IMPROVING STRUCTURAL LUMBER QUALITY IN A SAMPLE OF *PICEA MARIANA* LOGS SAWN ACCORDING TO THE KNOTS

Hugo Lemieux
Education Coordinator

Michel Beaudoin†
Professor
Département des sciences du bois et de la forêt
Université Laval
Ste-Foy, Quebec
Canada G1K 7P4

S.Y. Zhang†
Scientist
Forintek Canada Corporation
319 rue Franquet
Ste-Foy, Quebec
G1P 4R4

and

François Grondin
BPR-CSO
4655 Wilfred Hamel Blvd.
Quebec City
Canada G1P 2J7

(Received August 2000)

ABSTRACT

This paper examines the effect of knots on the strength recovery of black spruce lumber. A model was developed and used to simulate sawing and grading of boards from knotty logs. Since a log internal defect scanner was unavailable, the internal knot morphology was modeled from external measurements. A standard cant and flitch sawing pattern was used in the simulations and rotated about the log axis. For each 30° of log rotation, the theoretical lumber grades were obtained based on knot sizes and positions within the boards. A best and worst sawing rotation angle based on the potential lumber grade yield was retained for each of 54 logs simulated Half of the logs were sawn into 2 × 4 nominal lumber according to the best rotation angle and the other half according to the worst rotation angle. The resulting pieces of lumber were first visually graded according to the knots and then according to all defects, followed by dynamic MOE testing and finally tested to destruction using a third-point standard bending procedure. The results demonstrate that there was little difference in visual grades between the "best" and "worst" groups and that knots played a minimal role in grade determination of the boards. However, there was significant difference in terms of MOE values, where the group of "best" boards showed an overall 15% increase over the "worst" boards. This result significantly impacts the potential MSR yield of the sample pieces of lumber. Bending tests showed a further 25% difference in average MOR between the two groups. These results suggest that there is potential for black spruce to yield higher strength lumber when knots are considered during breakdown. Further refinements should include a model that determines quality in terms of knot position within the board section rather than one that determines quality in terms of potential visual grades.

Keywords: Sawing, modeling, knots, lumber, quality, simulation.

† Member of SWST.

Wood and Fiber Science, 34(2), 2002, pp. 266–275

INTRODUCTION

It is generally accepted that internal log scanning is beneficial in the sawing process. Internal scanning of hardwood and softwood logs provides valuable information on the internal morphology, which can be used to optimize the sawing strategy and increase the potential value of sawn products (Wagner et al. 1989; Occena and Schmoldt 1994). The accuracy of these predictions depends on both the accuracy of the scanned data and on the accuracy of the simulation model used (Bhandarkar et al. 1999; Chang and Guddanti 1995). To quantify potential gains, Steele et al. (1994) found through simulations that hardwood lumber value could be increased by 10% if internal defects were considered before breakdown.

Internal log scanning is also being used to build data bases on growth features of native tree species (Chiorescu and Grönlund 2000). These data banks help the forest industry to characterize the forest resource and improve value through better utilization. Extensive research using internal log data has led to tree growth models that predict log internal morphology based on external tree features. Basic forest inventory data can be input into the model, which gives a better indication of the potential value and uses of the trees and their logs (Leban et al. 1996). These models have wide applications (i.e., characterize stands and forests rather than individual trees) and give a statistical potential lumber grade recovery of the stand.

When internal log scanners are not available, external scanners have been used to predict potential log grade (Jäppinen and Nylinder 1997). This is particularly useful, as external scanners are cheaper and more readily available than internal scanners. Moreover, modeling can be a valuable research tool when scanners are not readily available. In New Zealand, the AUTOSAW simulation program has been used to determine the potential quality yield of sawn lumber (Todoroki 1996). The data obtained are used to model internal defects, which makes it possible to simulate the sawing and grading of those logs and therefore to optimize the sawing.

Barbour et al. (1999) showed that a manual method to obtain data on internal defects along with the use of a sawing simulation system could be a useful replacement for an expensive internal defect scanner. Chiorescu and Grönlund (2000) compared internal log scanning and sawing simulations to real sawn output and found that the modeling approach was accurate for predicting a sawmill's output. These findings are encouraging, especially when an attempt is made to determine the possible impact of scanning on a particular resource without sophisticated equipment.

In the boreal forest of Canada where small diameter logs prevail, efficiency is measured in terms of volume recovery. Expensive equipment accurately measures log shape, which is subsequently used to find the best sawing strategy. However, internal log characteristics are not considered. It is perceived that for a species of prime industrial importance like black spruce, the logs will yield the same board quality regardless of the orientation of the defects, namely knots, inside sawn boards. However, the effect of knots on quality recovery has never been quantified in this species. More specifically, variation in knot morphology in this species has never been exploited during the primary breakdown so that higher strength lumber could be extracted from knotty logs.

Studies have shown that northern species may be prone to have more knots on the southern side of the trees than on the northern side (Lemieux et al. 1997; Shalaev 1983). This heterogeneous knot distribution could make it possible to find an optimal log rotation/position that yields higher strength lumber if knots are considered during breakdown. Until now, no study has been performed that explores the possibility of improving black spruce lumber strength by considering the knots through a rotation of the log. Samson (1993) showed that the rotation of a log could place the knots in an optimal position in the board so that their impact on lumber strength would be minimized and higher quality sawn boards could be obtained.

Most of the research done on scanning explores visual grade output as it relates to tree and log characteristics. A general school of thought is that if visual grades are improved, then lumber strength properties should also improve. Few have performed mechanical tests of lumber to determine the actual strength improvements from scanning for knots.

This study explores the possibility of improving black spruce lumber strength through a rotation of the log and a consideration of the knots during breakdown. As this may have implications for both visually graded and MSR lumber, the study has two distinct parts. The first part determines if the sawing and grading model developed by Lemieux et al. (2000) can find a best and worst log rotation angle based on grade recovery for the study logs when knots are considered in the sawing solution. The second part will consist of verifying if the model predictions are true by performing actual tests of the sawn lumber.

MATERIALS

A total of 21 trees were obtained from a mixed natural stand of black spruce and balsam fir that had not received any silvicultural treatment. The samples were collected to represent a range of dbh sizes for a broader application of the results. The experimental setup in Table 1 shows three distinct dbh classes for the trees as well as height subclasses since the trees were bucked into three 2.6-m-long logs. These dbh classes were based on simulations performed with the Optitek© Sawing Simulation Software (Grondin and Drouin 1998), which approximated the amount of sawn 2 × 4 lumber that could be extracted from a bottom log of the sampled trees. In other words, the number of boards that could potentially be extracted from the bottom logs determined the diameter class in which a tree belonged.

There were seven trees in each diameter class. Since no internal log scanner was available for the study, one of the seven trees was dissected to study knot morphology. Internal knot geometry was modeled based on the dissection data (Lemieux et al. 2001). This information was subsequently used in the sawing and grading model. Both log shapes and surface knots were also characterized. Furthermore, the north direction was marked on all logs to keep a rotational frame of reference. Since the species does not prune itself easily (depending on stand density), no assumption was made on the possible position and size of overgrown branches. It was assumed that the overgrown knots were so small that they did not have any effect on the grade yield nor the mechanical properties of the boards.

TABLE 1. *Experimental setup showing each subgroup in which 3 logs are sawn to best or worst solution according to grade along with 1 log for knot dissections.*

	Small tree	Medium tree	Large tree
Top log	3 Best	3 Best	3 Best
	3 Worst	3 Worst	3 Worst
	1 Dissection	1 Dissection	1 Dissection
Middle log	3 Best	3 Best	3 Best
	3 Worst	3 Worst	3 Worst
	1 Dissection	1 Dissection	1 Dissection
Bottom log	3 Best	3 Best	3 Best
	3 Worst	3 Worst	3 Worst
	1 Dissection	1 Dissection	1 Dissection

The remaining six logs were used in simulations as well as in real sawing experiments. The simulations determined which logs would be sawn into 'better' lumber according to grade and which three would be sawn into 'worst' lumber.

METHODS

Model and simulation

The sawing and grading model is based on previous work by Samson et al. (1996) and Bindzi et al. (1996). It describes the log as a straight axis truncated cone with central pith (Lemieux et al. 2000). Likewise, the knots are described as a series of truncated cones that are interconnected on a common radial axis. They can be located at any longitudinal or ra-

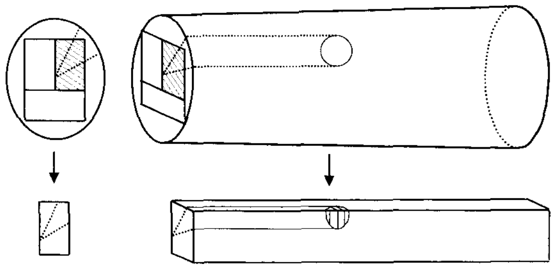

FIG. 1. Sawing pattern used to mark the small end of logs.

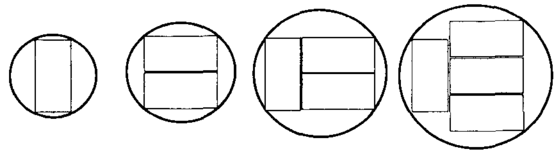

FIG. 2. Patterns used in sawing experiments.

dial position on the log pith. The sawing pattern consists of perpendicular lines in the log section (radial-tangential plane) which represent planes parallel to the log axis. The intersection of the saw planes with each knot gives the shape, diameter, and position of the knot in the sawn boards as shown in Fig. 1. The model calculates an equivalent knot diameter, which is compared to the maximum diameters for each structural lumber grade based on the National Lumber Grades Authority Visual Strength Grading Rules (1996).

Each log was virtually sawn into 2 × 4 nominal lumber according to a centered cant and flitch sawing pattern, as shown in Fig. 2. The amount of lumber that each log could yield was determined using Optitek©. When only two boards could be sawn in a log, the center cant took a 4 × 4 section plus a saw kerf. In the case where three or four boards were sawn in a log, the center section was slightly greater than 4 × 6 and 6 × 6, respectively, because one board was sawn perpendicular to the others. A centered pattern was used because it allowed the sawing pattern to rotate freely around the log axis without affecting volume recovery, especially in logs with irregular sections or slight curvature.

Once the log, the knots, and sawing pattern were entered into the model, simulations were performed at every 30° of log rotation, and lumber grades were recorded each time. The north direction of the logs was used as a reference. For each board grade, a bending MOR was estimated, based on the ASTM Standard D245 (1993) for knots. This method provided a means of comparing solutions based on the relative mechanical properties of each grade. The idea behind this procedure was to find the relative weight of each grade in terms of its bending strength. Although price could have been another way of comparing the solutions, a preliminary examination of lumber prices showed variations and discrepancies in market values due to demand. The MOR equivalency for each grade is shown in Table 2.

For each sawing simulation, the estimated working service MOR value for the sawn boards was summed to give an overall value for the particular solution. The maximum sum was compared to the minimum sum, which showed the possible strength improvement of the boards sawn from a log. Table 3 shows the overall difference in MOR between the best and worst solutions for each log. The simulation results allowed the orientation of the logs to be found for the sawing strategy.

Sawing

The simulation results were validated through actual sawing experiments. In order to determine the potential increase in lumber mechanical properties, it was necessary to max-

TABLE 2. *Modulus of rupture equivalency for each visual strength grade.*

Grade no.	Grade	Modulus of rupture equivalency (MPa)
0	Select Structural	10.6
1	No. 1	8.7
2	No. 2	7.1
3	No. 3	4.1
4	Economy	4.1
5	Reject	—

TABLE 3. *Results of the sawing and grading simulations for the black spruce logs. The numbers indicate the MOR equivalence. The symbol "—" indicates no grade difference between best and worst solutions.*

	Bottom			Middle			Top		
	Tree #	Solution	Δ (Mpa)	Tree #	Solution	Δ (Mpa)	Tree #	Solution	Δ (Mpa)
Small	10	b	—	10	b	—	10	b	—
	26	b	—	26	b	—	26	b	—
	31	b	—	31	b	—	31	b	—
	5	w	—	5	w	1.9	5	w	—
	13	w	3.8	13	w	—	13	w	—
	19	w	1.9	19	w	1.9	19	w	1.9
Medium	22	b	1.9	22	b	—	22	b	—
	25	b	—	25	b	—	25	b	1.9
	30	b	—	30	b	—	30	b	1.9
	6	w	8.1	6	w	3.8	6	w	1.9
	17	w	5.7	17	w	1.9	17	w	1.9
	33	w	6.5	33	w	5.7	33	w	3.8
Large	4	b	—	4	b	3.8	4	b	1.9
	13a	b	—	7	b	1.9	7	b	1.9
	29	b	1.9	29	b	1.9	29	b	1.9
	7	w	1.9	13a	w	3.8	13a	w	1.9
	34	w	1.9	34	w	7.6	34	w	8.4
	45	w	5.7	45	w	3.8	45	w	1.9

imize the difference between best and worst solutions. This was accomplished by separating the logs that showed a difference in lumber quality yield based on a rotation of the logs from those that showed no difference at all and yielded consistently high quality lumber, as shown in Table 3. In the experimental setup, half of the logs were assigned a best sawing solution and the other half, a worst solution. The logs that showed no lumber quality difference were placed in the 'best' category, while those that showed a difference in grade yield were sawn according to the 'worst' solution.

A centered cant and flitch sawing pattern was scribed at the end of each log, as shown in Fig. 1. The North reference, as well as the geometric center, was used to position the sawing pattern at the logs small end. Afterwards, they were transported to a portable sawmill and sawn into 135 pieces of 2 × 4 lumber. The lumber was then dried in a low-temperature dehumidification kiln to a moisture content of approximately 12% and planed to a final 38-mm × 89-mm dimension. They were also trimmed to exactly 244 cm (8) in length.

Grading and mechanical testing

The lumber was professionally graded twice: first according to the knots and second according to all defects. There was wane on some boards as a result of sawing uneven logs, although this was minimized by using a conservative sawing pattern. Also, some boards had coloration and mild fungi attacks and were consequently downgraded.

The lumber was tested for dynamic MOE using a Metriguard 540 E-computer. The supports were set 94 in. apart as shown in Fig. 3A, so that an overall MOE was measured for the boards and used to evaluate MSR grade potential. Afterwards, the pieces were tested to destruction using the ASTM D-198 standard third point bending test as shown in Fig. 3B (ASTM 1997). Both static MOE and MOR values were recorded during the bending test. Although the boards were symmetrically positioned on the bench, they were randomly oriented to avoid having the largest knots on the bottom sections of the board all the time.

RESULTS AND DISCUSSION

The simulations showed that a log rotation did not affect the strength of the boards in

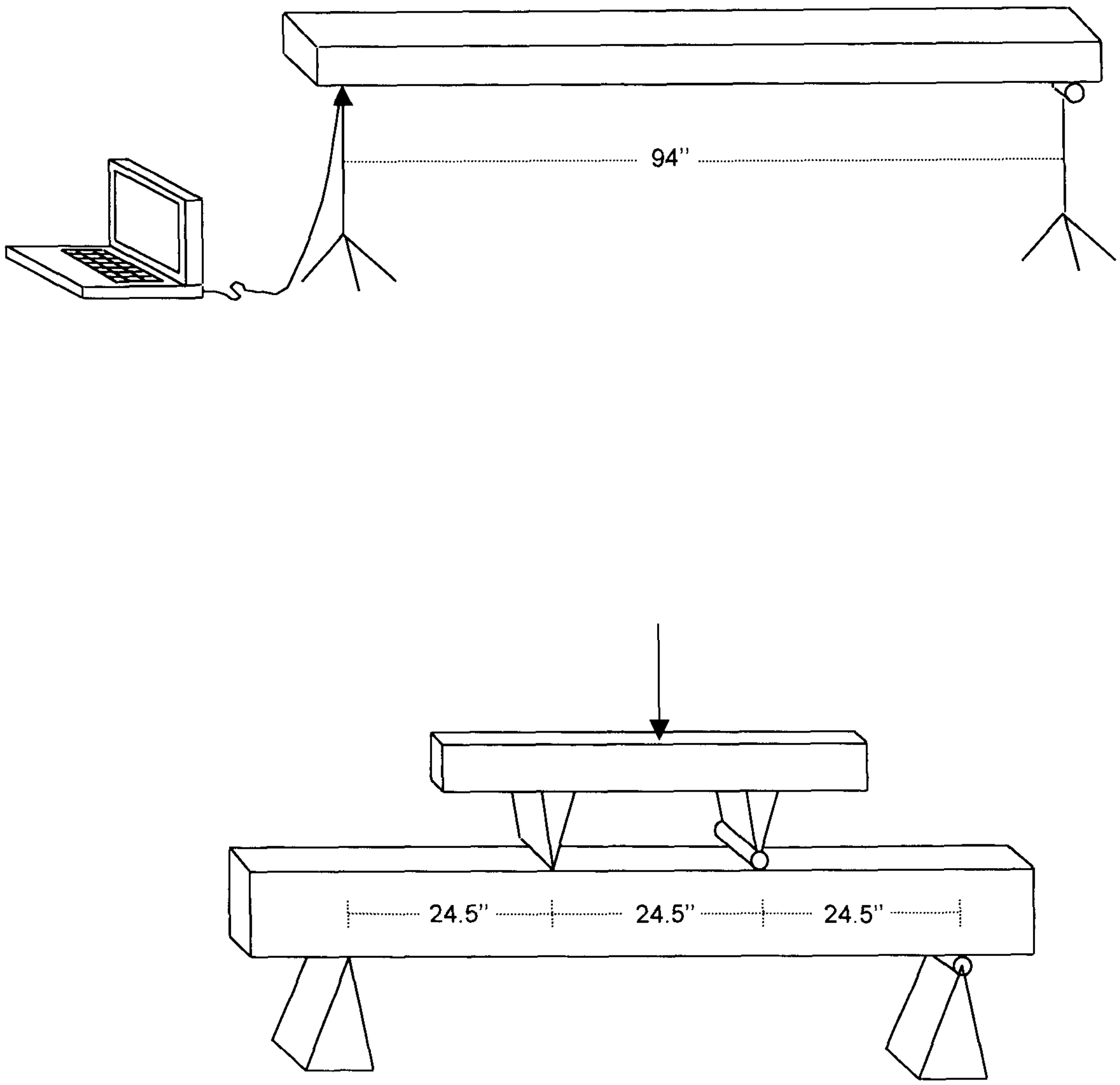

FIG. 3. A) Testing the boards using an e-computer. B) Standard third point bending test for the boards.

some cases, as shown in Table 3. In others, however, there was a net difference in the overall strength of the boards for a particular rotation of the logs. These results were quite encouraging since they predicted that lumber strength could be controlled through a consideration of the knots coupled with a log rotation. This has particular relevance in the MSR lumber industry where greater mechanical properties are generally related to higher values if demand is appropriate.

The results in Table 4 indicate that the model could accurately predict board grade based on knots only, irrespective of the log position in the tree. In this table, the grades were labeled from 1 to 5, with 1 being a Select Structural (best grade) and 5 being a reject. For the top logs, the model underestimated board grade slightly, while it overestimated it slightly in the middle and butt logs. This is because the knot model had predicted larger knot sizes inside the bottom logs. Earlier dissections of

TABLE 4. *Difference between grading methods. The number 1 in the table indicates a one grade difference between the grading method (e.g., from No. 1 to No. 2 grade).*

	Bottom logs		Mid logs		Top logs	
Grading method	AVG (STD)	# Samples	AVG (STD)	# Samples	AVG (STD)	# Samples
Simulation vs. Grade (knot only)	−0.26 (0.92)	57	−0.24 (0.48)	49	0.14 (0.88)	29
Simulation vs. Grade (all defects)	2.12 (1.65)	57	1.59 (1.26)	49	1.62 (0.98)	29
Grade (all defects) vs. Grade (knots only)	2.39 (1.39)	57	1.84 (1.23)	49	1.48 (0.99)	29

black spruce butt logs revealed that the majority of knots in the bottom logs were dead at the logs' surface. However, the live portion of the knots inside the logs was larger than the dead portion. On average, the knots were therefore larger inside the log and smaller at the surface (Lemieux et al. 2001). Since the model did not differentiate live from dead knots, it oversized the live knots. Hence, larger knot size meant a greater chance to be downgraded. In the middle and top logs, the assumption of larger knot size inside the bark was not held as most knots were alive at the bark and consequently the surface knot diameter had the largest value and was more representative of knot size inside the logs.

Simulated grades as well as grades based on knots only were not representative of overall board grades, as shown in Fig. 4. For all lumber, especially for those from the butt logs, the overall grade was overestimated by both the model and by grading with knots only. In other words, knots had little effect on the visual grades. Other defects such as wane and wood degradation were more important in downgrading as shown in Fig. 5. The low impact of knots in downgrade was expected since black spruce knots are generally small in size. Therefore, for this species, limited variation in lumber grade output could be expected if knots are considered during breakdown.

In the simulations, the larger trees generally had larger variations in grade yield as compared to the smaller trees, which have nearly no difference, as shown in Table 3. Cases that showed no difference at all were indicative that knots were generally too small to cause lumber downgrade or reduction in strength properties. Few logs showed a very large variation in grade yield. In most, however, the difference existed in only one board whose quality was downgraded from Select Structur-

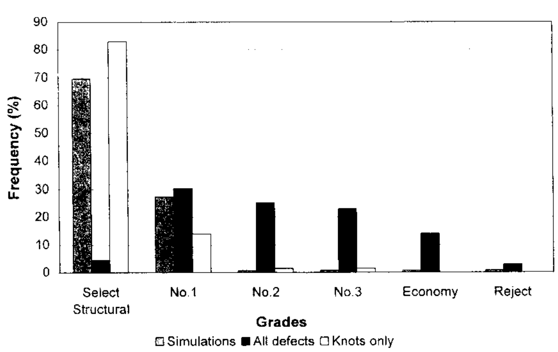

FIG. 4. Distribution of grades—comparison among simulations, actual board grades (knots only) and grades (all defects) based on board grade output.

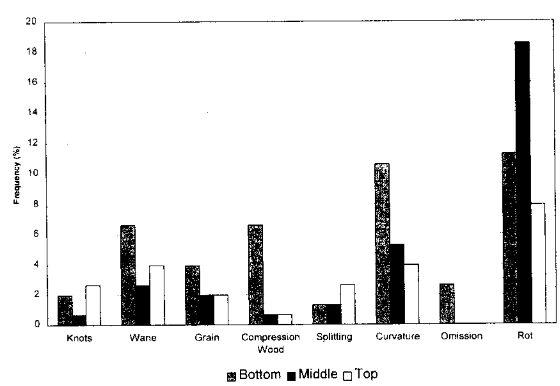

FIG. 5. Impact of the various defects in the overall grade of the boards.

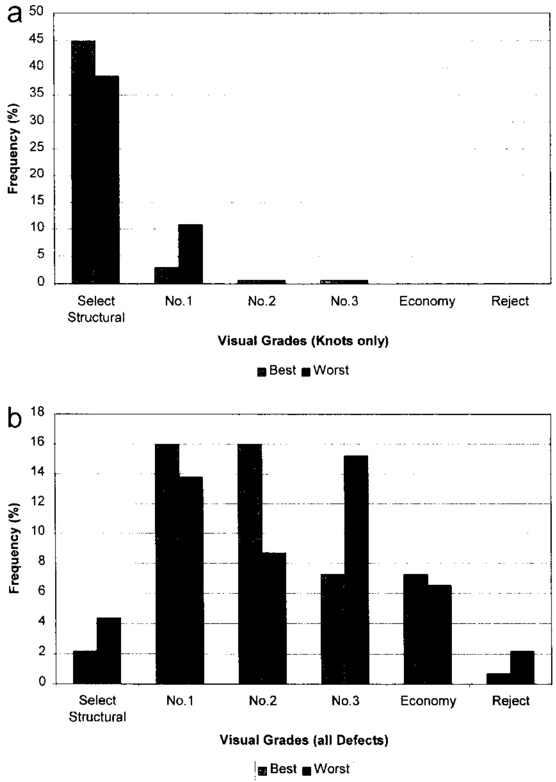

FIG. 6. A) Frequency distribution between best and worst solutions for grading by knots only and B) when all defects are considered.

al to No. 1, which, in practice, amounts to nothing because lumber is generally graded No. 2 and better. Therefore, this slight improvement would go unnoticed unless grading techniques were drastically modified to account for these differences in grade recovery or an alternative grading method such as MSR was used to assess lumber strength.

Even though the difference between best and worst sawing solutions would not have any significant impact based on visual grade, the model nevertheless made a distinction in lumber quality from the grade solutions in some of the logs. This is shown in Figs. 6a and b where the better solutions had a higher percentage of better lumber, both when knots only and all defects are taken into account. However, the difference in strength between the best and the worst solutions was quite significant when the results from the mechanical tests were examined. Table 5 shows the difference in MOE and MOR between the two groups. The table reveals an overall difference of 15% in MOE and 23% in MOR, respectively. Both values are statistically significant at a 95% confidence level. The strength properties of the sample of black spruce lumber was therefore significantly increased by a consideration of the knots during breakdown even though average knots size for this species tends to be irrelevant according to visual strength grading rules. The full benefits of considering knots during breakdown would only be obtained using an alternate grading method such as Machine Stress Rating.

TABLE 5. *Actual difference in strength properties between 'Best' and 'Worst' groups.*

	MOE (MPa)		MOR(Mpa)	
	Best	Worst	Best	Worst
Top log	9658	9143	40.7	35.0
Middle log	9951	9294	45.0	38.5
Bottom log	9077	6812	42.5	31.5
Total	9523	8269	43.0	34.9

A similar strength increase was obtained with the values of dynamic MOE. These values were used as a means to predict the MSR potential of the boards. In this part of the analysis, only the boards which met the visual criteria of No. 2 or better were kept for MSR. The results in Fig. 7 clearly demonstrate a difference in MSR yield between the two groups.

A considerable difference in lumber mechanical properties is very encouraging and indicates that refinements in the model should be aimed at predicting lumber properties in terms of size and geometric position of knots rather than visual grades only. However, one aspect that was not examined is quality versus quantity. With a recovery of only 32%, volume was compromised. The reason for such low recovery is that the same sawing pattern is needed to fit inside the log regardless of its orientation. The most conservative sawing pattern was therefore selected. Strength improvement should be compared to volume re-

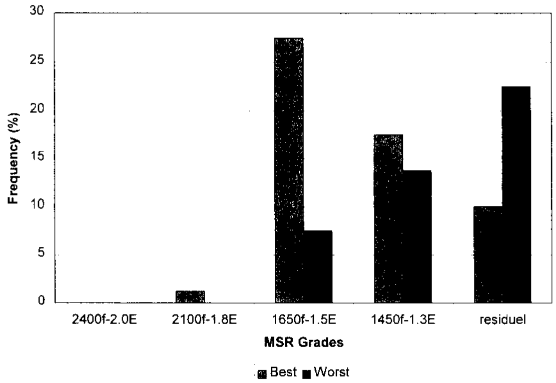

FIG. 7. MSR potential of the lumber for the Best/Worst groups.

covery in order to obtain a better appreciation of the impact of internal log scanning in an industrial context. Changing species for one with larger, more strength reducing knots may also impact the results.

CONCLUSIONS

Sawing and grading simulations of lumber while rotating the logs around their axis showed that some orientations yielded higher strength lumber. However, in terms of visual grades, the difference is limited, even in subsequent sawing and grading of lumber. Lumber downgrades in the studied material were due mostly to other defects such as wane. However, there was a significant difference of 15% MOE and 23% MOR between lumber sawn according to the best and the worst solutions. These mechanical tests suggest that the model was capable of recognizing the difference in black spruce lumber strength.

The research indicates that knowledge of black spruce log internal morphology can help to predict as well as increase strength of sawn lumber. However, further research is needed with an actual scanner in order to find the true impact of such equipment in a northern sawmilling context. It can be hypothesized that a species with inherent large knots such as Jack pine will only accentuate the quality improvement. The model should be refined using a mechanical approach rather than a grade approach for better results.

REFERENCES

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) 1993. Standard D245-92. Standard practice for establishing structural grades and related allowable properties for visually graded lumber. Philadelphia, PA. 18 pp.

——— (ASTM). 1997. Standard D198-97. Standard test methods of static tests of lumber in structural sizes. Philadelphia, PA. 19 pp.

BARBOUR, J., E. LOWELL, C. L. TODOROKI, D. L. PARRY, AND G. A. CHRISTENSEN. 1999. Simulating North American lumber grade recovery with AUTOSAW using externally visible branch and stem form characteristics. Proc. IUFRO WP S5.01-04 Third Workshop Connection between Silviculture and Wood Quality through Modelling Approaches and Simulation Software. France. 645 pp.

BHANDARKAR, S. M., T. D. FAUST, AND M. TANG. 1999. CATALOG: A system for detection and rendering of internal log defects using computer tomography. Machine Vision and Applications 11:171–190.

BINDZI, I., M. SAMSON, AND L.-M. KAMOSO. 1996. Geometric modeling of a sawlog. Annales des sciences forestières 53:21–30. (In French)

CHANG, S. J., AND S. GUDDANTI. 1995. TOPSAW-HW: A training and optimisation system for sawing hardwood logs. Paper presented at the XX IUFRO World Congress, August 6–12, Tampere, Finland.

CHIORESCU, S., AND A. GRÖNLUND. 2000. Validation of a CT-based simulator against a sawmill yield. Forest Prod. J. 50(6):69–76.

GRONDIN, F., AND N. DROUIN. 1998. OPTITEK Sawmill Simulator—User's Guide. Forintek Canada Corporation, Québec, Canada.

JÄPPINEN, A., AND M. NYLINDER. 1997. Automatic sorting of spruce (*Picea abies* (L.) Karst.) sawlogs by grade. Holz Roh- Werkst. 55:301–305.

LEBAN, J.-M., R. DAQUITAINE, AND L. ST-ANDRÉ. 1996. WinEpifn: A software for wood quality evaluation for a Douglas-fir resource. Forêt-entreprise (109):11–15.

LEMIEUX, H., M. SAMSON, AND A. USENIUS. 1997. Shape and distribution of knots in a sample of *Picea abies* logs. Scand. J. Forest Res. 12:50–56.

———, M. BEAUDOIN, AND F. GRONDIN. 2000. A model for the sawing and grading of lumber according to knots. Wood Fiber Sci. 32(2):179–188.

———, ———, AND S. Y. ZHANG. 2001. Characterization and modeling of knots in black spruce (*Picea mariana*) logs. Submitted to Wood Fiber Sci.

NATIONAL LUMBER GRADES AUTHORITY. 1996. Standard grading rules for Canadian lumber. Burnaby, BC.

OCCENA, L. G., AND D. L. SCHMOLDT. 1994. Computer-generated optimum hardwood log sawing using internal defect information. Proc. 1994 NSF Design and Manufacturing Grantees Conference, January 5–7, Cambridge, MA.

SAMSON, M. 1993. Method for assessing the effect of knots in the conversion of logs in tree trunks. Wood Fiber Sci. 25(2):298–304.

———, I. BINDZI, AND L.-M. KAMOSO. 1996. Mathematical representation of knots in tree trunks. Canadian J. Forest Res. 26(2):159–165 (In French).

SHALAEV, V. S. 1983. Evaluation of the effectiveness of sawing spruce sawlogs oriented according to the knots. Lesnoi Zhunal (4):70–73 (in Russian).

STEELE, P. H., T. E. G. HARLESS, F. G. WAGNER, L. KUMAR, AND F. W. TAYLOR. 1994. Increased lumber value from optimum orientation of internal defects with respect to sawing pattern in hardwood sawlogs. Forest Prod. J. 44(3):69–72.

TODOROKI, C. 1996. Developments of the sawing simulation software, AUTOSAW linking wood properties, sawing, and lumber end-use. IUFRO S5.01-04 Second Workshop—Connection between Silviculture and Wood Quality through Modelling Approaches and Simulation Softwares. August 26–31. South Africa. 456 pp.

WAGNER, F. G., F. W. TAYLOR, D. S. LADD, C. W. MCMILLIN, AND F. L. RODER. 1989. Ultrafast CT scanning of an oak log for internal defects. Forest Prod. J. 39(11/12):62–64.