RAYSAW: A LOG SAWING SIMULATOR FOR 3D LASER-SCANNED HARDWOOD LOGS

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Abstract.—Laser scanning of hardwood logs provides detailed high-resolution imagery of log surfaces. Characteristics such as sweep, taper, and crook, as well as most surface defects, are visible to the eye in the scan data. In addition, models have been developed that predict interior knot size and position based on external defect information. Computerized processing of complete log shape data, combined with predicted internal defect information, promises to reduce waste and improve grade recovery in primary breakdown operations. RAYSAW is a hardwood log sawing research tool that processes high-resolution 3D laser-scan data and uses internal defect prediction models to estimate the occurrence of defects on sawn board faces. RAYSAW uses mathematically based ray-tracing image generation methods to generate virtual boards that can be graded, remanufactured, or processed into dimension parts using available free software. The RAYSAW sawing simulator allows researchers to examine the impacts of various sawing practices and log quality and shape characteristics on grade and value recovery.

INTRODUCTION

Ray-tracing is a mathematically based methodology for creating photo-realistic images on a computer. As such, ray-tracing creates a 2D picture of a 3D world where objects are defined with light sources and view point (Watkins and Sharp 1992). In ray-tracing, a "light" ray is cast from the observer into the scene onto the objects in the scene. Wherever the light ray intersects an object, a pixel records the color parameters of the intersection point. In addition, the light ray can bounce from object to object, generating photo-realistic object reflections and transparencies.

In RAYSAW, the light ray is replaced by a simulated band saw blade. Instead of the light rays emanating from viewpoint, the band saw blade "rays" emanate from a line parallel to the longitudinal axis of a log. The series of intersection points with the log and defects define the edge and defect points of a board. RAYSAW processes 3D log data collected using a three-head high- resolution laser-scanner and predicted internal defect data based on log surface defect indicators (Thomas 2008, 2009). The ability to process the 3D log data on a computer allows researchers to examine the impact of various sawing practices and different log quality and shape characteristics on lumber grade and value recovery. Once this technology is industrialized, it promises to improve grade recovery in hardwood sawmills. Recent advances in image processing have resulted in methods capable of detecting external log defects in the 3D laser data cloud (Thomas et al. 2006, Thomas and Thomas 2011). To make image data usable, the incoming 3D laser data are first processed to remove outlier points and fill areas of missing data using surrounding area information. Figure 1 shows a sample log from a laser-scanner as a dot cloud image.

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Figure 1.—Sample dot cloud image of a 3D laser-scanned red oak log.

Several simulators and a computerized sawing system for hardwoods have been developed in recent years. One of the first was a mathematically based hardwood log sawing program developed at the Forest Products Laboratory (FPL), in Madison, WI (Richards et al. 1979). The FPL log sawing program processed rough geometric log shape data (small- and large-end diameters, taper, sweep, and crook) and defect data. Defect data were manually placed on the log and internally modeled as a conic shape with the tip at the log center and the open end of the cone terminating inside or just outside the log surface. The FPL program would examine 12 different starting rotation degrees and do a complete sawing solution for each starting position using the same sawing pattern. The FPL sawing program was not user-interactive and simply provided end results based on the input log data and sawing specifications.

Later programs such as GRASP (Occeňa and Schmoldt 1996) were interactive and allowed users to guide the sawing process. The input data for GRASP are in a complete wire-frame form generated from CT scan data and digitized log coordinates. Log defects for GRASP were reconstructed using CT cross-sectional profiles and were modeled as separate solids within the wire-frame log representation. GRASP required the use of a third-party 3D computer-aided modeling program.

Perhaps the most advanced log sawing system is the one developed at West Virginia University (WVU) by Lin et al. (2011). Their sawing system processes summarized 3D laser-scan data and inferred internal defect shape and position data (Thomas 2008, 2009). The 3D laser-scan data are summarized to a circular single scan line for every foot of log length. The WVU system was not developed so much as a simulator but as a real-time system for determining the optimal breakdown of hardwood logs. As such, their system includes modules for grading lumber and for optimal edging and trimming operations. However, their sawing system uses a circular log shape model that prevents the system from accurately sawing elliptical or irregularly shaped logs.

RAYSAW was designed to use the native high-resolution data format directly from a laser log scanner. As such it processes true log shape data accurately to the nearest 1/16 inch. RAYSAW is a non-interactive, non-optimizing sawing simulator that determines the grade recovery given a log's shape and size, its defects, a sawing pattern, and a starting rotational degree. The starting rotational angle defines the starting position for a log. As in the Lin et al.'s (2011) sawing system, RAYSAW uses the internal defect prediction models developed by Thomas (2008, 2009) to determine internal defect shape and position. Combining the external laser imagery, surface defect locations and sizes, and predicted internal dimensions yields a 3D view of the log complete with external and internal defect data. This provides a near ideal data platform for conducting sawing research. And it allows the impact of alternative processing strategies given specific log features to be evaluated with respect to grade recovery. By using high-resolution data, RAYSAW generates accurate and realistic board profile data, from which accurate volume information can be calculated. This paper describes RAYSAW's mathematical basis and the system's sawing processes.

METHODS

The quality of the sawing solution depends on the computer model of the log being as accurate as possible. Abstractions and generalizations of log shape and log characteristics can result in less accurate solutions. The log surface is represented by a series of scan lines 1/16 inch apart that encircle the log. Each scan line is composed of 200 to 500 points depending on log circumference with smaller logs having fewer surface points. Outliers are statistically defined as any data point that is numerically distant from the rest of the data. In the log data, outliers are typically caused by the supports that hold the log during scanning, loose or dangling bark, and laser reflections off airborne dust. Outliers are removed from the original data by statistically comparing the location of points to neighboring points. The second step is filling in any missing data points to ensure a completely defined surface. Missing data points are commonly caused by outlier removal or by surface shadowing by the log supports and dangling bark. Missing data points are filled in using an average of neighboring points.

After the log data are cleaned of outliers and missing data points are filled, the external and internal defect representations can be added. External defect data consist of surface length, width, rise, and position (angle and distance from large end). The external defect data can be supplied by the automated defect detection software (Thomas et al. 2006, Thomas and Thomas 2011), or from a manually recorded log diagram. A log diagram records log shape and size as well as the position and type of all surface defects (Bulgrin n.d.). Internal defect features are generated using a series of prediction models (Thomas 2008, 2009). These models were developed using multiple linear regression methods to determine the correlations among external defect indicators such as log diameter, defect width, length, and rise to internal features such as encapsulation depth, total depth, penetration angle, and cross-sectional dimensions. The models were created by analyzing 842 red oak (*Quercus rubra* L.) and 1,000 yellow-poplar (*Liriodendron tulipifera* L.) defect samples collected from logs that were harvested from three sites in central Appalachia. Using the prediction models. an internal log defect representation is created. All defects have eight sides and two segments: internal endpoint to midpoint, and midpoint to external endpoint (Fig. 2). In instances where the defect has been encapsulated by clear wood, the external defect endpoint begins at the predicted beginning of the defective wood. The defect surface is modeled as a series of facets or triangles as shown in Figure 2.

In ray-tracing, a ray of light is traced from the observer back into the scene. As the ray hits objects, points and reflections are registered. For sawing a log, the ray-tracing process is greatly simplified because we are interested only in recording the points of intersection. While conventional ray-tracing has a single observer point, ray-tracing based sawing uses a line of starting points corresponding to the track of the saw along the log's length. For log sawing, the process of ray-tracing is further simplified to use two different intersection formulae. The first is a simple line intersection formula that locates the board edges. Each scan line around the circumference of a log at a given longitudinal point consists of 200 or more data points. Figure 3 shows the points of a single scanned line of a sample log and the outline of an internal defect. Line segments are defined between adjacent points

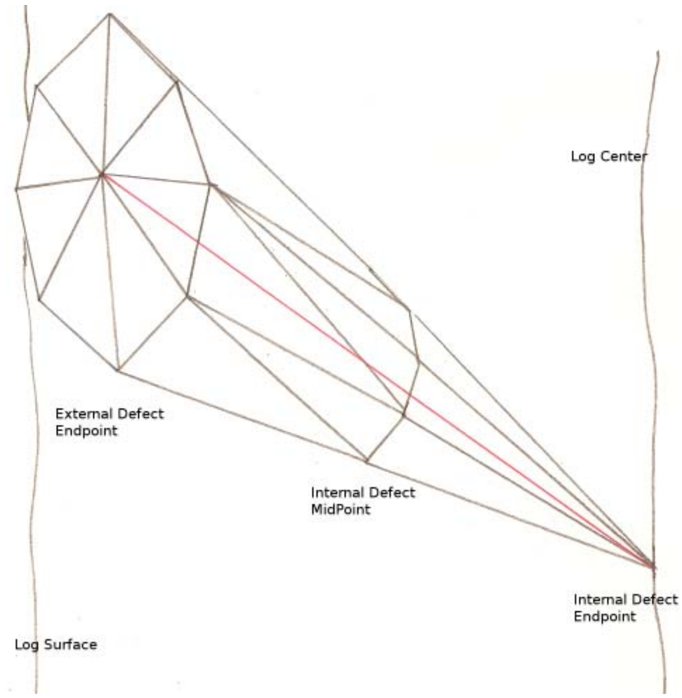

Figure 2.—Computer modeled internal and external representation of a log defect.

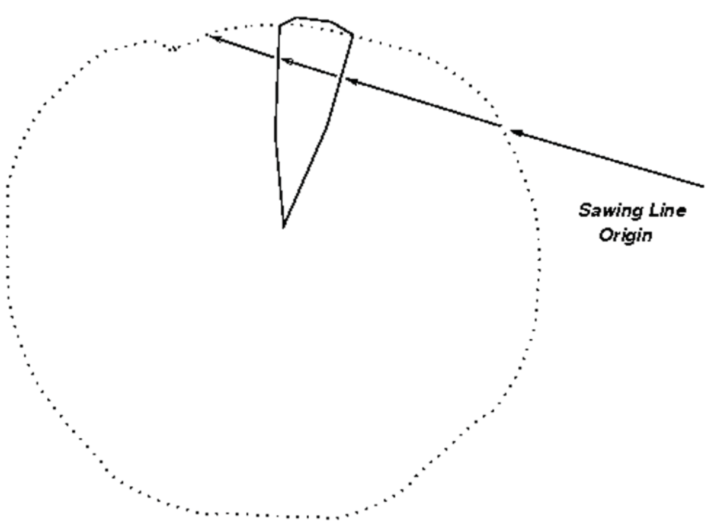

Figure 3.—Ray-traced sawing diagram of a log cross-section with an internal defect.

of a single scan line of a log. The equation for a sawing line S and a line segment L that connects two adjacent points in the scanned log circumference, where S has two points A and B, and L two points C and D are:

$$S = A + u_a(\ B - A)$$
$$L = C + u_b(D - C)$$

Solving for the intersection of point of S and L gives the following equations:

$$Ax + u_a(Bx - Ax) = Cx + u_b(Dx - Cx)$$
$$Ay + u_a(By - Ay) = Cy + u_b(Dy - Cy)$$

Solving for u_a and u_b:

$$u_a = \frac{(Dx - Cx)(Ay - Cy) - (Dy - Cy)(Ax - Cx)}{(Dy - Cy)(Bx - Ax) - (Dx - Cx)(By - Ay)}$$

$$u_b = \frac{(Bx - Ax)(Ay - Cy) - (By - Ay)(Ax - Cx)}{(Dy - Cy)(Bx - Ax) - (Dx - Cx)(By - Ay)}$$

The intersection point can be determined via substitution as:

$$x = Ax + u_a\,(Bx - Ax)$$
$$y = By + u_b\,(By - Ay)$$

Using the above equations, all log circumference line segment intersections with the sawing line are calculated. By moving the saw line along the length of the log, the entire board is “sawn” from the log. Because the saw line moves from scanned slice to scanned slice, the points and line are always coplanar, thus we need only consider two dimensions. The above equations also are used to detect when a saw line intersects a previous saw line. When this situation occurs, an edged, rather than wane edged, board is produced.

Detecting the intersection of the saw line with defects and generating the respective defect outline on the board’s surfaces is more complex. The defects are modeled by a set of triangles, where the three points of the triangle define a plane. Thus, a line and plane intersection equation is used. Given a defect facet F with the normal vector n indicating the direction of F, and a saw line vector s, respectively. First, determine the vector w, the difference between n and s.

$$w = n - s$$

The next step is finding r, the distance from the origin of s to the intersection point on the facet.

$$r = \frac{-n \cdot w}{n \cdot s}$$

Adding s to the direction vector u by the distance r gives the intersection point P.

$$P = s + r * u$$

The above equations will find the intersection of the saw line s and the facet F. However, because F defines a plane, the next step is to determine if the intersection lies within the three points, Fa, Fb, and Fc that define the facet. Given the vectors:

$$U = Fa \rightarrow Fb \qquad\qquad V = Fa \rightarrow Fc$$

Determine the following dot products:

$$UU = U \cdot U \qquad\qquad UV = U \cdot V \qquad\qquad VV = V \cdot V$$

Next, find the vector from Fa to the intersection point P:

$$W = Fa \rightarrow P$$

Then, determine the following dot products with the vector W:

$$WU = W \cdot U \qquad\qquad WV = W \cdot V$$

Finally, determine the unit vector distances of the intersection point from the points Fb and Fc using the dot product values.

$$Q = \frac{UV * WV - VV * WU}{UV * UV - UU * VV}$$

$$T = \frac{UV * WU - UU * WV}{UV * UV - UU * VV}$$

If either Q or T is less than 0 or greater than 1, then the intersection lies outside of the facet, and the sawline does not intersect that portion of the defect.

As the sawing line moves along the length of the log, RAYSAW stores the distance of all intersects with the log surface, other sawlines, and defects. The distance data are processed such that a virtual board face with defects is produced. For example, Figure 3 shows a sawline intersecting a log cross section. The distance from the origin where each intersection occurs and the type of object (defect or log) intersected is recorded. Two passes of the sawing line at different cutting depths yields a complete board. RAYSAW can produce board data compatible with the ROMI rough mill simulator (Weiss and Thomas 2005) or the UGRS hardwood lumber grading and remanufacturing program (Moody et al. 1998).

RESULTS

As a demonstration of RAYSAW and the internal prediction models, the red oak log shown in Figure 2 was sawn with the sawing pattern shown in Figure 4. For this example, the log was sawn on a portable bandsaw mill. The sawing pattern and rotational positions were then reproduced in the sawing pattern for RAYSAW. The log was sawn into eight boards and a 2.125 by 5.875 inch cant. In the interest of brevity, only the first boards from sawn faces 1 and 3 are examined. Sawing started with a slab and a board being removed from face 1 (labeled “Board 1” in Figure 4). A photograph of the actual board and the computer predicted board are shown in Figure 5. Next, a slab is removed from face 2. From face 3 a slab and three boards are sawn. The outermost board sawn and the computer predicted board from this face are shown in Figure 6 (labeled “Board 2” in Figure 4).

There are two basic types of errors: missed defects and false-positive defects. Missed defects are actual defects whose occurrence the models did not predict. False-positive defects are ones that were predicted, but did not actually exist. For those defects predicted that did actually exist, there are two additional types of errors: positional and dimensional. Positional error is the distance between centers of the actual and predicted defect centers. Dimensional error is the difference between actual and predicted defect lengths and widths.

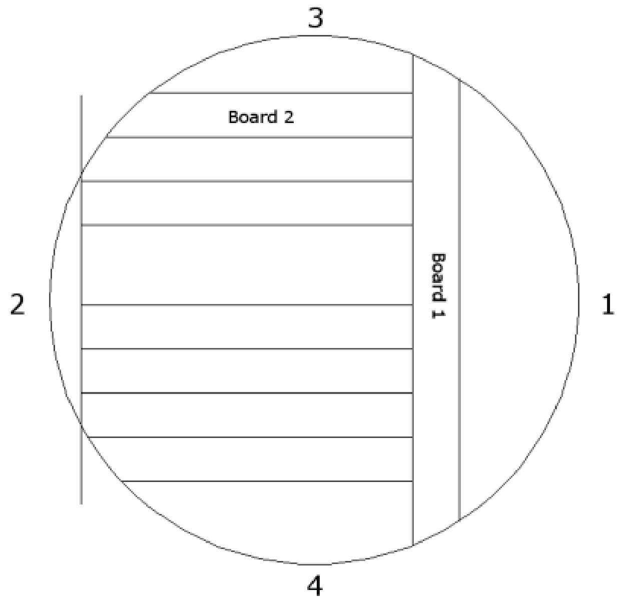

Figure 4.—Sawing pattern used to process log shown in Figure 1. Boards named are displayed in Figures 5 (Board 1) and 6 (Board 2). Faces are labeled by sawing sequence.

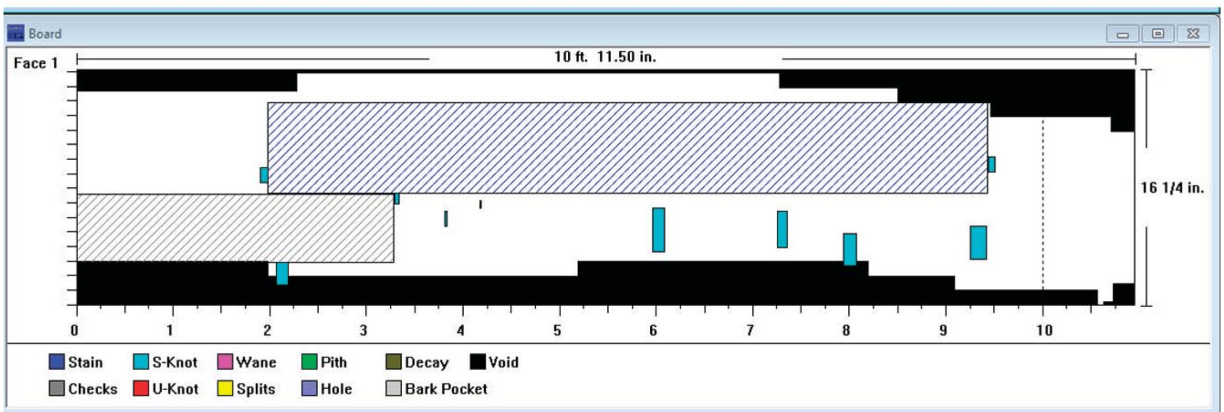

Figure 5.—Computer generated and actual board cut for Board 1.

On Board 1, there are a total of 11 defects. Of these, the internal prediction models predicted the occurrence of eight, missing three. In addition, the models predicted two false-positive defects. The average positional error for Board 1 was 3.64 inches and the average length and width dimensional error was 1.04 and 0.93 inches, respectively. For Board 2, the models predicted the occurrence of two of four total defects. There was one false-positive defect prediction. The average positional error for Board 2 was 3.63 inches and the average length and width dimensional error was 1.50 and 0.63 inches, respectively. Overall, the average positional error was 3.64 inches and the average length and width dimensional error was 1.13 and 0.87 inches, respectively.

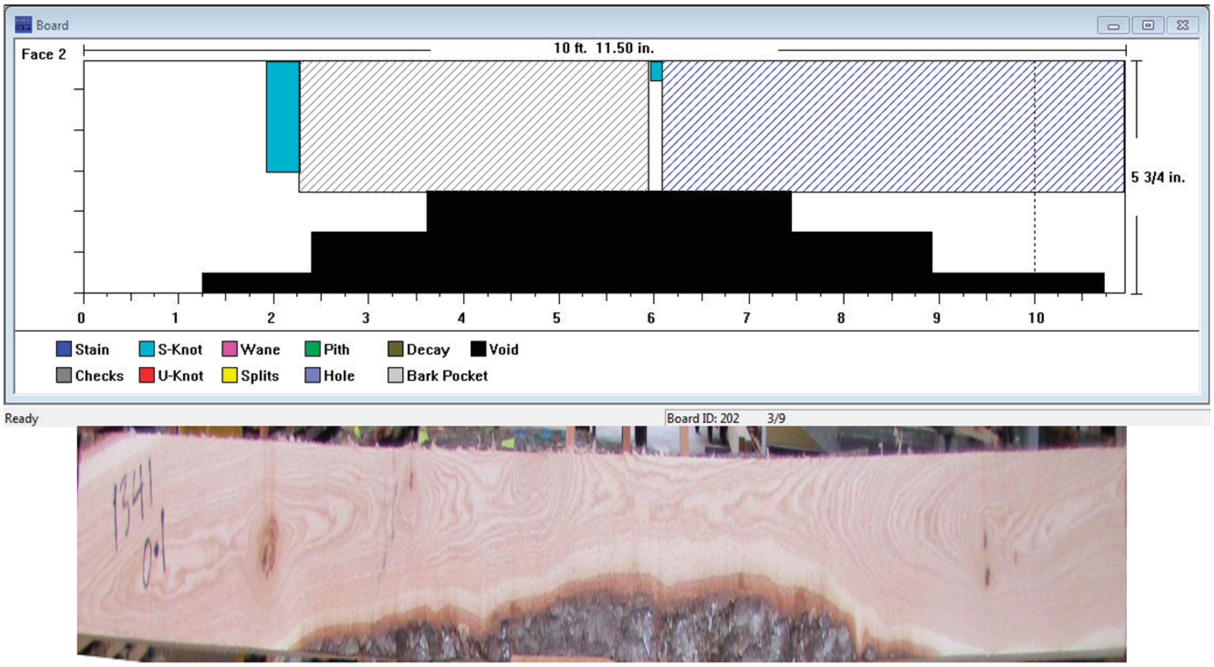

Figure 6.—Computer generated and actual board cut for Board 2.

In a further study, the accuracy of the red oak prediction models were examined by scanning a set of three logs and predicting the occurrence of knot defects on the sawn board faces (Thomas 2011a). The logs were then sawn on a portable sawmill to replicate RAYSAW's sawing parameters and log positioning. The study found that the models accurately predicted approximately 80 percent of all knot-type defects. The prediction models accurately placed internal knot defects with a median positional error of 0.875 inch. The error was measured from the center of the actual defect to the center of the predicted defect. In most cases the predicted and actual defect areas often overlapped, potentially minimizing the impact of defect location error on predicted grade and yield. For 32.8 percent of predicted internal defects, the difference between predicted and actual defect area was 2.5 in^2 or less, with an overall median size error of 4.94 in^2. Although this error may sound large, consider a knot with an actual size of 3 by 3 inches and a predicted size of 3.7 by 3.77 inches, which has an error of 0.7 by 0.77 inches. This size error is 4.94 in^2 with a relatively small error in predicted defect dimensions. In addition, missing the location of a defect by 1 inch on a board is unlikely to lead to lower grading of the board, nor will it likely impact yield when the board is processed in the rough mill (Thomas 2011b).

DISCUSSION

Although the defect model predictions of location, width, and length seem acceptably small, a second study was conducted to determine if these errors have a significant impact on predicted lumber quality (Thomas 2011b). In this study, 26 red oak logs were scanned and their defect locations manually located and diagrammed. The internal prediction models were modified to generate internal defect measurement and location estimates that randomly varied between +/- mean absolute error (MAE) for each internal characteristic. A total of 30 random defect variations, as well as the normal variation and the normal +MAE, and normal –MAE, were generated, producing 33 defect variations for each scanned log. Each log was then sawn with four different sawing patterns and the resulting boards graded with the UGRS grading program (Moody et al. 1998). Overall, there were few significant differences among the random only sawn lumber sets. Within the 33 defect size variations sets, 8 of the 26 logs had no significant differences in lumber recovery, and 9 had five or less significant differences. The remaining nine sets had one or more sawing rotation where a defect variation resulted in a significant difference with all other lumber sets. Some of the significant differences between the random variation sets were linked to logs that had knot clusters or more than an average number of bark distortions. Knot clusters and bark distortions have some of the weakest correlations to internal features and thus had a greater variability in internal size and position in the random variation sets (Thomas 2008, 2009). The random defect variation sets are more likely true to reality than the worst (+MAE) and best (-MAE) case defect datasets. When the worst and best defect sets were combined with the random variation defect sets, significant differences were observed between the worst case and the random variation defect sets. Also, as expected, there were significant differences between the best and worst case defect size variations.

SUMMARY

RAYSAW was developed for research purposes, specifically to provide a means of testing the internal defect prediction models. As such, RAYSAW lends itself well to answering questions about the impacts of various sawing practices and log quality and shape characteristics on grade and value recovery of hardwood logs. For example, an elliptical log could be processed using different patterns to determine if log rotation has a significant impact on recovery. RAYSAW processes high-resolution laser-scan data and reports accurate sawing and waste volumes. The simulator saws to a pre-defined pattern that specifies the sawing line and board thickness. The boards produced by RAYSAW can be viewed graphically, graded to NHLA rules, and processed into rough dimension parts using freely available software. A graphical user interface for designing sawing patterns is available. Additional internal log defects are being collected to refine internal defect modeling especially for those defects with low internal to external feature correlations, such as knot clusters, and light and medium distortions.

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