CHARACTERIZATION AND MODELING OF KNOTS IN BLACK SPRUCE (*PICEA MARIANA*) LOGS

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ABSTRACT

A knot study on black spruce was performed on 21 trees originating from a natural stand located in Quebec. Branch (knot) frequency, distribution, and diameter along different directions in the trees were evaluated. A destructive protocol for dissection was developed to slice each knot into a series of sections for modeling the knot morphology (or internal distribution) within the log. In addition, attempts were made to establish the relationship between external branch parameters and internal knot morphology.

The study showed that there were higher numbers of knots on the southern sides of the trees than on the northern sides, but the knot diameters on average were smaller on the southern sides. This heterogeneous distribution of knots around the stem may increase the chance of finding a log rotation that is optimal for lumber grade yield when the knots are considered during breakdown.

The dissection data were smoothed with second degree polynomial equations using an SAS® program. The equations yielded knot angles and other knot dimensional characteristics. The study indicated that internal knots in black spruce logs showed large variations in their angles, but their diameters could be predicted from the external measurements. This information is particularly important for sawing and grading models that require precise diameter data.

Keywords: Knots, modeling, characterization, black spruce, dissections.

INTRODUCTION

Knots are an important log characteristic that greatly affects the quality of solid wood products. Defined as the internal attachment of branches to tree stem, knots deviate and distort the fibers of the wood. In structural lumber, they are one of the most weakening factors as they effectively create stress concentrations from a discontinuity within the fibers of the wood (Bodig and Jayne 1982). The size and distribution of knots in a tree are directly determined by branchiness, which is, to a large extent, determined by the growth conditions of the tree. Since the growth conditions of a tree can be manipulated by silviculture (e.g., thin-

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ning), this type of intervention thus has an impact on knot size and distribution along with other stem characteristics. For example, a recent study by Zhang et al. (1998) on balsam fir showed that precommercial thinning had a significant effect on branchiness and knottiness at both tree and stand levels. As a result of affected knottiness, the strength and stiffness of lumber from heavily thinned stands are significantly lower than those of lumber from the unthinned stands. In addition, the abovementioned study also revealed that the difference in visual grade yields between thinned and unthinned stands was due largely to the difference in knottiness.

A better understanding of knottiness in a species will not only help manage stands for high-quality sawlogs, but also allow considering knots during the primary breakdown for the possible improvement of product quality (Steele et al. 1994; Wagner et al. 1989). Therefore, numerous knot models have been developed over the years. Many models consider knots as numerical data matrices that are the result of scanning (Butler et al. 1989; Jaeger et al. 1999). Others describe knots using parameters such as knot angles and status (e.g., live, dead knot) (Björklund and Moberg 1999; Grönlund and Grundberg 1999). A modeling approach to knottiness has been developed by Samson et al. (1996) and used by Lemieux et al. (2000). In this context, a study on the characterization and modeling of knots was undertaken to collect sufficient knot data for the revised model.

In this study, black spruce (*Picea mariana*) was used because it is the most important commercial species in eastern Canada (Ministère des ressources naturelles 1996). This species is highly valued for both lumber and pulp production (Mullins and McKnight 1981). Many studies have described the tree growth and external stem characteristics in this species. However, no research had yet examined its internal knottiness. As part of a larger study, this paper reports on the characterization and modeling of knots in black spruce in order to simulate them in the model

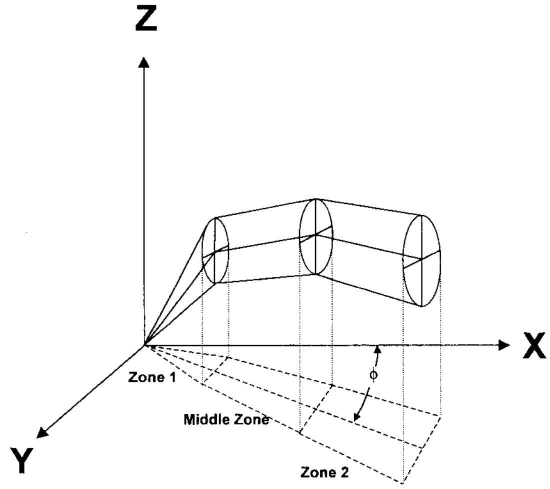

FIG. 1. Knot model showing three distinct zones.

described in Lemieux et al. (2000). In addition, this study examines the possibility of predicting the knot morphology based on log surface measurements.

MATERIAL AND METHODS

The experiments followed a modeling approach revised in Lemieux et al. (2000). In this case, the knot is represented as a series of straight conical sections or zones as shown in Fig. 1. Although each conical section must overlap with the next, it has an angle that is independent of the adjacent sections. It then follows that the knot created by this model can have any angle or change of angle within its length. The revised approach is useful for modeling black spruce knot morphology because this species is known both for its lower dropping branches that can cause the tree to reproduce by layering and also for its upper branches that point upward towards the sun (Hosie 1990). This means that black spruce may have large variations in knot angles depending on its position in the tree.

Material

Twenty-one black spruce trees were collected from a natural stand located 75 km north of Quebec City (47° latitude). The stand,

TABLE 1. *Basic information on the sample trees.*

	Small tree diameter (14–16 cm)	Medium tree diameter (17–19 cm)	Large tree diameter (20–24 cm)
Tree height (m)	13.1	14.4	15.0
DBH (cm)	19.4	20.7	24.7
Tree age (Min–Max)	66 (54–82)	61 (52–82)	65 (56–80)
Diameter @2.6 m	16.5	18.4	20.9
Height to first live branch (m)	4.3	4.3	4.7
Max. crown width (m)	2.5	2.6	2.7
Height to max. crown width (m)	6.5	7.9	8.5

which is part of the Montmorency Experimental Forest of Laval University, contained 30% black and white spruce and 70% balsam fir and had a stand density of about 2,300 stems/ha. The trees ranged from 60 to 100 years old. The selection of the sample trees was based on tree diameter at breast height, but other factors (e.g., trunk straightness, crown structure) were also considered. In order to examine tree size effect on knot morphology, the group of twenty-one trees was separated into 3 classes containing 7 trees each. Diameter at breast height was the criterion that differentiated these classes. A sawing simulation software called Optitek (Grondin and Drouin 1998) was used to assist in tree sampling. The software helped to determine the impact of log size on lumber yield. In turn, this helped to determine the potential tree diameter for each class. However, a difficulty in finding very large trees made the difference in diameter between the 3 classes smaller than originally intended. Selected tree characteristics for the sample trees are shown in Table 1. Each tree was sawn into three 2.6-m-long logs and marked for the north direction. Branch stubs 30 cm long were left on the logs to obtain an angle measurement.

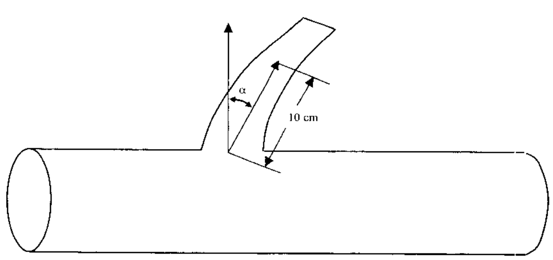

FIG. 2. Method for measuring branch angle.

External measurements

Surface measurements of the logs were made; dimension, size, and position of the knots were also obtained in both longitudinal and tangential directions. A protractor, positioned at the base of the branches, was used to record their angles. The angle between the axis of the log and the central point of the branch at 10 cm from its base was defined experimentally as the branch angle (Fig. 2). The 10-cm distance along the branch was an experimentally determined value. It was away from the bark and from any disturbance such as branch collar and gave a true central reference of the branch. Afterwards, the branches were sawn flush with the bark. The knot circumferential position with respect to the north direction was obtained using a string with a nail that was placed in the pith of the knot. The string was then extended along the axis of the log to the top end. A protractor was placed at the top section of the log and zeroed on the north axis. The string was brought to the middle of the protractor, and the knot angle was measured as shown in Fig. 3. The longitudinal position of the knot was measured from the bottom of the log to the knot pith.

Dissection

Three trees from the twenty-one samples (corresponding to one tree from the 7 samples in each class) were randomly selected for dissections. Hence, a total of 9 logs (3 logs per

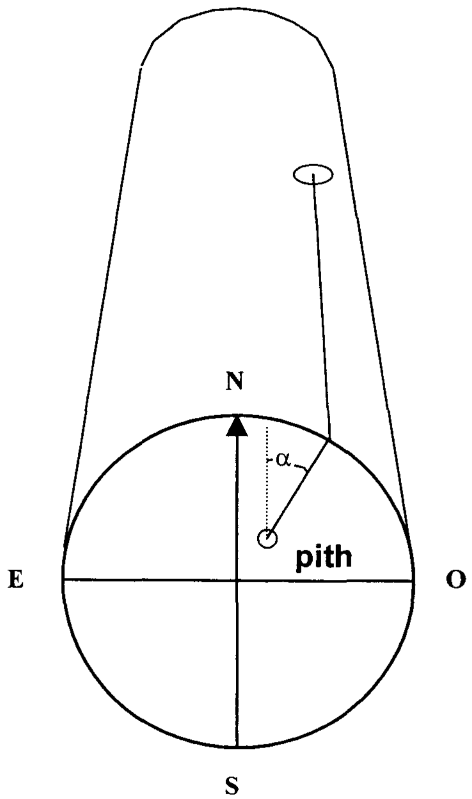

FIG. 3. Measurement of radial knot angle (position) with respect to the north direction.

tree) would be used for the labor-intensive dissections. The remaining 18 trees were used in real sawing experiments. The dissection logs were crosscut into bolts with lengths varying between 10 and 20 cm. The shorter lengths improved control in subsequent manipulations. The bolts were debarked and labeled to keep their position in the logs. The upper section of the bolts was marked with radial lines extending from the pith to the bark, and the marked section (as in a piece of pie) contained a complete knot. They were also used as sawing guidelines. The bolts were then sawn to extract the sectors containing one knot. The knots were re-sawn into 6-mm slices perpendicular to the radial axis from pith to bark. Information about the knot was thus obtained through a series of sliced sections at 8-mm intervals (including the 2-mm saw kerf to the thickness of the slices). The entire procedure is illustrated in Fig. 4.

Longitudinal and transversal diameters of the knots were measured at each slice. The longitudinal position of the knots was measured from the bottom of the knot to the bottom of the slice. The accuracy of this measurement depends on the sharpness of the knot delimitation as well as the accuracy of the bolt crosscut.

Knot reconstruction

Data obtained from the dissections were used to reconstitute the Longitudinal-Radial (L-R), Radial-Tangential (R-T), and the pith profiles of the knots from the log pith to the bark. An SAS® algorithm (SAS Institute Inc. 1985) was developed to smooth the data using quadratic equations. The fitted lines were restricted at the log pith where they had to converge to the same origin. The axis of the knot was assumed to run through its pith; hence the fitted knot pith was examined for curvature.

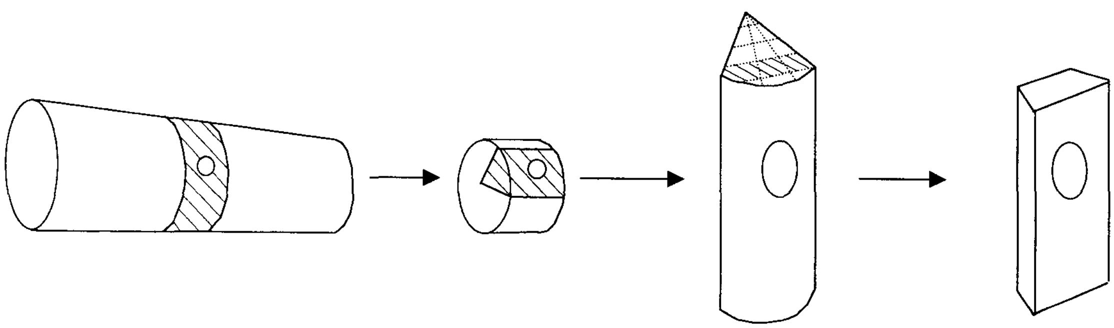

FIG. 4. Dissection procedure for characterizing knot morphology.

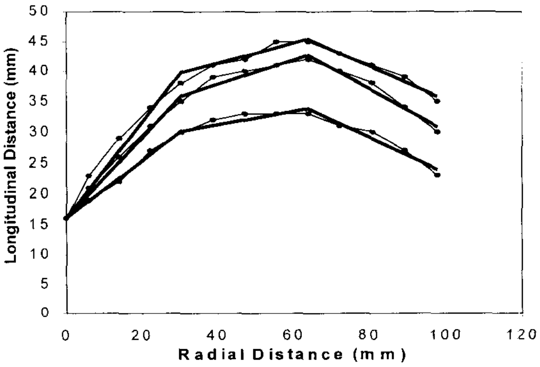

FIG. 5. Knot reconstruction along with fitted profiles.

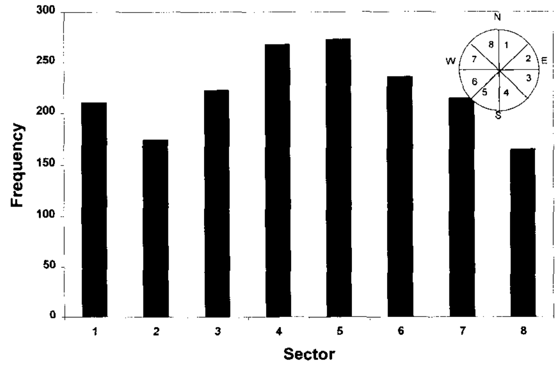

FIG. 6. Frequency distribution of knots around the stems.

The objective of the procedure was to represent the knots as accurately as possible using straight conical sections. Since the knots' axes generally have a smooth curvature, the slopes of the pith along the length of the knots were compared with slopes at the origin. Once the difference had reached a threshold empirically set at 26 degrees (0.5 radians), a cutting point was placed to delimit two zones. The procedure was applied throughout the length of the knot. It is important to note that curvature in the L-R plane was not the only criterion used to determine the number of zones. Since knot growth can promote a non-linear lateral profile, the knot R-T plane was also examined. Once segmented, the knots were reconstituted with linear conical sections through the original data points. All fitted conical sections were attached to the previous zone to ensure continuity in the profile from pith to bark. However, slope at the intersection between two zones could vary. A typical fitted knot profile is shown in Fig. 5. Parameters such as number of zones, angles, knot diameters, and zone lengths were obtained from these fitted profiles and used in subsequent analyses.

RESULTS AND DISCUSSION

Knot distribution

The radial knot distribution on the bark surfaces was examined in all 21 trees. This procedure was performed before the dissections had begun. Each black spruce tree was separated into 8 sectors as shown in Fig. 6. It was clear that the study black spruce trees had more knots (branches) on the south sectors than on the north sectors. This is in agreement with other studies that found that northern tree species tended to have more branches on the southern side than on the northern side of the tree, possibly due to less light on the north side (Lemieux et al. 1997; Shalaev 1983). However, there was one exception in the first sector, where there was an abnormally high number of branches. This is attributed to a possible response of the tree to evenly distribute the branch weight around the stem in order to reduce stress. As shown in Fig. 7, knots in the northern sectors on average had a larger diameter than in the southern sectors. Although the largest knots were found in the northern sectors where, on average, knot diameter was more sizable, the southern sectors

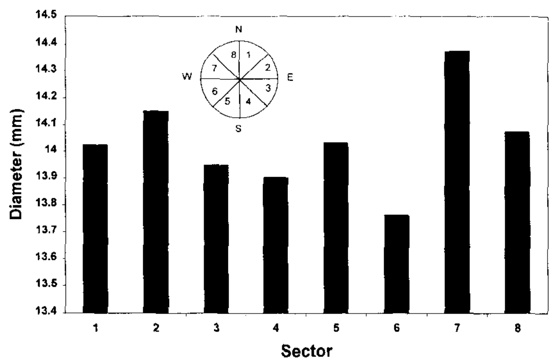

FIG. 7. Average knot diameter per sector.

TABLE 2. *Large knot (>19 mm) distribution around stems.*

Sector	1	2	3	4	5	6	7	8
Average knot diameter >19 mm	24.9	25.8	21.8	21.9	22.6	23.1	23.3	24.5
Maximum knot diameter (mm)	67.5	56.5	28	27	34.5	33	60	45
Number of knots	15	16	25	26	33	21	31	18

still had a higher number of exceptionally large knots (larger than 19 mm in diameter), as shown in Table 2.

Compared to other boreal coniferous species, black spruce is a slim tree with small branches. It is not surprising that the average knot diameter at bark was only 14 mm (or approx. $\frac{9}{16}$ in.), which is an acceptable knot size even for the best structural grade (NLGA 1996). In addition, average knot diameter remained quite constant along the stem height. However, exceptionally large knots were found in the live crown area, as shown in Table 3. While 10% of the knots had diameters greater than 19 mm (¾ in.), only 4% of the knots had diameters greater than 25 mm (1 in.) at bark.

The uneven distribution of knots, especially large ones, may have a positive implication for sawing structural lumber. The knots located on the northern side had larger diameters; consequently, they would be more damaging to board quality in terms of grade and mechanical properties than the knots on the southern side. The heterogeneity of the knot sizes and distribution may offer an opportunity to improve lumber grades when knots are considered during breakdown by providing an optimal orientation of the log and the knots with respect to the sawing pattern.

Knot parameter analysis

The knot morphology study was based on the dissection results. The data were smoothed using the statistical analysis program described earlier and yielded parameters for the various knot zones. Table 4 presents the results for Zone 1 (closest to the pith) and Zone 2 (closest to the bark) at three log heights: top log, middle log, and butt log. The parameters described in Table 4 include the length of the first and last zones ($Long_1$, $Long_2$), the rise in the zone (Z_1, Z_2), the angle of the zone (α_1, α_2), the Radial-Tangential (R-T) diameter of the zone ($Diam_{RT1}$, $Diam_{RT2}$), the eccentricity of ratio between Longitudinal-Radial (L-R), and R-T diameters of the knots (Ecc_1, Ecc_2), and the off-center position of the pith in the knot ($Offset_1$, $Offset_2$).

The graphic visualization of the knot zones in between revealed that the transition in geometry was quite smooth from the beginning to the end; thus the middle zones were iterated from the values of the two extreme zones as shown in Fig. 1. In Table 4, there was a large

TABLE 3. *Average large knot diameter (>19 mm) distribution in relation to diameter class and log position (value in each bracket is the maximum knot diameter; on the bottom are the number of knots).*

Log position	Tree diameter class			Total
	Small	Medium	Large	
Top log	23.5 (60) 28	24.1 (45) 68	23.1 (67.5) 29	23.7 (67.5) 125
Middle log	20.4 (22.5) 4	20.5 (22.5) 14	21.0 (23.5) 17	20.7 (23.5) 35
Butt log	21.8 (23) 2	24.8 (56.5) 21	21.0 (21.5) 2	24.3 (56.5) 25
Total	23.0 (60) 34	23.7 (56.5) 103	22.2 (67.5) 48	23.2 (67.5) 185

TABLE 4. *Knot parameters obtained from the dissections.*

Variable	n	Mean	Std dev	Minimum	Maximum	C.V. (%)
			Top Log			
$Long_1$ (mm)	123	34.33	12.73	13	65.47	37
Z_1 (mm)	123	19.58	13.93	−4.53	114.59	62
α_1 (degrees)	123	29.47	15.13	−7.35	69.78	44
$Diam_{RT1}$ (mm)	123	11.71	3.19	3	20.11	27
Ecc_1	123	0.84	0.11	0.43	1.13	13
$Offset_1$	123	0.66	0.19	0.15	1.23	30
ZONE	123	2.21	0.80	1	4	38
$Long_2$ (mm)	97	23.68	8.22	11.85	47.48	48
Z_2 (mm)	97	6.22	8.54	−21.06	41.82	53
α_2 (degrees)	97	12.77	17.65	−35.82	66.75	34
$Diam_{RT2}$ (mm)	97	12.88	3.05	5.09	19.72	20
Ecc_2	97	0.92	0.10	0.6	1.17	10
$Offset_2$	97	0.58	0.21	0.15	1.04	35
			Middle Log			
$Long_1$ (mm)	83	30.87	10.07	15	70.19	30
Z_1 (mm)	83	19.47	7.58	3.48	51.14	39
α_1 (degrees)	83	32.66	11.20	5.88	61.28	34
$Diam_{RT1}$ (mm)	83	11.20	2.68	5.18	21.14	22
Ecc_1	83	0.82	0.09	0.56	0.96	11
$Offset_1$	83	0.68	0.16	0.28	1.05	23
ZONE	83	2.80	0.60	1	4	20
$Long_2$ (mm)	81	25.79	9.27	11.61	48.32	40
Z_2 (mm)	81	4.93	9.97	−11.89	41.89	188
α_2 (degrees)	81	7.87	18.50	−34.56	49.60	215
$Diam_{RT2}$ (mm)	81	12.90	2.65	7.24	19.64	21
Ecc_2	81	0.93	0.08	0.72	1.1	9
$Offset_2$	81	0.59	0.20	0.14	1.15	34
			Butt Log			
$Long_1$ (mm)	43	37.09	12.75	19.3	71.99	36
Z_1 (mm)	43	9.93	14.59	−29.2	30.75	37
α_1 (degrees)	43	16.00	21.25	−45.63	42.19	34
$Diam_{RT1}$ (mm)	43	13.26	1.66	9.84	18.18	12
Ecc_1	43	0.84	0.09	0.53	1	10
$Offset_1$	43	0.65	0.12	0.41	0.90	19
ZONE	43	3	0.53	2	4	18
$Long_2$ (mm)	43	29.68	7.91	15.51	46.62	26
Z_2 (mm)	43	0.86	10.40	−23.52	19.05	60
α_2 (degrees)	43	1.06	16.86	−31.16	29.57	62
$Diam_{RT2}$ (mm)	43	11.06	1.82	5.43	15.07	14
Ecc_2	43	0.96	0.07	0.78	1.20	7
$Offset_2$	43	0.78	0.11	0.53	1.02	14

variation in most parameters, especially in knot angle of the last zone. However, knot diameter was quite stable and consequently easier to simulate.

Knots in the butt logs had a higher number of zones because the lower branches had steeper downward angles. This implies that they had a greater amount of curvature as compared to the knots that grew nearly straight out in the top logs. Furthermore, in the butt logs, the average diameter of the first zone was larger than the diameter at bark probably because most knots in the butt logs were dead at the bark. Table 5 shows the percentage of variation in the various parameters between trees, between logs within a tree, and

TABLE 5. *A percent variation of the external and internal parameters due to trees, logs within a tree, and knots within a log.*

Parameter	Dissections			Experimental setup		
	Between trees	Between logs	Between knots	Between trees	Between logs	Between knots
ϕ	1.4	0	98.6	0.5	0	99.5
$Diam_T$	1.8	0	98.2	4.6	1.3	94.1
$Length_1$	18.0	2.5	80.0			
Z_1	4.9	6.9	88.3			
α_1	13.4	10.3	76.3			
$Diam_{RT1}$	10.6	4.4	85.0			
$Length_2$	6.3	6.4	87.3			
Z_2	24.3	2.9	72.9			
α_2	34.6	4.7	60.7			
$Diam_{RT2}$	5.0	5.8	89.2			
Zone	10.6	26.7	62.7			

between knots within a log. Variation due to between-knots within a log accounted for the majority of the variation in most parameters. As shown in Table 5, knot angle varied less significantly between trees than within-a-tree. Moreover, the number of zones in each knot was more affected by log position in the tree. The large variability in knot zones suggested that it was better to develop a knot model at the log (height) level than at the tree level.

Knot model

An objective of this study was to develop a black spruce knot model that would predict knot morphology based on the logs' surface measurements. To this end, correlations were made between the external measurements and the various internal knot parameters, as shown in Table 6. The external parameters included longitudinal position on the stem, radial position, knot diameter, eccentricity, and knot length (defined as half of the log diameter at the knot position). External branch angle as described earlier was not used. When the external knot angle was correlated with the knot angle near the bark, a large variation between the two measurements was noticed. This variation was probably due to the fact that black spruce has branches with large amounts of curvature. As a result, a measurement taken 10 cm from the branch base was considerably off, compared to the angle projected at the base of the branch.

The basic model was expressed as a vector of internal knot parameters, which are functions of the external parameters, or

$$\text{Knot} = \begin{bmatrix} \text{Long}_y(\text{Diameter}_{\log}, \text{Position}) \\ Z_y(\text{Ecc}, \text{Diameter}_{\log}, \text{Position}) \\ \text{Diam}_{\text{RT,zone}-1}(\text{Diameter}_{\text{knot}}, \text{Position}, \text{Ecc}) \\ \alpha_y(\text{Position}) \\ \text{Ecc}_y(\text{Position}, \text{Ecc}) \\ \text{Zone}(\text{Position}) \end{bmatrix} \quad (1)$$

where the subscript "y" represented a particular knot zone and can vary between 1 and "zone," the total number of zones in the knot. The parameter $Diam_{RT}$ shows a "zone-1" subscript because the diameter value at bark was the measured value. There was no need to iterate it (i.e., $Diam_{RT,zone} = Diameter_{knot}$).

The number of zones making up the knot depended on the position of the log where the knot was located (butt, middle, top log). In the butt and middle logs, knots usually had three zones, while knots in the top logs had only two zones, as shown in Table 4. The larger number of zones for the butt logs can be explained by the low branch angle in the butt

TABLE 6. *Correlations between the internal and external knot parameters. The values in bold show a correlation coefficient (r) with a 95% significance level or greater. Values on the bottom represent the number of samples.*

External parameters	Internal parameters													
	$Length_1$	Z_1	α_1	$DIAM_1$	Ecc_1	$Offset_1$	$Length_2$	Z_2	α_2	$DIAM_2$	Ecc_2	$Offset_2$	Curvature	# zones
ϕ	0.187	0.082	0.021	0.060	−0.069	0.065	0.124	0.056	0.054	0.134	−0.178	−0.075	−0.008	−0.128
	106	106	106	106	106	106	80	80	80	80	80	80	106	106
Position	0.058	−0.151	−0.108	0.029	0.081	−0.064	0.194	0.225	0.216	**−0.237**	0.116	−0.124	**−0.338**	**−0.366**
	106	106	106	106	106	106	80	80	80	80	80	80	106	106
Diameter	−0.009	0.161	0.150	**0.230**	−0.086	0.100	−0.075	−0.011	0.006	**0.450**	**−0.236**	−0.076	0.124	0.121
	106	106	106	106	106	106	80	80	80	80	80	80	106	106
Length	**0.218**	0.036	−0.104	0.027	**0.338**	0.121	0.183	−0.204	**−0.348**	−0.121	0.097	0.135	**0.325**	−0.059
	106	106	106	106	106	106	80	80	80	80	80	80	106	106
Ecc	−0.091	**−0.194**	−0.093	−0.004	0.081	0.175	**−0.247**	**−0.309**	**−0.289**	−0.108	0.201	**0.419**	**0.275**	0.188
	106	106	106	106	106	106	80	80	80	80	80	80	106	106
Middle Logs														
ϕ	−0.099	0.137	0.215	−0.055	−0.171	−0.045	0.019	0.013	0.099	0.072	−0.074	**−0.304**	0.029	−0.030
	81	81	81	81	81	81	80	80	80	80	80	80	81	81
Position	0.248	0.209	0.010	0.107	0.144	−0.051	−0.201	−0.039	−0.066	0.044	−0.105	**−0.322**	0.069	**−0.306**
	81	81	81	81	81	81	80	80	80	80	80	80	81	81
Diameter	−0.037	**0.314**	**0.315**	**0.333**	**−0.300**	**0.235**	0.105	**0.408**	**0.433**	**0.740**	**−0.375**	−0.200	**−0.268**	−0.079
	81	81	81	81	81	81	80	80	80	80	80	80	81	81
Length	0.130	0.080	−0.007	**−0.360**	**0.283**	−0.203	0.042	**−0.649**	**−0.718**	**−0.286**	0.114	−0.162	**0.780**	0.129
	81	81	81	81	81	81	80	80	80	80	80	80	81	81
Ecc	0.015	0.142	0.061	0.102	−0.149	0.096	−0.125	0.100	0.045	−0.187	0.141	0.051	−0.003	−0.014
	81	81	81	81	81	81	80	80	80	80	80	80	81	81
Bottom Logs														
ϕ	−0.272	0.117	0.130	−0.117	0.008	0.003	−0.016	0.158	0.177	0.011	0.200	−0.179	−0.035	0.107
	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Position	−0.277	**0.880**	**0.896**	−0.188	0.200	**0.366**	0.004	**0.766**	**0.780**	0.029	**0.485**	**−0.492**	0.363	−0.291
	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Diameter	−0.324	0.054	0.191	**0.342**	**−0.428**	0.161	**0.455**	**0.325**	0.300	**0.905**	−0.050	−0.013	−0.107	−0.028
	34	34	34	34	34	34	34	34	34	34	34	34	34	−34
Length	**0.761**	**−0.688**	**−0.754**	0.268	−0.165	−0.127	−0.231	**−0.659**	**−0.690**	−0.193	**−0.536**	**0.559**	−0.259	0.099
	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Ecc	−0.129	**0.464**	**0.417**	−0.018	0.377	−0.017	0.162	0.212	0.171	−0.286	0.320	−0.085	**0.434**	−0.280
	34	34	34	34	34	34	34	34	34	34	34	34	34	34

log, while the branches in the top logs are straighter. The inherent variability of the internal parameters reduced the goodness of the model based on the external parameters. However, the external knot diameter appeared to be a good predictor of the internal knot diameter for the various knot zones. This is crucial for softwood lumber grading models because the visual grading rules assess impact of knot on board quality by the knot diameter and position within the board section.

The large variation in the internal parameters with log position in the tree made it difficult to predict the knot morphology based on the external parameters. The model was thus modified as follows:

$$\text{Knot}_x = \begin{bmatrix} \text{Long}_y(A_{x,y}, \text{Diameter}_{log}) \\ \text{Diam}_{RT,y}(\text{Diameter}_{knot}, B_{x,zone-1}) \\ \alpha_y(C_{x,y}) \\ \text{Ecc}_y(G_{x,y}) \end{bmatrix} \quad (2)$$

where the subscripts "x" and "y" represent, respectively, the position of the log where the knot is located and the zone number in the knot. The constant coefficients $A_{x,y}$, $B_{x,zone-1}$, $C_{x,y}$, $G_{x,y}$ were found experimentally. These constants applied to each particular zone of the knot and to each log. Hence, the knot angle that was used in the butt logs was different from that in the middle logs. The external parameters included those related to the positioning (e.g., longitudinal position, radial position Φ), and knot diameter. Analyses using knot eccentricity showed no correlation with knot curvature or angle. The internal parameters obtained from the dissections were then compared with the external parameters. Since the external diameter was related to the internal diameter, a relation was established between the diameter at bark and the diameter of the first zone. The constants are shown in Table 7.

The number of zones in a knot depended on the log position. The total length of each zone was the fraction of the knot length (coefficient $A_{x,y}$) multiplied by half the tree diameter. Also, the angle of each zone was obtained from the average value for each log. The knots located in the top log had fewer zones because the branches at the top logs had an upward angle. Conversely, the knots located in the butt log were more curved because the branches dropped near the ground. Furthermore, in the bottom logs, the first knot zone had a diameter that was 20% larger than the diameter at bark. This phenomenon was attributed to the high frequency of dead knots in the butt logs. The knot zone near the pith was usually alive, while the zone near the bark was dead and thus smaller in diameter.

TABLE 7. *Values of the experimental coefficients for the knot model.*

Internal parameter coefficient	Butt log	Middle log	Top log
$A_{x,1}$	0.4	0.4	.50
$B_{x,1}$	1.20	0.93	1.00
$C_{x,1}$	18.6	32.6	29.7
$A_{x,zone}$	.30	.30	.50
$C_{x,zone}$	2.6	8.1	14.7
# Zones	3	3	2

As part of a larger study, the knot model provides valuable information on the knot morphology in black spruce logs so as to predict lumber grade before logs are sawn. Although this study shows some difficulties in predicting knots' angles, knot diameter in the log can be estimated based on the external information. Further research is needed to better understand the relationship between the external and internal parameters.

CONCLUSIONS

Black spruce trees studied generally have a heterogeneous branch distribution around the stem in terms of both branch frequency and diameter. Furthermore, there is a small proportion of knots (approximately 4%) that have diameters at bark greater than 25 mm. A small number of large knots in this species suggest that there may be potential for improving lumber grade if these knots are considered during the breakdown. Use of log scanning equipment in the sawing process will help to take full advantage of this phenomenon. The dissections on three trees revealed a large variation in knot morphology, especially in knot angle. However, knot diameters are quite constant throughout knot length. Upon predicting the knot morphology based on the external measurements, knot (branch) diameter was the most reliable predictor of the internal knot size. This information will be useful in a grading model as knot diameter is of prime importance.

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