A MODEL FOR THE SAWING AND GRADING OF LUMBER ACCORDING TO KNOTS

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ABSTRACT

As a means to determine the grade improvement potential of black spruce, a sawing and grading model is presented. It uses an analytical representation of the knots, the boards, the log, along with the National Lumber Grades Authority Visual Strength Grading Rules, as a means to grade the sawn lumber according to the knots. A simulation was performed using knot data collected on the surface of a black spruce log. The log was then sawn, and the data were collected on the board surfaces. The simulation shows that, in general, the model approximates well the knot diameter on the boards using data collected on the log's surface, but the "equivalent diameter" as calculated from the NLGA Rules underestimates it.

Keywords: Model, sawing, grading, knots, structural lumber.

INTRODUCTION

The eastern Canadian black spruce forest industry is faced with a serious reduction in resource quality. This reduction has forced sawmills to increase productivity and to reduce costs in order to remain competitive in the global market (Ministère des ressources naturelles 1996). The trees used have decreased in size and as a result some structural softwood lumber sizes have become almost inaccessible. Although silvicultural techniques help to counteract this decrease in size by increasing growth and productivity, such an improved growth environment has also increased the occurrence and size of branches and knots (Hoibo et al. 1996; Jozsa and Middleton 1994; Väisänen et al. 1989). Profits are becoming more difficult to obtain as a result of low recovery from sawing small logs with large defects (Wagner et al. 1998; Jozsa and Middleton 1994).

The industry has therefore put a maximum emphasis on volume recovery. Black spruce and other boreal species are sawn without considering grade defects except for wane. In general, primary breakdown consists of scanning the log and fitting the sawing pattern either at the small end or slightly inward for maximum volume yield. However, this emphasis on optimum volume recovery may play a role in quality (Steele et al. 1993). In the actual context, methods to predict grade recovery are practically nonexistent.

Numerous studies throughout the world explored the potential of scanning equipment for

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internal defect location as a means to predict lumber grades from logs. For hardwoods, the growth characteristics detected are avoided, thereby yielding mostly clear lumber. However, in regard to softwood, the aim is to have these characteristics positioned in the lumber so that the effect on strength is reduced as much as possible. If these methods are to achieve an appreciable level of success, the defects must be positioned such that consideration of these while processing the logs will be favorable for the end product quality. Furthermore, the methods used to assess lumber quality must be representative of what is used in the industry. So far, there are few clues as to whether this type of improvement is possible using black spruce, a species that is significantly different by its small size and apparently homogeneous knot distribution.

The black spruce sawmilling industry is presently looking for alternative solutions to increase the grades of lumber. With the high potential of internal log scanning, the industry is hoping to find a means to increase this recovery. Some effort has been expended to develop scanners for internal defects (Aune and So 1991) although this technology is not used on an industrial basis in Canada. In this context, a simulation approach offers a relatively cheap means of determining this without the use of expensive equipment.

This paper presents a computerized sawing and grading model that will be used to evaluate the extent to which black spruce lumber grades can be improved if knots are considered before logs are actually sawn. It incorporates algorithms that emulate the National Lumber Grades Authority Visual Strength Grading Rules, which are the rules presently used in the softwood structural lumber industry in eastern Canada. The model uses knot information on the surface of the log as a means to predict the internal morphology. It will therefore help the lumber manufacturing industries to determine if advanced scanning technology for log internal defects is applicable to eastern Canadian sawmills using the available resources.

LITERATURE REVIEW

Knots and primary breakdown

Primary breakdown determines the location of log internal characteristics within the lumber. Research suggests that increased knowledge of the geometry of these characteristics, coupled with the sawing pattern, should affect the lumber grade output (Harless et al. 1991; Hodges et al. 1990). This potentially significant improvement promoted the development of new technology involving various types of scanners to examine the interior of logs in an attempt to nondestructively evaluate their internal morphology (e.g., Chang and Guddanti 1995; Hodges et al. 1990; Thomas and Bush 1998; Wagner et al. 1989). This also led to the development of simulators for hardwood sawing and grading (Chang and Guddanti 1995; Steele et al. 1994). In eastern Canada, Pnevmaticos et al. (1974); Pnevmaticos and Mouland (1978) used a model to predict the grade of hardwood lumber in which the defects were represented as rectangles because he knew that in re-sawing the flitches, the defects would be removed as rectangles.

Most of the methods describe the internal morphology of logs in a discrete manner because scanning equipment stores data on defects in data arrays. Manipulation then relies heavily on the resolution of linear equations, which can become quite long if the computing equipment is inadequate. However, accuracy is improved since details on the morphology of the characteristics are available and fewer interations are needed.

Few have used analytical approaches to describe and manipulate internal defects. Analytical models have the advantage of requiring fewer input data on the morphology compared to discrete models. Computing time is also greatly reduced. Samson (1993) used a strength of material approach to demonstrate that sawing a softwood log while knowing the shape and position of the knots can yield knotty boards of superior strength. Using only three knots, he found a significant difference in lumber strength. More recently, Todoroki

(1996) used geometrical parameters to describe the knots in logs. The knots are sectioned into two parts: a cone for the live part of the knot and a cylinder for the dead part of the knot. The intersection of the knot with the saw plane is then described by conical sections. The model seems to adapt well to radiata pine, although using a knot with two zones may be restrictive with a variable resource such as black spruce, which can have large variations in knot shapes.

Lumber grading

In the present industrial context, lumber quality is evaluated after being processed; that is, when the defects in the lumber cannot be relocated. The most widely used method of evaluating softwood structural lumber strength is Visual Strength Grading (Madsen 1992). Theoretically, this method should consider many visual features as a means of gauging lumber strength. Unfortunately, this visual evaluation is performed in less than 2 seconds. The workers barely have time to notice defects, much less to evaluate their effect on strength so as to grade them accordingly. Worker fatigue can also cause gross errors. As a safeguard, it is common practice to group softwood lumber grades into a more easily distinguishable grade (e.g., No 2 and better). Consequently, many pieces of lumber in this grade have better strength characteristics than attributed by the grade, thus reducing sawmill profits and ending in misuse of the lumber (Madsen 1992; Pham and Alcock 1998).

As a means to remove the uncertainty of the actual grading techniques, systems are being developed to perceive and grade defects on lumber (e.g., Wagner et al. 1991; Zeng et al. 1997). These expert systems have the advantage of grading actual features on the lumber; that is, the features are real and are not assumed to be on the board. However, this may also be a disadvantage because the grading is of a final product. Once the processing is done, there are no means of improving the lumber value unless by very accurate grading. Pham and Alcock (1998) mention that difficulties persist with the identification of defects by cameras, especially in dusty areas such as sawmills. Nevertheless, expert grading systems are successful and constantly improving compared to human grading which, is at a threshold.

The poor quality of lumber can be partially attributed to low quality and size of the resource available for transformation, and also to the control over the grading process. Many researchers throughout the world have based their modeling and scanning work on the hypothesis that knowledge of log internal defects before breakdown can improve process control and therefore the quality of the end product. Much of the work done applies to hardwoods, while little attention is given to small diameter softwoods, possibly because the volume recovery is a major issue for those trees that tend to be of low economical value. In this context, a simulation model that helps to close the gap between the process and the end product could be beneficial. It will serve as a means to determine the possible benefits that scanning technology can have on the industry. The gap between the resource and the transformation will be reduced by identifying and quantifying the effects of growth characteristics on the graded output, along with improving the grading of the end product.

MODEL DESCRIPTION

Knot and saw plane

The model describes the log as a straight axis truncated cone. The log pith is parallel to the Z-axis, and the X and Y axes represent the radial/tangential planes. A simple log form is used because the objective of the model does not include improving volume recovery. The model will be used on short study logs (slightly over 8 ft) such that the taper, crook, and sweep are kept to a minimum.

In the model, the knot can be located anywhere along the log pith. It is a function of the length r from the log pith and the sectional angle θ. It is described by the following equations

$$\text{knot}(r, \theta) = \begin{pmatrix} x(r, \theta) \\ y(r, \theta) \\ z(r, \theta) \end{pmatrix} = \begin{pmatrix} X_p + r\cos(\phi) - \dfrac{\gamma r \sin(\theta)\sin(\phi)}{\cos(\alpha) - \tan(\eta)\cos(\theta)\sin(\alpha)} \\ Y_p + r\sin(\phi) + \dfrac{\gamma r \sin(\theta)\cos(\phi)}{\cos(\alpha) - \tan(\eta)\cos(\theta)\sin(\alpha)} \\ Z_p + r\dfrac{\sin(\alpha) + \tan(\eta)\cos(\theta)\cos(\alpha)}{\cos(\alpha) - \tan(\eta)\cos(\theta)\sin(\alpha)} \end{pmatrix} \tag{1}$$

for $0 < r \leq$ diameter/2 and $-\pi/2 < \theta \leq \pi/2$, and where (X_p, Y_p, Z_p) are the co-ordinates of the knot origin; ϕ is the angle of the knot in the radial/tangential (R/T) plane; γ is the lateral opening of the knot; α is the angle between the knot axis and the R/T plane; η is the longitudinal opening of the knot (from Samson et al. 1996).

It is suggested that readers examine the references for details on the origin of the equations. All parameters except r and θ are known or are derived from the data entry on the shape of the knot. Equation (1) represents a simple truncated cone knot shape. It served as the basic element for the knot model, since the knot is basically a number of straight truncated cones as shown in Fig. 1a. These zones are aligned such that their axes form a straight line. The widest profile of the knot (in the R/T plane) is obtained by solving the equations when $\theta = -\pi/2$ and $\theta = \pi/2$. This profile is most important in grading since it effectively represents the section of a board occupied by the knot. The equation was then simplified to consider only the widest profile for the zones of the knot. This is a function of the length r from the log pith, the rise z of each section of the knot with respect to the origin of the pith and also on the dimensions of the sections at both ends of the zone as shown in Fig. 1b. Mathematically, this is represented as

$$\text{Knot}(r) = \begin{bmatrix} X(r) \\ Y(r) \\ Z(r) \end{bmatrix} = \begin{pmatrix} X_p + r\cos(\phi) - \left[\dfrac{r_2 - r}{r_2 - r_1}(\pm a_1) + \dfrac{r - r_1}{r_2 - r_1}(\pm a_2)\right]\sin(\phi) \\ Y_p + r\sin(\phi) + \left[\dfrac{r_2 - r}{r_2 - r_1}(\pm a_1) + \dfrac{r - r_1}{r_2 - r_1}(\pm a_2)\right]\cos(\phi) \\ Z_p + \dfrac{r_2 - r}{r_2 - r_1}\tan(\alpha) \end{pmatrix} \tag{2}$$

for $0 \leq r_1 < r_2 \leq$ pith-bark distance and where X_p, Y_p and Z_p are the 3-D coordinates of the knot pith attachment to the log pith; ϕ is the angle of the knot in the R/T plane; α is the angle between the knot axis and the R/T plane.

As the figures demonstrate, r_1 and a_1 represent the dimensions at the zone closer to the pith, and r_2 and a_2 are closer to the bark also in the radial/tangential plane. The knot is described along a plane parallel to the axis of the zones. If the z coordinates are not considered, the equations describe the shadow of the knot on the R/T plane, which is the widest plane of the knot and also the most important for grading.

According to unpublished work by Samson et al. (1995), the saw plane is described by the simple line equation in the R/T plane

$$X \cos \Psi + Y \sin \Psi - d = 0 \tag{3}$$

where Ψ represents the angle of the saw plane with respect to the X-axis and d is the distance from the saw plane to the origin of the co-ordinates of the log. A board is obtained by defining four planes and their intersection from which the co-ordinates of the board edges are then obtained.

Another way to define a saw plane is to use the board's edges when they are known. If P_1 and P_2 are the edges on one side of the board,

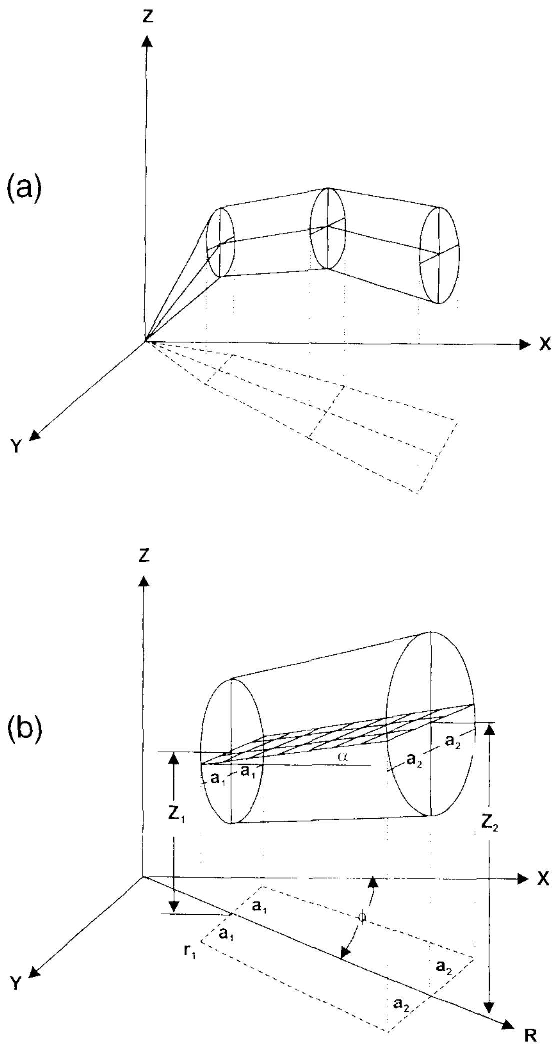

FIG. 1. Knot model showing the parameters needed to characterize various angles and the axis system. The origin of the knot is on the log pith.

then any point on the line joining P_1 and P_2 can be found using the following equation:

$$P = P_1 + T(P_2 - P_1) \tag{4}$$

In particular, if $0 \leq T \leq 1$, then P is between P_1 and P_2. This equation can be reduced to Eq. (3) using the appropriate transformation, and will be used later.

In the R/T plane, Eq. (2) can be rewritten such that points on the left and right profiles of the knot can be described in the following vector form

$$\vec{v} = \langle \cos\phi, \sin\phi \rangle,$$

$$\vec{n} = \langle \sin\phi, -\cos\phi \rangle$$

$$P_{left} = Pith_{origin} + r\vec{v} + r\frac{(a_1 - a_2)}{r_2 - r_1}\vec{n} + \frac{r_1a_2 - r_2a_1}{r_2 - r_1}\vec{n}$$

$$P_{right} = Pith_{origin} + r\vec{v} - r\frac{(a_1 - a_2)}{r_2 - r_1}\vec{n} - \frac{r_1a_2 - r_2a_1}{r_2 - r_1}\vec{n} \tag{5}$$

where $\vec{\mathbf{v}}$ is the direction of the knot on the R/T plane and where $\vec{\mathbf{n}}$ is orthogonal to $\vec{\mathbf{v}}$. A point located on the knot pith can be written as

$$P_{pith} = pith_{origin} + r\vec{\mathbf{v}} \tag{6}$$

by setting the values of a_1 and a_2 to zero. The first part of the knot is defined by setting a_1 to 0. The intersection of the knot with the board is found by finding a T that satisfies the following equation

$$P_1 + T(P_2 - P_1) = Pith_{origin} + r(\vec{\mathbf{v}} \pm A\vec{\mathbf{n}}) \pm B\vec{\mathbf{n}} \tag{7}$$

where $A = (a_1 - a_2)/(r_2 - r_1)$ and $B = (r_1a_2 - r_2a_1)/(r_1 - r_2)$ so that the right side of the equation is Eq. (5) and where P_1 and P_2 are the board's edges. In order for the knot to intersect the board, there must exist a value for T between 0 and 1 which makes a point on the knot profile equal to a point on the board face. Equation (4) can be broken down into its X and Y components such that the r component vanishes, leaving T as the only unknown. With T known and between 0 and 1, the value for r can be found, which will determine in what zone the knot has intersected the board.

Knot diameter

The knot diameter on a face is obtained from the difference between the two points

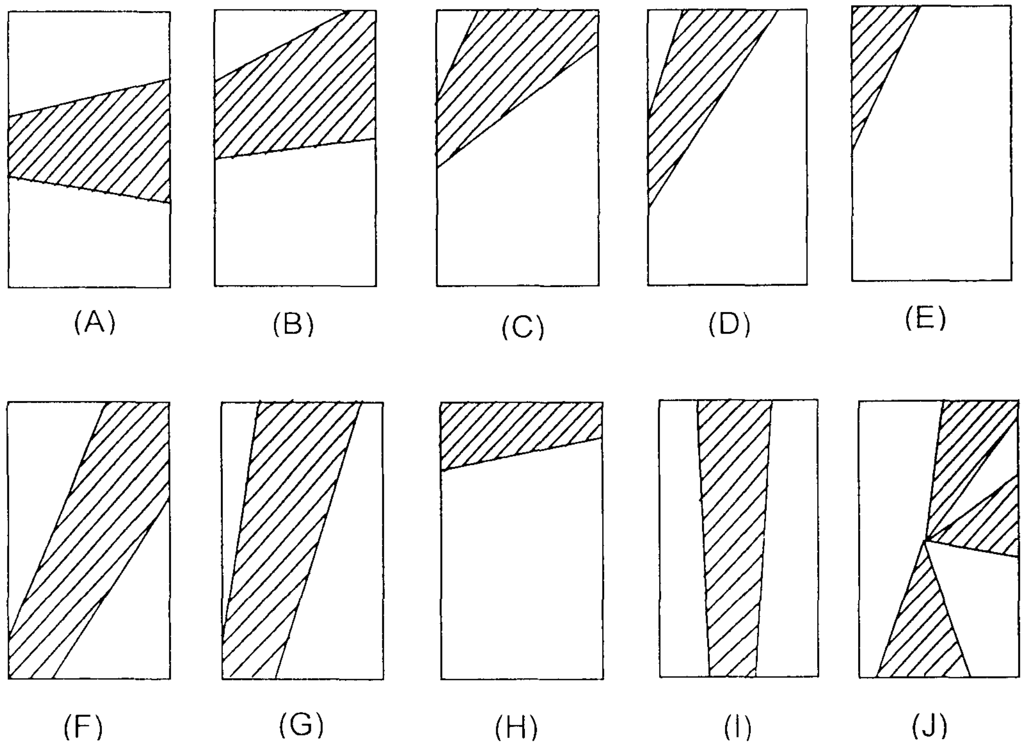

FIG. 2. Various cases of knots in the section of a board. A) Center knot; B) Partial center knot (Center knot); C) Partial margin knot (Edge knot); D) Partial edge knot (Edge knot); E) Spike knot (Edge knot); F) Diagonal knot (Edge knot); G) Partial diagonal knot (Edge knot); H) Margin knot (Edge knot); I) Edge knot; J) Cases when pith is in board.

representing the full width of the knot (from the intersection of the saw plane with the left and right side of the knot). In the case of an edge knot, the difference is between the co-ordinates of the knot edge that intersected the board and the co-ordinates of the board edge. For face and edge knot types, this is shown mathematically as

$$\text{Diameter}_{\text{face}} = \sqrt{(X_{\text{left}} - X_{\text{right}})^2 + (Y_{\text{left}} - Y_{\text{right}})^2}$$

$$\text{Diameter}_{\text{edge}} = \sqrt{(X_{\text{knot}} - X_{\text{BoardEdge}})^2 + (Y_{\text{knot}} - Y_{\text{BoardEdge}})^2} \quad (8)$$

Grading rules

The knots can be located anywhere within the section of the board. Their position and geometry within the board depend on their size and position in the log and also on the position of the saw planes in the log. Knot size and position are crucial to grade the boards. The possible cases considered by the NLGA Visual Grading Rules are represented in Fig. 2.

For all possible types of knot intersections, the NLGA Visual Grading Rules specify the knots as being center or edge and give a measurement method for each. An "equivalent diameter" is calculated using the area that the knot occupies in the section of the board and dividing it by the width or the thickness of the board, depending on the type of intersection. This procedure is the recommended procedure for precise calculation of the knot diameter on the surface, and it is quite close to the concept of Knot Area Ratio. The model considers five grade classes: Select Structural, No. 1, No. 2, No. 3, Economy. Since the model uses precise data as input, the classes available in the grading rules are fully exploited; that is, the best class "Select Structural" is completely differentiated from the next one, "No. 1". There are no categories "No. 2 and Better" as is frequently found in the industry because such grades are used as safeguards against overgrading (Madsen 1992).

The grading model considers knot clusters in the same manner as in the NLGA rules. Any knots within 6 inches of each other inside the lumber are considered to be in a cluster. In such a condition, the knot diameters measured on the board's surfaces are summed and evaluated according to different rules. An algorithm has also been developed to consider knots in the same section of the board.

SIMULATIONS

The model was used to simulate the sawing and grading of a black spruce log with a 15-cm diameter. Data such as log geometry and knot position and size were recorded on the surface. The geometry of the knots inside the log was predicted based on their external shape and also on data collected from an ongoing study of black spruce knot morphology. A sawing pattern for two 2 × 4 lumber was calculated based on the geometry of the small end section of the log followed by the sawing and grading simulation. The log was then sawn according to the exact pattern. All knots that were measured on the surface of the log were found on the boards' surfaces because their position was recorded.

RESULTS AND DISCUSSION

The results of the simulation and the real sawing are shown in Table 1. In almost all cases, the model predicts the type of knot that appears on the board. Sometimes, two measured diameters appear for some knots; these were on edge, and thus face and edge diameter measurements were taken. On some occasions, the model predicted one type of knot while in reality, it is another. These knots are marked with an asterisk beside the measured diameter. They appeared as edge knots on the board while the model had predicted partial edge or partial center knots, which means that the knots were not quite fully on the edge in the simulation. In these cases, it can be seen that one of the measured diameters is low, which means that the knot was close to being fully on edge.

In general, the model seems to consistently underestimate the knot diameters that appeared on the board. This is the result of using an "equivalent diameter" equation in the model. This procedure greatly reduces the surface diameter of the knot because it divides the area that the knot occupies in the board section by either the width or thickness of the board. Figure 3 demonstrates the reduction in surface diameter. In that particular case, the estimated surface diameter is almost exactly half of the real surface diameter. A close examination revealed that the model's predicted surface diameters were generally within 3 mm of the true surface measurements. Using the equivalent diameter may result in higher predicted grades than in reality. The equivalent diameter procedure is used in the NLGA Grading Rules because it effectively removes the bias associated with the knot measurement on the board surface; that is, the equivalent diameter considers the shape of the knot within the board section as a means to predict its effect on strength.

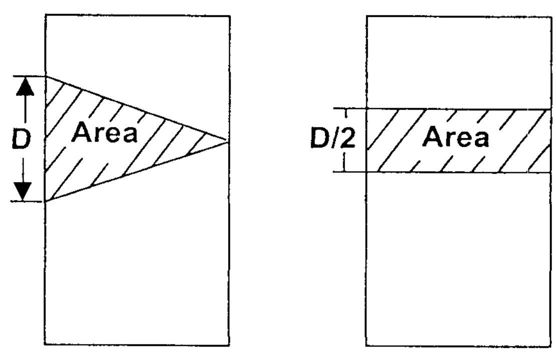

FIG. 3. Measurement of the equivalent diameter requires dividing by the width or thickness of the board whether the knot is in the center as in this case or on edge. This procedure reduces the diameter of the knot.

TABLE 1. *Comparison between the actual knot diameter and the simulated knot diameter.*

Knot	Type	Simulated diameter (mm)	Measured diameter (mm)	Simulated longitudinal position (mm)		Measured longitudinal position (mm)
Board 1						
1	Spike	7.32	15	31.1	28.6	11
2	P. margin	12.81	14–18	37.2	34.6	16
4	Centre	8.44	11–13	351.5	348.3	336
5	Spike	11.53	21	368.3	365.5	353
8	Centre	5.29	11	566.9	564.2	560
9	Spike	0.83	5–35	569.1	567.4	551
10	P. centre	15.02	21*	586.4	583.5	572
11	P. margin	5.74	13*	688.2	686.2	646
12	Centre	6.14	16	751.3	748.3	702
13	Centre	17.29	34	826.2	823.2	749
15	Spike	0.62	3–20	906.3	904.8	887
19	Spike	1.50	8–46	1,070.2	1,068.4	1,065
21	P. centre	5.76	10*	1,207.3	1,205.0	1,200
23	P. edge	15.07	18–16	1,282.5	1,279.3	1,250
Board 2						
3	Centre	6.39	16	149.9	149.9	145
6	P. margin	24.51	25–30	419.8	419.6	382
7	Centre	6.71	16	469.8	469.8	419
9	P. margin	11.78	5–14	566.7	569.2	549
14	Edge	12.70	17	897.6	897.6	876
15	P. margin	8.03	1–45	903.9	906.3	888
16	Centre	7.83	18	930.6	930.6	902
17	P. margin	8.27	16	1,012.5	1,012.4	1,014
18	Centre	4.10	14	1,065.6	1,065.6	1,045
20	Centre	8.37	17	1,194.1	1,194.1	1,182
24	Edge	10.41	14	1,365.4	1,365.4	1,348

The diameter underestimation is also a consequence of predicting the size and shape of the knots from external measurements. The live and dead knots are not yet differentiated in the model. Generally, dead knots that appear on the bark surface have a slightly larger, live knot diameter inside the bark. Since only the outer knot diameter is considered regardless of quality, the assumption is that its diameter only decreases to the pith. This diameter underestimation may also cause an overestimation of the grade of the boards by the model. Although this is an exception rather than the norm, consideration of knot quality may help to improve accuracy in such occurrence.

In the simulations, the knots were assumed to have a slight upward angle. However, it was found that the knots had a steep upward angle, resulting in an overestimation of the longitudinal position of the simulated knots. Since black spruce usually have dropping branches, finding steep upward branches proves the great inherent variability of black spruce knots. The assumption that the knots were nearly horizontal was a good compromise between steep upward and downward knot angles. However, the simulation demonstrates that the model will be greatly improved in accuracy once black spruce knots have been well characterized.

CONCLUSIONS

A model for sawing logs and grading boards according to knots was developed using simple geometric equations. It incorporates the National Lumber Grades Authority Visual Strength Grading Rules for softwood lumber as a means to grade the boards. The