12	9.00	0.50	0.50	0.25	9.62	--	0.48	0.00
6	14	AK	4	11.25	0.25	0.25	0.75	9.60	--	0.57	0.00
6	14	AK	4	6.25	0.50	0.50	0.25	9.64	--	0.21	0.00
6	14	D	7	4.50	1.00	1.00	0.00	9.65	--	1.39	1.54
6	14	OK	2	19.50	1.25	1.25	0.50	9.54	--	1.63	0.00
6	14	SK	12	0.50	0.50	0.50	1.75	9.68	--	0.84	0.00
6	15	AK	12	1.25	0.25	0.50	0.25	9.52	--	0.12	0.00
6	15	AK	3	4.75	0.25	0.50	0.25	9.49	--	0.12	0.00
6	15	AK	2	8.25	0.25	0.50	0.25	9.47	--	0.07	0.00
6	15	AK	8	12.50	0.25	0.50	0.25	9.43	--	0.11	0.00
6	15	D	6	3.50	1.50	1.50	0.00	9.50	21.63	6.77	0.33
6	15	D	3	24.25	1.25	1.50	0.00	9.35	38.92	2.86	0.55
6	15	OK	4	19.50	4.00	3.50	0.75	9.38	42.75	10.16	0.30
6	16	AK	6	2.25	0.50	0.50	0.25	9.38	--	0.32	0.00
6	16	AK	9	6.50	0.25	0.25	0.25	9.24	--	0.12	0.18
6	16	SK	12	21.50	4.50	3.50	4.50	8.76	29.86	84.84	0.00
6	16	SK	5	20.50	3.75	3.25	3.50	8.80	44.47	37.21	0.00
6	16	UK	6	5.50	0.75	0.75	0.50	9.27	45.11	8.68	0.00
6	16	UK	11	21.75	0.75	0.50	1.00	8.76	45.64	2.94	0.00
6	16	UK	3	4.00	0.50	0.50	0.50	9.32	51.10	3.60	0.00
6	17	SK	12	16.00	3.25	2.50	2.00	8.38	37.22	37.16	0.00
6	17	SK	7	11.00	0.50	0.50	1.00	8.44	--	0.81	0.00
6	17	UK	6	14.00	1.00	0.75	0.00	8.41	32.24	9.55	0.00
6	18	AK	4	18.75	0.25	0.25	0.25	7.78	--	0.18	0.00
6	18	AK	1	16.00	0.50	0.50	0.25	7.85	--	0.12	0.35
6	18	SK	11	13.50	3.50	3.00	4.00	7.92	23.14	65.37	0.00

		Defect	Defect Location		Defect Size			DOB	Angle	Volume	Minimum
Tree #	Log #	Type[a]	Angle[b]	Dist. From LE (in)	Length	Width	Height	at Defect	Rel. to Pith[c]	(in^3)	Depth
6	18	SK	12	22.50	3.75	3.50	4.00	7.68	31.43	54.53	0.00
6	18	UK	3	19.50	1.25	1.25	1.00	7.76	30.09	11.87	0.00
7	1	AK	3	11.50	0.25	0.75	0.25	12.13	--	0.13	1.37
7	1	OK	12	10.50	3.50	3.00	1.00	12.15	45.51	12.81	0.00
7	2	AK	9	10.00	0.25	0.50	0.25	11.94	--	0.13	0.00
7	2	OK	12	12.75	2.25	2.50	0.50	11.92	37.44	4.71	0.33
7	3	AK	6	11.25	0.50	0.50	0.25	11.98	--	0.39	0.00
7	3	OK	2	11.25	2.25	2.00	0.75	11.98	47.06	8.59	0.00
7	3	OK	12	9.75	2.25	2.00	1.00	11.99	56.04	6.71	0.00
7	4	OK	6	15.00	3.00	2.50	0.75	11.80	32.16	13.88	0.08
7	4	OK	3	26.00	2.25	3.00	0.75	11.68	57.77	6.14	0.00
7	4	SK	12	12.00	2.25	2.25	2.75	11.84	21.90	26.63	0.00
7	4	SK	6	23.25	2.25	2.00	1.00	11.71	--	14.93	0.00
7	5	OK	12	12.75	2.50	2.25	0.50	11.47	58.87	4.63	0.00
7	6	AK	6	4.50	0.50	0.50	0.25	11.29	--	0.23	0.00
7	6	OK	3	2.00	1.75	1.75	0.25	11.34	-2.64	2.97	0.00
7	6	UK	12	4.00	0.25	0.25	0.00	11.30	--	0.83	0.00
7	7	OK	7	10.25	2.75	2.50	0.75	11.10	47.52	7.52	0.00
7	7	OK	5	24.25	3.50	3.50	1.00	11.00	54.61	5.56	0.00
7	7	SK	9	23.50	2.75	2.50	1.00	11.01	--	14.12	0.00
7	7	SK	12	21.00	3.50	3.50	1.50	11.03	--	27.79	0.00
7	8	OK	4	15.50	3.00	3.00	0.50	10.61	44.83	6.33	0.32
7	8	OK	12	14.00	2.50	2.25	0.50	10.62	47.98	5.86	0.00
7	9	OK	12	12.25	3.00	2.50	0.75	10.48	35.31	6.20	0.00
7	9	SK	12	21.00	4.50	4.00	1.00	10.43	5.18	27.21	0.00
7	9	SK	6	20.00	1.25	1.25	1.25	10.44	--	10.01	0.00
7	9	SK	8	24.25	3.25	2.50	1.50	10.41	--	20.77	0.00
7	9	SK	11	7.75	0.25	0.25	0.75	10.51	--	0.46	0.00
7	10	AK	1	17.25	0.50	1.00	0.25	10.32	--	0.19	0.39
7	10	AK	1	22.25	0.25	1.00	0.25	10.27	--	0.19	0.00
7	10	AK	9	25.00	0.25	0.50	0.25	10.24	--	0.19	0.45
7	10	AK	10	12.50	0.25	0.25	0.25	10.37	--	0.13	0.47
7	10	D	8	25.50	1.25	2.00	0.00	10.23	56.52	1.50	0.99
7	10	OK	12	18.75	3.00	2.50	0.75	10.30	31.60	10.61	0.00
7	10	OK	3	25.50	2.50	2.75	0.50	10.23	46.81	4.04	0.33
8	1	OK	12	10.00	6.00	5.50	1.00	12.45	26.72	33.45	0.26
8	2	D	9	18.25	2.75	3.00	0.00	11.99	36.08	9.76	0.91
8	2	OK	12	10.50	3.00	3.00	0.75	12.07	40.21	16.51	0.00
8	3	D	9	13.50	2.00	2.00	0.00	11.66	30.46	8.99	0.55
8	3	D	12	15.25	3.50	2.50	0.00	11.64	33.19	8.08	0.85
8	3	D	7	17.75	1.50	1.75	0.00	11.61	33.47	4.20	0.66
8	4	D	2	5.00	2.00	2.50	0.00	11.63	33.45	9.02	1.30
8	4	OK	12	11.25	2.00	2.00	0.75	11.59	34.67	5.32	0.00
8	5	D	8	20.50	1.25	1.50	0.00	11.27	39.44	2.83	1.09
8	5	OK	9	12.00	3.50	3.50	1.00	11.38	33.06	5.27	0.00
8	5	SK	12	21.25	0.75	0.75	1.00	11.27	16.27	9.90	0.00
8	5	SK	6	6.25	1.50	2.00	0.75	11.46	--	6.14	0.00
8	5	SK	9	6.25	3.25	2.75	1.00	11.46	--	6.47	0.00
8	6	SK	12	9.00	2.50	1.75	0.50	11.19	18.33	7.86	0.00
8	7	D	7	6.75	2.00	2.25	0.00	11.33	34.18	3.42	0.96
8	7	UK	1	23.00	0.75	0.75	0.75	11.30	--	1.63	0.00
8	8	D	4	16.00	2.50	2.50	0.00	10.89	17.45	14.53	0.52
8	8	SK	11	23.50	1.00	1.00	0.75	10.65	24.88	5.69	0.00
8	9	AK	2	16.25	0.25	0.25	0.25	10.23	--	0.10	0.00
8	9	SK	12	15.00	0.25	0.25	0.25	10.25	0.15	3.38	0.00
8	9	SK	9	7.00	1.50	1.25	0.50	10.39	--	7.91	0.00
8	9	SK	12	16.50	0.50	0.50	1.00	10.23	--	1.66	0.00
8	9	SK	1	9.50	0.75	0.75	3.00	10.35	--	2.76	0.00
8	10	D	1	4.50	1.50	1.50	0.00	10.20	5.83	2.77	0.46
8	10	D	3	17.50	1.25	1.50	0.00	10.08	11.35	1.88	1.61
8	10	D	4	7.75	1.00	1.00	0.00	10.17	--	1.25	0.00
8	10	SK	12	9.25	2.00	2.00	0.75	10.16	12.31	6.97	0.00

		Defect	Defect Location		Defect Size			DOB	Angle	Volume	Minimum
Tree #	Log #	Type[a]	Angle[b]	Dist. From LE (in)	Length	Width	Height	at Defect	Rel. to Pith[c]	(in^3)	Depth
8	12	SK	12	9.50	3.75	3.75	0.50	9.84	--	9.94	0.00
8	13	D	6	15.75	1.75	2.00	0.00	9.58	24.57	4.64	1.00
8	13	SK	12	13.25	2.25	2.50	0.75	9.59	--	7.74	0.00
8	14	D	12	11.00	1.25	2.00	0.00	9.67	31.33	6.48	0.56

[a] Respectively, defect codes AK, D, OK, SK, and UK represent adventitious knots, bark distortions, overgrown knots, sound knots, and unsound knots.

[b] Angle value represents the clockwise angle of the defect center from an arbitrary reference point marked on the small end of the log.

[c] Angle values for defects that occurred on less than 5 CT slices were not included.

11 Appendix D – SAS Output for Regression Analysis

Adventitious Knot Volume

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	5	0.60573	0.42917	ln_length	width2	height2	ln_diameter	ln_lw
2	4	0.56338	0.39898	ln_length		height2	ln_diameter	ln_lw
3	4	0.59178	0.42794	ln_length	width2	height2		ln_lw
4	4	0.59480	0.42854		width2	height2	ln_diameter	ln_lw
5	4	0.60321	0.41400	ln_length	width2	height2	ln_diameter	
6	4	0.90754	0.03187	ln_length	width2		ln_diameter	ln_lw
7	3	0.52363	0.39208	ln_length		height2	ln_diameter	
8	3	0.53745	0.36409			height2	ln_diameter	ln_lw
9	3	0.55281	0.39559	ln_length		height2		ln_lw
10	3	0.58279	0.42718		width2	height2		ln_lw
11	3	0.59122	0.34535		width2	height2	ln_diameter	
12	3	0.59533	0.41115	ln_length	width2	height2		
13	3	0.85319	0.02408	ln_length			ln_diameter	ln_lw
14	3	0.85372	0.01885	ln_length	width2		ln_diameter	
15	3	0.87515	0.01055		width2		ln_diameter	ln_lw
16	3	0.88934	0.02755	ln_length	width2			ln_lw
17	2	0.51154	0.38925	ln_length		height2		
18	2	0.52420	0.35909			height2		ln_lw
19	2	0.54804	0.34300			height2	ln_diameter	
20	2	0.59088	0.33313		width2	height2		
21	2	0.81937	0.01791	ln_length			ln_diameter	
22	2	0.83142	0.00623		width2		ln_diameter	
23	2	0.83662	0.01628	ln_length	width2			
24	2	0.83700	0.02101	ln_length				ln_lw
25	2	0.84313	0.00884				ln_diameter	ln_lw
26	2	0.85818	0.00718		width2			ln_lw

The REG Procedure
Model: MODEL1
Dependent Variable: ak_volume

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.29116	0.14558	14.98	<.0001
Error	47	0.45683	0.00972		
Corrected Total	49	0.74799			

Root MSE	0.09859	R-Square	0.3893
Dependent Mean	0.19564	Adj R-Sq	0.3633
Coeff Var	50.39415		

Parameter Estimates

Parameter Standard

Variable	DF	Estimate	Error	t Value	Pr > |t|
Intercept	1	0.20365	0.03812	5.34	<.0001
ln_length	1	0.08550	0.04061	2.11	0.0406
height2	1	0.92617	0.17266	5.36	<.0001

Adventitious Knot Depth

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	4	4.51229	0.17921		ln_width	height	diameter2	ln_lw
2	4	4.51229	0.17921	ln_length	ln_width	height	diameter2	ln_lw
3	4	4.51229	0.17921	ln_length	ln_width	height	diameter2	
4	4	4.51229	0.17921	ln_length		height	diameter2	ln_lw
5	3	4.02375	0.13335			height	diameter2	ln_lw
6	3	4.06867	0.13469		ln_width	height	diameter2	
7	3	4.13268	0.15392	ln_length		height	diameter2	
8	3	4.23047	0.14561		ln_width	height		ln_lw
9	3	4.23047	0.14561	ln_length	ln_width	height		ln_lw
10	3	4.23047	0.14561	ln_length	ln_width	height		
11	3	4.23047	0.14561	ln_length		height		ln_lw
12	3	4.74266	0.05597	ln_length			diameter2	ln_lw
13	3	4.74266	0.05597	ln_length	ln_width		diameter2	ln_lw
14	3	4.74266	0.05597	ln_length	ln_width		diameter2	
15	3	4.74266	0.05597		ln_width		diameter2	ln_lw
16	2	3.75936	0.10493			height		ln_lw
17	2	3.83119	0.11713	ln_length		height		
18	2	3.84821	0.11195		ln_width	height		
19	2	3.90375	0.13119			height	diameter2	
20	2	4.20331	0.04116		ln_width		diameter2	
21	2	4.23638	0.03709				diameter2	ln_lw
22	2	4.43505	0.04245	ln_length			diameter2	
23	2	4.43769	0.01645	ln_length				ln_lw
24	2	4.43769	0.01645	ln_length	ln_width			ln_lw
25	2	4.43769	0.01645	ln_length	ln_width			
26	2	4.43769	0.01645		ln_width			ln_lw

The REG Procedure
Model: MODEL1
Dependent Variable: ak_depth

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.39295	0.19648	2.75	0.0739
Error	47	3.35212	0.07132		
Corrected Total	49	3.74507			

Root MSE	0.26706	R-Square	0.1049
Dependent Mean	0.14840	Adj R-Sq	0.0668
Coeff Var	179.96036		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.31676	0.11539	2.75	0.0085
height	1	-0.72956	0.31340	-2.33	0.0243
ln_lw	1	-0.00447	0.06090	-0.07	0.9419

Distortion Angle

Obs	Number of regressors in model	Press statistics	R-squared	Model
1	4	10897.58	0.11552	ln_length ln_width height ln_diameter ln_lw
2	4	10897.58	0.11552	ln_length ln_width height ln_diameter
3	4	10897.58	0.11552	ln_length height ln_diameter ln_lw
4	4	10897.58	0.11552	ln_width height ln_diameter ln_lw
5	3	10419.33	0.10509	ln_length height ln_diameter
6	3	10621.82	0.10584	height ln_diameter ln_lw
7	3	10650.83	0.10896	ln_width height ln_diameter
8	3	10769.05	0.09120	ln_length ln_width ln_diameter ln_lw
9	3	10769.05	0.09120	ln_length ln_width ln_diameter
10	3	10769.05	0.09120	ln_length ln_diameter ln_lw
11	3	10769.05	0.09120	ln_width ln_diameter ln_lw
12	3	11035.33	0.03146	ln_length height ln_lw
13	3	11035.33	0.03146	ln_length ln_width height ln_lw
14	3	11035.33	0.03146	ln_length ln_width height
15	3	11035.33	0.03146	ln_width height ln_lw
16	2	9643.82	0.10505	height ln_diameter
17	2	10242.76	0.08137	ln_length ln_diameter
18	2	10392.18	0.08322	ln_diameter ln_lw
19	2	10416.78	0.08680	ln_width ln_diameter
20	2	10653.13	0.01293	ln_length height
21	2	10745.42	0.02547	ln_width height
22	2	10762.58	0.01813	height ln_lw
23	2	11047.37	0.01995	ln_length ln_lw
24	2	11047.37	0.01995	ln_length ln_width ln_lw
25	2	11047.37	0.01995	ln_length ln_width
26	2	11047.37	0.01995	ln_width ln_lw

The REG Procedure
Model: MODEL1
Dependent Variable: dis_angle

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1001.44650	500.72325	2.29	0.1148
Error	39	8531.33902	218.75228		
Corrected Total	41	9532.78552			

Root MSE	14.79028	R-Square	0.1051
Dependent Mean	35.23617	Adj R-Sq	0.0592
Coeff Var	41.97470		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-70.89624	52.39442	-1.35	0.1838
height	1	44.28222	43.43393	1.02	0.3142
ln_diameter	1	44.17451	21.85981	2.02	0.0502

Distortion Volume

Obs	Number of regressors in model	Press statistics	R-squared	Model

1	5	313.785	0.51113	length	width2	height	diameter2	lw
2	4	278.889	0.51085	length		height	diameter2	lw
3	4	280.783	0.50990	length	width2	height	diameter2	
4	4	295.294	0.50941		width2	height	diameter2	lw
5	4	303.674	0.45718	length	width2		diameter2	lw
6	4	329.156	0.48127	length	width2	height		lw
7	3	262.997	0.50804			height	diameter2	lw
8	3	281.604	0.45639	length	width2		diameter2	
9	3	281.949	0.45651	length			diameter2	lw
10	3	289.885	0.48765	length		height	diameter2	
11	3	291.807	0.45545		width2		diameter2	lw
12	3	292.116	0.48124	length		height		lw
13	3	294.643	0.48053	length	width2	height		
14	3	295.829	0.39577		width2	height	diameter2	
15	3	304.580	0.43756	length	width2			lw
16	3	310.626	0.47838		width2	height		lw
17	2	269.875	0.45506				diameter2	lw
18	2	275.382	0.47140			height		lw
19	2	281.088	0.43731	length				lw
20	2	281.196	0.43707	length	width2			
21	2	287.222	0.43195	length			diameter2	
22	2	292.486	0.47080	length		height		
23	2	292.825	0.43488		width2			lw
24	2	307.890	0.35161		width2	height		
25	2	308.907	0.35978		width2		diameter2	
26	2	450.931	0.01787			height	diameter2	

The REG Procedure
Model: MODEL1
Dependent Variable: dis_volume

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	214.54192	71.51397	15.83	<.0001
Error	46	207.75555	4.51643		
Corrected Total	49	422.29747			

Root MSE	2.12519	R-Square	0.5080
Dependent Mean	3.62050	Adj R-Sq	0.4760
Coeff Var	58.69868		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	2.98786	1.54523	1.93	0.0593
height	1	-13.93413	6.26061	-2.23	0.0310
diameter2	1	-0.02412	0.01304	-1.85	0.0706
lw	1	1.26960	0.18754	6.77	<.0001

Distortion Depth

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	5	20.7507	0.060622	length	width	height	diameter2	lw
2	4	19.8032	0.060562	length		height	diameter2	lw

3	4	20.0200	0.057539		width	height	diameter2	lw
4	4	20.0539	0.042737	length	width	height		lw
5	4	20.0663	0.059279	length	width	height	diameter2	
6	4	20.9603	0.022786	length	width		diameter2	lw
7	3	19.0560	0.055420			height	diameter2	lw
8	3	19.0823	0.042638	length		height		lw
9	3	19.0953	0.057031	length		height	diameter2	
10	3	19.3328	0.054434		width	height	diameter2	
11	3	19.3504	0.041562		width	height		lw
12	3	19.3530	0.042450	length	width	height		
13	3	19.9679	0.022711	length			diameter2	lw
14	3	20.2997	0.021246	length	width		diameter2	
15	3	20.3696	0.018572		width		diameter2	lw
16	3	20.3739	0.011623	length	width			lw
17	2	18.4067	0.041076			height		lw
18	2	18.4270	0.042347	length		height		
19	2	18.5021	0.054412			height	diameter2	
20	2	18.7076	0.038751		width	height		
21	2	19.3364	0.018734	length			diameter2	
22	2	19.3694	0.011517	length				lw
23	2	19.3889	0.015595				diameter2	lw
24	2	19.6762	0.011075	length	width			
25	2	19.7440	0.012490		width		diameter2	
26	2	19.7464	0.009367		width			lw

The REG Procedure
Model: MODEL1
Dependent Variable: dis_depth

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.72710	0.36355	1.01	0.3732
Error	47	16.97437	0.36116		
Corrected Total	49	17.70147			

Root MSE	0.60096	R-Square	0.0411
Dependent Mean	0.78840	Adj R-Sq	0.0003
Coeff Var	76.22568		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.88362	0.16923	5.22	<.0001
height	1	-2.21764	1.74390	-1.27	0.2098
lw	1	-0.02512	0.05059	-0.50	0.6218

Overgrown Knot Angle

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	5	20363.99	0.14620	length2	width2	height2	ln_diameter	lw2
2	4	13262.31	0.06534	length2	width2	height2		lw2
3	4	14064.65	0.09635	length2	width2	height2	ln_diameter	
4	4	16090.03	0.14251	length2		height2	ln_diameter	lw2
5	4	20721.38	0.08454	length2	width2		ln_diameter	lw2

6	4	27774.56	0.11436		width2	height2	ln_diameter	lw2
7	3	12259.75	0.06229	length2		height2		lw2
8	3	12547.79	0.06668		width2		ln_diameter	lw2
9	3	12823.53	0.09309		width2	height2	ln_diameter	
10	3	12855.24	0.05768	length2	width2		ln_diameter	
11	3	13543.50	0.09369	length2		height2	ln_diameter	
12	3	13640.39	0.02874	length2	width2	height2		
13	3	14019.63	0.08443	length2			ln_diameter	lw2
14	3	16226.58	0.04229		width2	height2		lw2
15	3	21104.54	0.09833			height2	ln_diameter	lw2
16	3	23360.60	0.02969	length2	width2			lw2
17	2	11682.06	0.09307			height2	ln_diameter	
18	2	12005.04	0.06433				ln_diameter	lw2
19	2	12403.50	0.05534		width2		ln_diameter	
20	2	12659.69	0.04956	length2			ln_diameter	
21	2	12723.18	0.02639		width2	height2		
22	2	12772.45	0.01508		width2			lw2
23	2	12927.03	0.00725	length2	width2			
24	2	13070.07	0.02708	length2		height2		
25	2	14427.25	0.02969	length2				lw2
26	2	15943.94	0.02968			height2		lw2

The REG Procedure
Model: MODEL1
Dependent Variable: ok_angle

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1081.47601	540.73801	2.36	0.1057
Error	46	10539	229.09837		
Corrected Total	48	11620			

Root MSE	15.13600	R-Square	0.0931
Dependent Mean	38.55840	Adj R-Sq	0.0536
Coeff Var	39.25473		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-87.95512	70.27654	-1.25	0.2171
height2	1	-6.14030	3.92325	-1.57	0.1244
ln_diameter	1	53.21951	28.93843	1.84	0.0724

Overgrown Knot Volume

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	5	962.05	0.63267	length2	width2	height	diameter2	lw
2	4	859.11	0.60624	length2	width2		diameter2	lw
3	4	869.19	0.63251		width2	height	diameter2	lw
4	4	877.61	0.63179	length2	width2	height	diameter2	
5	4	879.66	0.63254	length2		height	diameter2	lw
6	4	930.05	0.63223	length2	width2	height		lw
7	3	790.42	0.60446		width2		diameter2	lw
8	3	802.12	0.60448	length2			diameter2	lw

9	3	802.32	0.60230	length2	width2		diameter2	
10	3	820.75	0.63250			height	diameter2	lw
11	3	829.66	0.60247	length2	width2			lw
12	3	837.71	0.63217		width2	height		lw
13	3	846.39	0.63158	length2	width2	height		
14	3	849.08	0.63219	length2		height		lw
15	3	874.32	0.60503		width2	height	diameter2	
16	3	925.29	0.61227	length2		height	diameter2	
17	2	747.68	0.60444				diameter2	lw
18	2	763.74	0.60149		width2			lw
19	2	774.45	0.59977	length2	width2			
20	2	775.25	0.60157	length2				lw
21	2	798.85	0.63214			height		lw
22	2	821.38	0.57865	length2			diameter2	
23	2	844.43	0.56556		width2		diameter2	
24	2	857.36	0.60501		width2	height		
25	2	895.45	0.61140	length2		height		
26	2	1295.96	0.28138			height	diameter2	

The REG Procedure
Model: MODEL1
Dependent Variable: ok_volume

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	969.76554	484.88277	37.44	<.0001
Error	49	634.63022	12.95164		
Corrected Total	51	1604.39576			

Root MSE	3.59884	R-Square	0.6044
Dependent Mean	7.35683	Adj R-Sq	0.5883
Coeff Var	48.91831		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-0.83092	3.33491	-0.25	0.8043
diameter2	1	0.01521	0.02514	0.60	0.5481
lw	1	0.86770	0.10385	8.36	<.0001

Overgrown Knot Depth

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	5	0.43124	0.33560	length2	width2	height	ln_diameter	lw
2	4	0.40637	0.31991	length2	width2	height		lw
3	4	0.43019	0.31452	length2		height	ln_diameter	lw
4	4	0.43522	0.30818		width2	height	ln_diameter	lw
5	4	0.43589	0.30567	length2	width2	height	ln_diameter	
6	4	0.49456	0.21105	length2	width2		ln_diameter	lw
7	3	0.41513	0.28928	length2		height		lw
8	3	0.41813	0.30193		width2	height	ln_diameter	
9	3	0.41893	0.30315			height	ln_diameter	lw
10	3	0.42080	0.27918	length2	width2	height		
11	3	0.42096	0.28263		width2	height		lw

12	3	0.43632	0.26496	length2 height ln_diameter
13	3	0.47551	0.16625	length2 width2 lw
14	3	0.48603	0.20392	length2 ln_diameter lw
15	3	0.48752	0.19969	width2 ln_diameter lw
16	3	0.48924	0.19927	length2 width2 ln_diameter
17	2	0.40295	0.27419	width2 height
18	2	0.41116	0.27953	height lw
19	2	0.42718	0.24377	length2 height
20	2	0.46478	0.19265	ln_diameter lw
21	2	0.46876	0.19911	width2 ln_diameter
22	2	0.47730	0.14611	width2 lw
23	2	0.47776	0.15104	length2 lw
24	2	0.47979	0.14529	length2 width2
25	2	0.48031	0.16859	length2 ln_diameter
26	2	0.55842	0.03677	height ln_diameter

The REG Procedure
Model: MODEL1
Dependent Variable: ok_depth

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.13917	0.06959	9.26	0.0004
Error	49	0.36840	0.00752		
Corrected Total	51	0.50758			

Root MSE	0.08671	R-Square	0.2742
Dependent Mean	0.04250	Adj R-Sq	0.2446
Coeff Var	204.02087		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.06214	0.03452	1.80	0.0780
width2	1	0.01217	0.00294	4.14	0.0001
height	1	-0.14899	0.05043	-2.95	0.0048

Sound Knot Angle

Obs	Number of regressors in model	Press statistics	R-squared	Model
1	4	5863.74	0.33670	ln_width ln_height ln_diameter ln_lw
2	4	5863.74	0.33670	ln_length ln_width ln_height ln_diameter ln_lw
3	4	5863.74	0.33670	ln_length ln_width ln_height ln_diameter
4	4	5863.74	0.33670	ln_length ln_height ln_diameter ln_lw
5	3	5105.10	0.33612	ln_width ln_diameter ln_lw
6	3	5105.10	0.33612	ln_length ln_width ln_diameter ln_lw
7	3	5105.10	0.33612	ln_length ln_width ln_diameter
8	3	5105.10	0.33612	ln_length ln_diameter ln_lw
9	3	5372.03	0.32866	ln_width ln_height ln_lw
10	3	5372.03	0.32866	ln_length ln_width ln_height ln_lw
11	3	5372.03	0.32866	ln_length ln_width ln_height
12	3	5372.03	0.32866	ln_length ln_height ln_lw
13	3	6757.92	0.17376	ln_width ln_height ln_diameter
14	3	6865.91	0.15744	ln_height ln_diameter ln_lw

15	3	6898.84	0.14745	ln_length		ln_height	ln_diameter	
16	2	4573.74	0.32348		ln_width			ln_lw
17	2	4573.74	0.32348	ln_length	ln_width			ln_lw
18	2	4573.74	0.32348	ln_length	ln_width			
19	2	4573.74	0.32348	ln_length				ln_lw
20	2	5708.31	0.13850			ln_height	ln_diameter	
21	2	6158.44	0.17199		ln_width		ln_diameter	
22	2	6366.41	0.15157				ln_diameter	ln_lw
23	2	6421.93	0.14411		ln_width	ln_height		
24	2	6504.63	0.13599	ln_length			ln_diameter	
25	2	6553.25	0.12907			ln_height		ln_lw
26	2	6605.48	0.12082	ln_length		ln_height		

The REG Procedure
Model: MODEL1
Dependent Variable: sk_angle

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1632.79533	816.39767	4.06	0.0361
Error	17	3414.81259	200.87133		
Corrected Total	19	5047.60792			

Root MSE	14.17291	R-Square	0.3235
Dependent Mean	25.04639	Adj R-Sq	0.2439
Coeff Var	56.58664		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	21.30830	4.17349	5.11	<.0001
ln_length	1	-44.68715	20.00925	-2.23	0.0393
ln_width	1	58.77868	23.48834	2.50	0.0228

Sound Knot Volume

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	5	69923.70	0.93385	length	width2	height	ln_diameter	lw
2	4	4780.72	0.92542	length	width2	height	ln_diameter	
3	4	25403.24	0.92989	length		height	ln_diameter	lw
4	4	70642.53	0.93314	length	width2	height		lw
5	4	79366.28	0.87941	length	width2		ln_diameter	lw
6	4	86763.06	0.91514		width2	height	ln_diameter	lw
7	3	4233.56	0.92541	length		height	ln_diameter	
8	3	4570.39	0.92529	length	width2	height		
9	3	4927.45	0.90930		width2	height	ln_diameter	
10	3	6656.44	0.87669	length	width2		ln_diameter	
11	3	22651.57	0.90855			height	ln_diameter	lw
12	3	25383.79	0.92964	length		height		lw
13	3	27826.35	0.87353	length			ln_diameter	lw
14	3	86260.38	0.91506		width2	height		lw
15	3	90101.67	0.85486	length	width2			lw
16	3	127453.92	0.83732		width2		ln_diameter	lw
17	2	4073.72	0.92529	length		height		

18	2	4753.44	0.90929		width2	height		
19	2	6473.22	0.87353	length			ln_diameter	
20	2	7596.35	0.85481	length	width2			
21	2	8936.72	0.83702		width2		ln_diameter	
22	2	22570.97	0.90816			height		lw
23	2	32940.79	0.33074			height	ln_diameter	
24	2	37392.34	0.85234	length				lw
25	2	45755.97	0.81074				ln_diameter	lw
26	2	136124.69	0.81311		width2			lw

The REG Procedure
Model: MODEL1
Dependent Variable: sk_volume

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	39934	19967	260.08	<.0001
Error	42	3224.43801	76.77233		
Corrected Total	44	43158			

Root MSE	8.76198	R-Square	0.9253
Dependent Mean	19.37794	Adj R-Sq	0.9217
Coeff Var	45.21628		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-15.35176	2.30082	-6.67	<.0001
length	1	9.65642	0.52450	18.41	<.0001
height	1	9.00918	1.39402	6.46	<.0001

Unsound Knot Angle

Obs	Number of regressors in model	Press statistics	R-squared	Model				
1	4	5503.90	0.13501	ln_length		height2	diameter2	ln_lw
2	4	5503.90	0.13501	ln_length	ln_width	height2	diameter2	ln_lw
3	4	5503.90	0.13501	ln_length	ln_width	height2	diameter2	
4	4	5503.90	0.13501		ln_width	height2	diameter2	ln_lw
5	3	5468.12	0.12534	ln_length		height2		ln_lw
6	3	5468.12	0.12534	ln_length	ln_width	height2		ln_lw
7	3	5468.12	0.12534	ln_length	ln_width	height2		
8	3	5468.12	0.12534		ln_width	height2		ln_lw
9	3	5671.19	0.09859	ln_length		height2	diameter2	
10	3	5719.07	0.08710			height2	diameter2	ln_lw
11	3	5756.00	0.07285	ln_length			diameter2	ln_lw
12	3	5756.00	0.07285	ln_length	ln_width		diameter2	ln_lw
13	3	5756.00	0.07285	ln_length	ln_width		diameter2	
14	3	5756.00	0.07285		ln_width		diameter2	ln_lw
15	3	5765.41	0.07456		ln_width	height2	diameter2	
16	2	5615.62	0.06729	ln_length				ln_lw
17	2	5615.62	0.06729	ln_length	ln_width			ln_lw
18	2	5615.62	0.06729	ln_length	ln_width			
19	2	5615.62	0.06729		ln_width			ln_lw
20	2	5664.16	0.08854	ln_length		height2		

21	2	5711.31	0.07663	height2 ln_lw
22	2	5751.20	0.04130	height2 diameter2
23	2	5753.30	0.06353	ln_width height2
24	2	5887.31	0.02957	ln_length diameter2
25	2	5919.63	0.02312	diameter2 ln_lw
26	2	5953.51	0.01708	ln_width diameter2

The REG Procedure
Model: MODEL1
Dependent Variable: uk_angle

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	690.21221	230.07074	1.77	0.1703
Error	37	4816.55541	130.17717		
Corrected Total	40	5506.76762			

Root MSE	11.40952	R-Square	0.1253
Dependent Mean	41.33769	Adj R-Sq	0.0544
Coeff Var	27.60077		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	40.82826	2.46095	16.59	<.0001
ln_length	1	-17.28493	10.68994	-1.62	0.1144
ln_width	1	14.67098	11.75914	1.25	0.2200
height2	1	0.64885	0.41405	1.57	0.1256

Unsound Knot Volume

Obs	Number of regressors in model	Press statistics	R-squared	Model
1	5	1758.24	0.79757	length width height ln_diameter lw
2	4	1211.34	0.79537	length height ln_diameter lw
3	4	1455.26	0.76731	width height ln_diameter lw
4	4	1625.21	0.79610	length width height ln_diameter
5	4	1694.29	0.79626	length width ln_diameter lw
6	4	1773.14	0.79030	length width height lw
7	3	1084.73	0.79491	length ln_diameter lw
8	3	1180.04	0.79230	length height ln_diameter
9	3	1212.04	0.78818	length height lw
10	3	1343.87	0.75985	width ln_diameter lw
11	3	1360.51	0.76720	width height ln_diameter
12	3	1412.36	0.76132	width height lw
13	3	1572.86	0.79464	length width ln_diameter
14	3	1647.59	0.78622	length width height
15	3	1725.58	0.78611	length width lw
16	3	4197.57	0.07804	height ln_diameter lw
17	2	1053.35	0.79196	length ln_diameter
18	2	1094.34	0.78552	length lw
19	2	1203.84	0.78135	length height
20	2	1264.24	0.75968	width ln_diameter
21	2	1315.17	0.76116	width height
22	2	1339.17	0.74814	width lw
23	2	1613.31	0.78065	length width

24	2	3731.92	0.04290		ln_diameter	lw
25	2	3745.10	0.06465	height	ln_diameter	
26	2	4036.39	0.06808	height		lw

The REG Procedure
Model: MODEL1
Dependent Variable: uk_volume

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2321.12809	1160.56404	41.88	<.0001
Error	22	609.71880	27.71449		
Corrected Total	24	2930.84689			

Root MSE	5.26446	R-Square	0.7920
Dependent Mean	10.41625	Adj R-Sq	0.7731
Coeff Var	50.54080		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-24.39964	18.05320	-1.35	0.1903
length	1	13.32873	1.48065	9.00	<.0001
ln_diameter	1	8.92737	7.45137	1.20	0.2436

12 Vita

Matthew Franklin Winn was born on March 4, 1971 in Richmond, Virginia to Otis and Joanne Winn. He continued to reside in the Richmond area until he graduated from Monacan High School in 1989.

In the fall of 1989, he entered Virginia Polytechnic Institute and State University in pursuit of an engineering degree. After a year in the engineering program, he decided that this was not the field for him and decided to transfer into forestry. He graduated in 1993 with a Bachelor of Science Degree in Forestry with an emphasis on resource management.

During his junior year in college, he began working part-time for the Primary Hardwood Processing, Products and Recycling research unit of USDA Forest Service Southern Research Station in Blacksburg, Virginia. His primary duties included data collection and analysis for various research projects. In 1994, he became a full-time term employee of the unit. One of his major accomplishments while working for the Forest Service was the development and maintenance of the unit's website as well as a website devoted to non-timber forest products. In 1999, while continuing to work for the Forest Service, he re-entered Virginia Polytechnic Institute and State University to pursue a master's degree in forest biometrics. In 2001, he finally obtained a permanent position with the research unit where he is currently employed.