Effect of Knot Detection Errors When Using a Computed Tomography Log Scanner for Sawing Control

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Abstract

Roundwood scanners utilizing X-ray computed tomography (CT) provide the information required for individual log-sawing optimization. However, errors in the automated detection of quality-relevant internal wood features for sawing control may lead to improper log positioning at breakdown, impairing the realization of value recovery potential. It is thus of interest to have an estimation of the impact of feature detection errors on the performance of sawing optimization. A sensitivity analysis was conducted to quantify the effect of errors in knot detection on a breakdown optimization by adjustment of log rotation. Therefore, sawing simulations were performed with the geometric descriptions of log shape and internal knots extracted from the CT scans of 57 Norway spruce (*Picea abies* (L.) Karst.) logs. Three types of artificially set knot description errors were tested under different pricing and product scenarios, each in different magnitudes as systematic or random error. Errors in knot diameter were found to have the greatest impact for both systematic and random errors. The effect of errors in dead knot border radial position was less pronounced but still substantial for higher error levels, while errors in knot rotational position could be neglected even for the highest magnitudes of error tested. The assumed price differentiation between product qualities had a major influence on the impact of the errors. It could be observed that with errors of higher magnitudes than those reported for present knot detection algorithms, an improvement in value recovery compared with outer-shape–based optimization still resulted in the simulated rotation optimization.

Raw material costs amount to 65 to 75 percent of the total costs of a sawmill (Chiorescu and Grönlund 2003), and thus there is great interest in utilizing the raw material in the most efficient way. Potential for further efficiency improvement is seen in optimizing the breakdown of each individual log.

Lundahl and Grönlund (2010) studied the potential to increase volume yield in Scandinavian sawmills by applying alternative log rotation and lateral positioning using breakdown simulations in which only the outer shape of the logs was taken into account. The authors noted that sawing the logs horns down, i.e., with the largest crook vertically aligned in the first saw—a principle commonly used by Scandinavian sawmills in conjunction with curve sawing—on average yields relatively high volume recovery. However, they also found that the individual yield-maximizing rotation for a log most often differs from the horns down rotation. They reported an increase in average volume yield of 8.6 percent when applying the optimal rotation and lateral position to each log.

In a study similar to the one by Lundahl and Grönlund (2010), Berglund et al. (2013) investigated the potential to increase the *value* recovery in Scandinavian sawmills by applying an alternative log rotation rather than sawing logs horns down. Consideration was given only to knots and wane when determining the quality of the boards in this study. An increased average value recovery of 13 percent was found for the logs in this study using the log rotation for greatest profit return for each log. An introduced rotational error of the sawing machine reduced the increased average value yield to 6 percent.

Since full knowledge of internal log properties is required for utilizing the value potential of each individual log, there is a demand for internal log scanning (Schmoldt et al. 2000),

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and X-ray computed tomography (CT) has early been recognized as one of the most feasible technologies for this purpose (Taylor et al. 1984, Hodges et al. 1990). Thus, much research has been devoted to its application for the control of primary log conversion, and diverse approaches for automated feature extraction in CT images of various hard- and softwood species have been presented in the last three decades (e.g., Funt and Bryant 1987, Grundberg and Grönlund 1992, Bhandarkar et al. 1999, Andreu and Rinnhofer 2003, Longuetaud 2005). Most of them have included or even focused on knot detection since knots are the main internal wood feature that, except for logs with severe defects such as rot or cracks, determines the quality of the sawn timber.

Recently, Johansson et al. (2013) reported evaluation results for a knot detection algorithm that is based on the method by Grundberg (1999). This algorithm has been tested on pine and spruce logs, and the resulting knot data have been compared with reference data from manual measurements retrieved in the original CT images and on physical boards that have been sawn from previously scanned logs in known orientation. It has been found that, in tests on Norway spruce (*Picea abies* (L.) Karst.) logs, the mean error for knot diameter measurement was about 0.6 mm for knots smaller than 10 mm, 3.1 mm for knots between 10 and 20 mm, and –4.1 mm for knots larger than 20 mm; standard deviations of the errors were 3.3, 5.3, and 8.2 mm, respectively. The detection of dead knot border position was not evaluated on spruce logs but showed a mean error of –4.0 mm with a standard deviation of 11.7 mm for Scots pine (*Pinus sylvestris* L.) logs. For both species, the errors in rotational position of the knots were small with mean errors below 0.5 degree and standard deviation of the errors below 2.5 degrees.

While the accuracy of knot detection has been evaluated for most of the other algorithms developed as well, it is still not known to what extent the application of internal knot measurement for sawing control at the individual log level, i.e., log rotation and positioning, is affected by inaccuracy in terms of systematic or random errors of the detected knots.

Grundberg and Grönlund (1999) carried out a sensitivity analysis in the context of validating sawing simulation software and found that errors in both knot diameter and dead knot border position have an effect on simulated product value. This effect was more pronounced for knot diameter errors than for dead knot border position errors. The sensitivity of sawing simulations to knot measurement errors was thus assessed, but an estimation of the impact of these errors on breakdown optimization for single logs could not be deduced from those findings.

In this context, the objective of the present study was to analyze the sensitivity of breakdown optimization, by adjusting log rotation to detected internal knottiness, to errors in the knot geometry description. As a result, an estimation of the required accuracy of knot measurement in CT scans can be provided.

The study has been conducted in conjunction with a research project with the objective of classifying wooden surfaces according to aesthetic perception of the visible features and incorporating this knowledge in sawn timber production procedures based on CT log scanning. The sample products used in this project are solid floorboards that have been sawn with custom sawing patterns. In this context, sawing patterns of that type are also tested here.

Materials and Methods

Material

The sample material used in this study was composed of 57 Norway spruce sawlogs that were collected from a stand on the western drop of the Black Forest mountain range in southwestern Germany. Their lengths varied between 3.9 and 4.2 m; 15 logs had top diameters in the range of about 45 to 58 cm, and the top diameters of the remaining 42 logs ranged from approximately 20 to 34 cm. The logs were graded according to European standard EN 1927-1 (Anonymous 2008). Their grade distribution is given together with the grade limits for knots and log outer shape features in Table 1.

CT scanning and feature extraction

All logs were CT scanned using the MiCROTEC CT.LOG scanner installed at the Forest Research Institute of Baden-Württemberg. The scanner was set to a resolution of 5 mm in the longitudinal direction and with a slice image size of 768 by 768 pixels (px), for a circular imaging area of 800 mm in diameter; resolution in the cross-section plane was approximately 1 mm^2/px.

The CT images were processed for knot detection using software for wood feature extraction in images from a high-speed CT log scanner with the algorithms developed by Johansson et al. (2013). For every log, the software saved the outer shape and the sapwood–heartwood border described by 360 radii in reference to the detected pith position on every cross section as well as the geometry of each knot defined by nine parameters (Oja 1999).

Sawing simulations

Sawing simulations were performed with the log breakdown simulation software Saw2003 (Nordmark 2005). This software performs simulation of cant sawing with curve sawing in the second saw and is specifically adapted to grading the simulated boards according to the appearance grading rules in ''Nordic Timber'' (Anonymous 1997). The breakdown simulations are controlled by setting the properties of the simulated sawing machine (e.g., kerf width), the sawing patterns for the different log top diameter classes, the quality definitions (i.e., the implementation of the grading rules), and the prices for center and sideboards of different grades. When the knot geometry description of a log is loaded by the software, it is possible to add systematic or random errors to the knot diameter, the dead knot border position, and the rotational or longitudinal position of each knot. Random errors are taken from a normal distribution with the set error level defining the standard deviation.

The results of the simulations were analyzed in two ways. First, the variation of apparent total value of the simulated sawn timber due to the imposed errors, when applying conventional log positioning, was assessed in order to estimate the magnitude of their impact. Second, the influence of the errors on the outcome of a breakdown optimization by adjustment of log rotation based on the knot information was examined.

Sawing patterns.—Two types of sawing patterns were used in this study. While the first set consisted of standard cant sawing patterns for logs up to a top diameter limit of 449 mm with target board dimensions typical for the production of Nordic sawmills (Lundahl and Grönlund 2010, Berglund et al. 2013), the sawing patterns in the

Table 1.—Excerpt of grade limits for knots and outer shape features from European roundwood grading standard EN 1927-1 and grade distribution of the sample logs.[a]

	Knot size (cm)		Crook (cm/m)		Taper (cm/m)		
Grade	Sound knots	Dead knots	20–34 cm	>35 cm	20–34 cm	>35 cm	No. of logs
A	Not allowed	Not allowed	1	1	No limit	No limit	1
B	4	3	1	1.5	1.5	2	36
C	8	6	1.5	2	2.5	4	19
D	No limit	No limit	3.5	4.5	No limit	No limit	—

[a] Crook and taper limits are differentiated for log size classes based on mid-diameter under bark; all given limits are inclusive.

second set were adjusted to the production of sideboards and center boards of a single dimension, 32 by 130-mm nominal target width, which is an intermediate dimension of solid softwood floorboards. The sawing patterns in this set will be referred to as floorboard sawing patterns. Schematic drawings of the sawing patterns are shown in Figure 1.

The set of standard sawing patterns was applied only to the 42 smaller logs, the top diameters of the 15 large logs being beyond the upper limit for these sawing patterns, whereas the set of floorboard sawing patterns was also used on the full sample, including the larger logs (see Fig. 2). The set of floorboard sawing patterns included patterns with one cant and one or two sideboards for logs with top diameters up to 427 mm as well as patterns with three cants and one or two sideboards for logs with a top diameter of 428 mm and above. Table 2 gives an overview of the floorboard sawing patterns and their corresponding log top diameter classes. In the floorboard sawing patterns, only the sideboards from the first saw were defined as sideboards, whereas all boards from the second saw were defined as center boards since no distinction based on dimension or board orientation could be made here. For the standard sawing patterns, the allowed sideboard widths of the first and second saws were 75, 100, 115, 125, 127, 150, 175, 200, and 225 mm.

Grading.—For all simulations, the original quality definition implemented in Saw2003 was used, and thus grading was performed according to the specifications of ''Nordic Timber,'' restricted to the grade limits for dead and sound knot size and frequency as well as wane depth, width, and length, which are specified in Table 3. Internal features other than knots were not taken into account in the quality definitions because they were not represented in the log descriptions.

Pricing.—Three different price lists were applied with each of the sawing pattern sets, representing a low, high, and intermediate (denoted as normal) price differentiation between board grades (see Table 4). While the price lists for the standard sawing patterns allowed board lengths from 1,800 to 5,400 mm in intervals of 300 mm, the price lists for the floorboard sawing patterns specified board lengths from 2,000 to 4,000 mm in intervals of 500 mm, thus reducing the number of trimming options to be evaluated by the trimming optimizer for the given logs by about 40 percent. This, together with the fixed sideboard dimensions instead of the sideboard width options of the standard sawing patterns, characterized the floorboard sawing patterns as considerably less variable than the standard sawing patterns.

Error settings.—Three types of errors were analyzed in this study: errors added to the knot diameter, to the radial position of the dead knot border, and to the rotational position of a knot (see Fig. 3). For each error type, both systematic and random errors were tested with different error levels specified for each of them (see Table 5). Absolute errors were specified for dead knot border and knot rotational position. Knot diameter error levels were defined as relative values based on the maximum diameter of each knot because inaccuracy in knot diameter measurement was assumed to be dependent on knot size.

For the specification of the error levels, evaluation results from the work by Johansson et al. (2013) were taken as orientation with the range of the error levels tested covering,

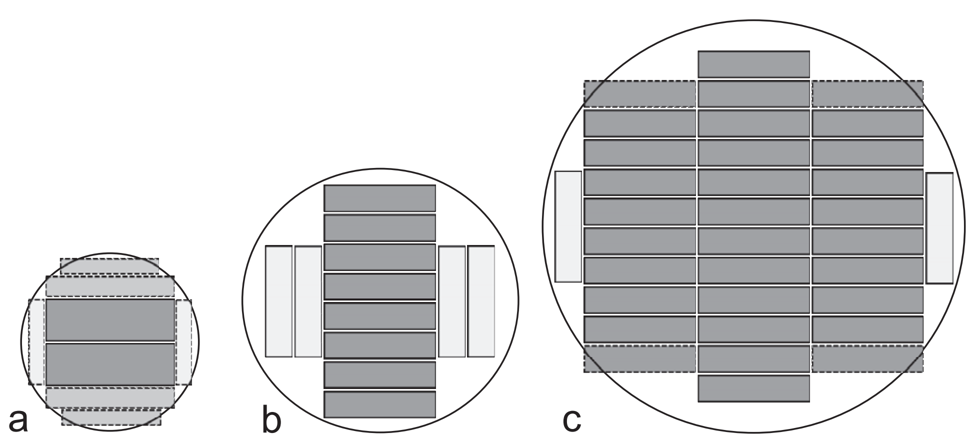

Figure 1.—Schematic drawings of the sawing patterns applied in the simulations. (a) An example of a standard pattern. (b and c) One- and three-cant floorboard patterns, respectively. The circles represent log top diameter, and the different gray values indicate sideboards from first and second saw and center boards, respectively; boards that are not located fully within the top diameter are drawn with dashed outlines.

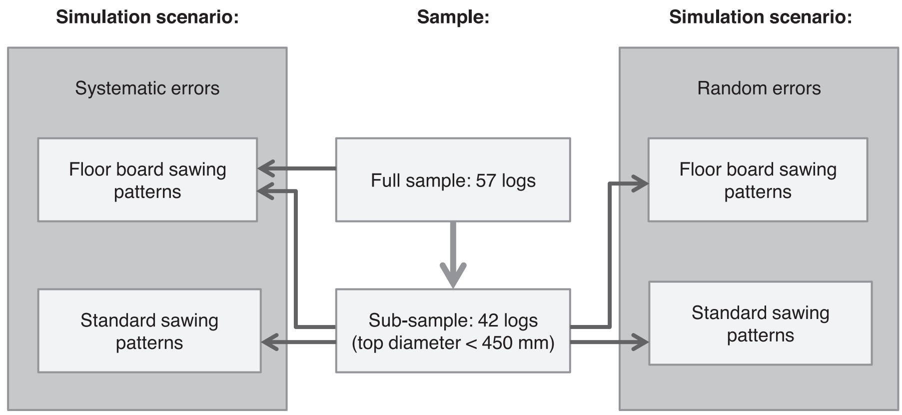

Figure 2.—Allocation of the samples to the simulation scenarios of the study.

and to some extent exceeding, the magnitude of errors reported there.

All errors were tested separately, i.e., there was no combination of different error types or systematic and random errors because the priority of this study was to identify the critical magnitudes of those error types having the largest effect on their own before examining the interactions of different errors.

Simulation procedure.—For every log, several simulation runs were executed. In each run, sawing of the log was simulated in 180 rotation angles. Curve sawing was enabled in the second saw, and lateral offset and skew were set to zero in both the first and second saws; therefore, logs and cants were always centered.

The simulation procedure can be divided into three steps:

1. Simulation runs with the original log models (i.e., without added knot errors)
2. Simulation runs with internal knottiness disregarded (i.e., only outer shape considered)
3. Simulation runs with the different knot error types imposed on the knots

In the first step, simulation runs without introduced knot errors for each combination of sawing pattern type and price list applied were conducted. The value-versus-rotation curves for each log obtained from these simulations were treated as truth and used as the basis for all calculations.

In order to assess the effect of errors on simulated total value recovery and on the value improvement through rotation optimization with respect to internal knottiness, a baseline for comparison was required for each log. Because the current practice in most high-production softwood sawmills is controlling the rotation of a log on the basis of its outer shape, this approach was simulated in the second step of the procedure. Knots were therefore not regarded in trimming and grading during the simulated breakdown of each log, yielding a value-versus-rotation curve governed only by wane.

In the third step, sawing simulation runs were performed for all combinations of price differentiation, sawing pattern type, and specified levels of the tested error types. For each level of the random errors, the simulation run of each log was repeated 10 times. Because the simulations in 10 repetitions for the random error settings led to considerable computation time, the 15 large logs were not used in the random error simulation series with the floorboard sawing patterns (Fig. 2).

The rotation angles yielding the greatest *apparent* value for each log were gathered from the simulation runs of the second step when knots were disregarded and set as

Table 2.—Set of floorboard sawing patterns used in the simulation.[a]

	Log top diameter (mm)		Saw machine center (mm)	
Sawing pattern	Minimum	Maximum	First saw	Second saw (curve sawing)
32 × 130 × 3	140	175	32, 130, 32	3 × 32
32 × 130 × 4	176	211	32, 130, 32	4 × 32
32 × 130 × 5	212	247	32, 130, 32	5 × 32
32 × 130 × 6	248	283	32, 32, 130, 32, 32	6 × 32
32 × 130 × 7	284	319	32, 32, 130, 32, 32	7 × 32
32 × 130 × 8	320	355	32, 32, 130, 32, 32	8 × 32
32 × 130 × 9	356	391	32, 32, 130, 32, 32	9 × 32
32 × 130 × 10	392	427	32, 32, 130, 32, 32	10 × 32
32 × 130 × 11	428	463	32, 130, 130, 130, 32	11 × 32
32 × 130 × 12	464	499	32, 130, 130, 130, 32	12 × 32
32 × 130 × 13	500	535	32, 32, 130, 130, 130, 32, 32	13 × 32
32 × 130 × 14	536	571	32, 32, 130, 130, 130, 32, 32	14 × 32
32 × 130 × 15	572	607	32, 32, 130, 130, 130, 32, 32	15 × 32

[a] Second saw machine center is given for center cant only; for the side cants of a pattern, the respective number of boards is reduced by two.

Table 3.—"Nordic Timber" grade limits for knot size and frequency and wane applied in the simulations.

Feature	Board thickness (mm)	Board width (mm)	Grade A	Grade B	Grade C
Sound knot size (mm)					
Face	16–25	75–115	20	35	50
		125–150	25	40	55
		175–225	30	45	60
	32–38	75–115	25	40	55
		125–150	30	45	60
		175–225	35	50	65
	44–50	75–115	30	45	60
		125–150	35	50	65
		175–225	40	55	70
	63–75	75–115	35	50	65
		125–150	40	55	70
		175–225	45	60	75
Edge	16–19		15	[a]	[a]
	22–25		20	[a]	[a]
	32–38		25	30	[a]
	44–50		30	40	[a]
	63–75		35	50	[a]
Dead knot size reduction factor (% of sound knot size)			70	70	100
No. of knots[b]					
Face			4	5	6
Edge			2	3	4
Wane length (% of board length)					
Board thickness up to 25 mm					
On both edges			20	30	40
On one edge			30	40	50
Board thickness above 25 mm					
On both edges			10	20	30
On one edge			20	30	40
Wane depth (% of board thickness) on each edge			10	15	20
Wane width on face (mm) on both edges			7	12	17

[a] Equal to board thickness.
[b] Total number of knots with maximum allowed size on the worst meter of the board. If individual knot sizes are below the limits for a grade, a higher number of knots is allowed, provided that the sum of their sizes does not exceed the allowed total knot size sum (number of knots multiplied with the maximum size) for the respective grade.

Table 4.—Price lists with different levels of price differentiation between board grades.[a]

Board grade	Relative price (%) Low	Normal	High
Center boards			
Grade A	108	116	123
Grade B	100	100	100
Grade C	81	63	44
Sideboards			
Grade A	138	188	238
Grade B	88	88	88
Grade C	78	69	59

[a] Relative prices with the price for center boards Grade B as reference.

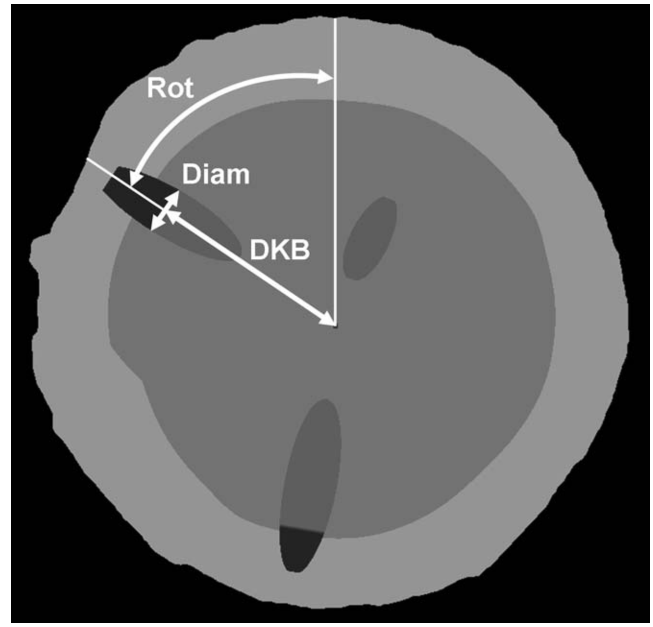

Figure 3.—Screenshot of the slice (log cross section) view in the Saw2003 software. Knot variables that were modified by the errors set are marked: knot diameter (Diam), dead knot border radial position (DKB), and knot rotational position (Rot).

reference. Then the *true* value (i.e., value when accounting for knots, obtained in the first step) resulting from the respective rotation angle was retrieved for each log and used as the previously mentioned baseline. The same procedure of retrieving the apparent value-maximizing rotation position and the corresponding true value of a log was also applied to the results of all simulation runs with different error settings performed in the third step. Exemplary value-versus-rotation curves for one log resulting from the simulation runs of the three steps described are presented in Figure 4, including indications of the true and error-influenced optimum rotation positions and corresponding true value recovery figures.

The optimization approach assumed an idealized case since the rotation angle yielding the global value maximum was always taken as the suggested optimum rotation position regardless of the shape of the value-versus-rotation curve. This means that errors in log rotation due to the sawing machines (that in a realistic case would make it necessary to choose only rotations that were sufficiently distant to minima of the value-versus-rotation curve) were not taken into account.

Table 5.—Error levels tested for the different types of systematic and random errors imposed on the knot description.

Error type	Error levels: Systematic errors	Random errors
Knot diameter (%)	−50, −25, −10, 10, 25, 50	10, 25, 50
Dead knot border position (mm)	−30, −20, −10, 10, 20, 30	10, 20, 40, 60
Rotational position (degrees)	−6, −4, −2, −1, 1, 2, 4, 6	4, 8

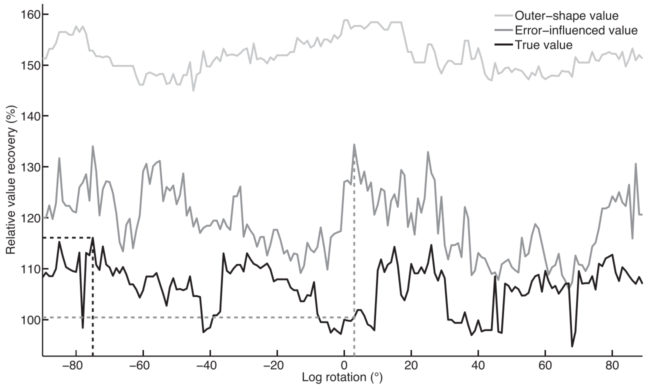

Figure 4.—Value as function of log rotation shown exemplarily for a single log. Note that the true value curve lies at 100 percent at a rotation angle of 0 degrees, that is, at the reference rotation angle (global maximum of the outer-shape–based apparent value curve); the absolute value at this rotation angle was taken as the base value for all value difference calculations. The error-influenced value curve shown results from a systematic error in knot diameter of –25 percent when sawing in a standard pattern and applying a normal price list. The vertical and horizontal lines indicate the apparent value-maximizing rotation angle and the corresponding true value recovery, respectively, for the true and error-influenced value curves.

Results and Discussion

Effect of knot description errors on simulated total value

Simulated total value resulting from virtually processing the whole sample of 57 logs or the subsample of the 42 smaller logs, respectively, was retrieved for each level of the error types tested under the different settings. Each log was sawn in the individual optimum rotation angle determined by its outer shape. The relative differences in apparent total value recovery based on the case of unaltered knot description were calculated.

Effect of systematic errors.—The most pronounced effect on simulated total value recovery could be found for errors in knot diameter. Reducing knot diameter by 50 percent resulted in an increase of apparent total value between 12 and 53 percent, depending on price differentiation and sawing pattern type, while increasing knot diameter to the same extent led to value decreases between 8 and 38 percent. Figure 5A shows simulated relative total value as a function of the tested levels of knot diameter error; these results are explicitly given in Table A1.

Errors in dead knot border position in general showed less effect. For the highest error levels tested, i.e., shifting dead knot border 30 mm inward or outward, changes in total value were between approximately –2 and –9 percent and between 3 and 17 percent, respectively. For this error type, a plot of total value against error level is presented in Figure 5B, with the underlying figures also listed in Table A1.

In contrast to the effect of these two types of knot description errors, the impact of a shift in rotational position of the knots was negligible, altering aggregated value by a maximum of about –0.6 percent. Thus, presenting these values has been omitted.

Comparing the simulation results of the full sample with those of the subsample of smaller logs, both sawn with floorboard patterns, it can be observed that for the subsample, the resulting value recovery generally shows a higher sensitivity to the knot description errors. While in most cases for the standard sawing patterns the value differences were between those observable when sawing either the small logs or the full sample with floorboard patterns, enlargement of knot diameter caused a stronger decrease of apparent value recovery for the standard sawing patterns.

Effect of random errors.—When only random errors are imposed on the knot geometry descriptions, the effect on the resulting apparent value recovery is considerably less distinct, at a maximum of an 18 percent value decrease in the case of the highest level of the knot diameter error in conjunction with high price differentiation and standard sawing patterns (see Fig. 6A or Table A2). It can be observed that in all cases tested with a random knot diameter error, the effect on total value seems to be greater for the standard sawing patterns than for the floorboard sawing patterns applied to the smaller logs.

Random errors in dead knot border position had only very limited impact on apparent total value, with no greater difference than about 2 percent occurring for the highest error level in combination with the standard sawing patterns

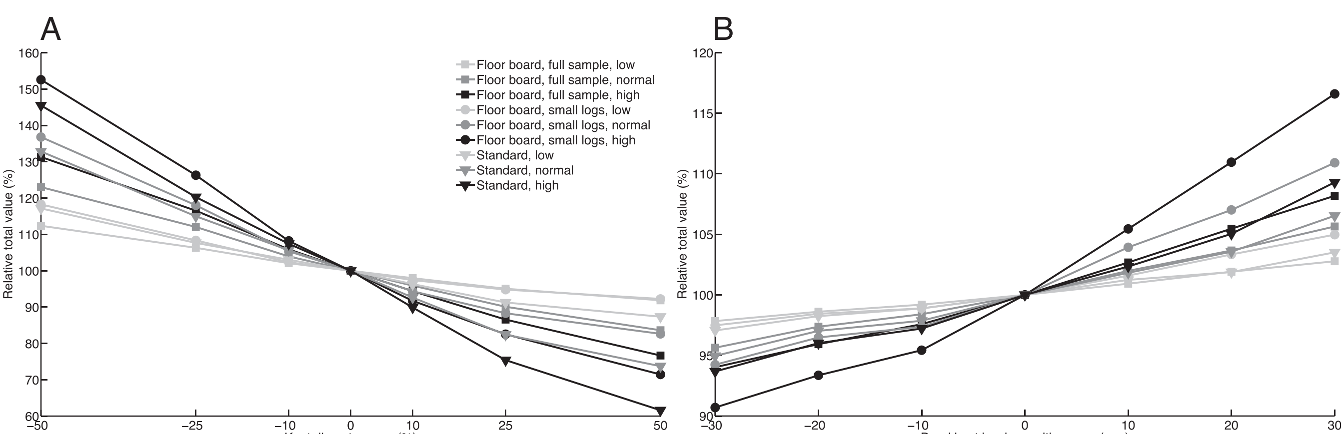

Figure 5.—Simulated relative total value versus the tested levels of (A) a systematic error in knot diameter and (B) a systematic error in dead knot border position. In the legend, the simulation scenarios represented by the graphs are specified with sawing pattern type applied, sample used, and price list applied.

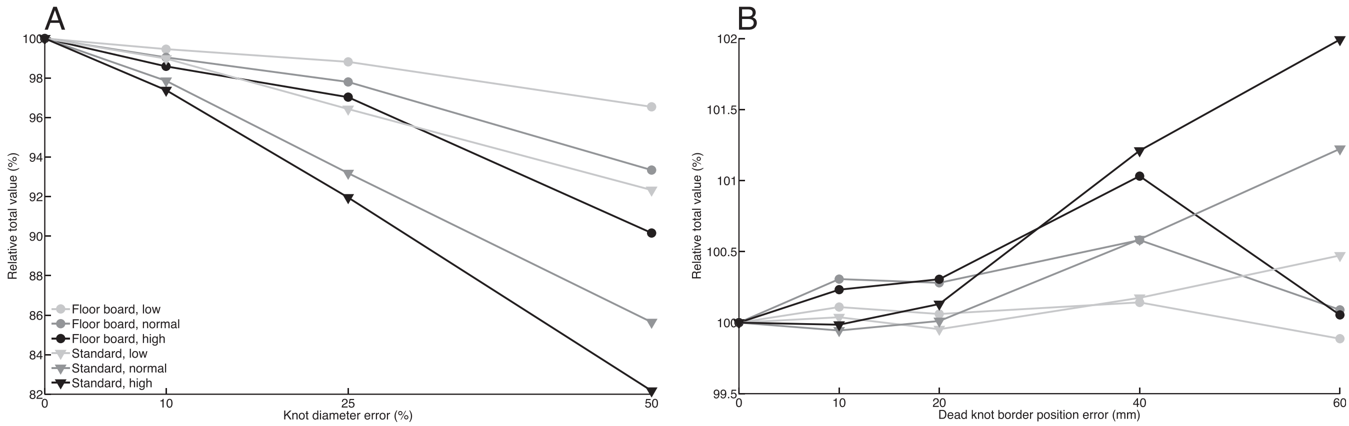

Figure 6.—Simulated relative total value versus the tested levels of (A) a random error in knot diameter and (B) a random error in dead knot border position. Note that only the subsample of small logs has been used in the random error simulations. In B, the interval on the y *axis spans only 2.5 percent. In the legend, the simulation scenarios represented by the graphs are specified with sawing pattern type and price list applied.*

and high price differentiation. While random errors in knot diameter within each scenario of price differences and sawing pattern solely simulated decrease in aggregated value, the effect of random dead knot border position errors was more indistinct, simulating positive changes in aggregated value in the majority of cases but mostly on a very small scale, as can be seen in Figure 6B and Table A2, respectively.

Just like in the case of systematic errors, random errors in knot rotational position least affected simulated total value recovery, causing an apparent reduction in aggregated value of only slightly more than 0.5 percent in the most distinct case, namely, the combination of high price differences and floorboard sawing patterns with the highest level of a random knot rotation error tested.

The tested levels of an error in dead knot border position seem to have an effect comparably as low as that of an error in knot rotational position in the random error case, while in the case of systematic errors, the impact of dead knot border position errors is considerably more pronounced.

Effect of knot description errors on log rotation optimization

For each log, the relative difference in value recovery between sawing in true optimum rotation with respect to internal knottiness (not influenced by a knot error) and sawing in optimum rotation determined by outer shape alone, based on the latter value, was calculated. For each error level, the same calculation was also done using the true value recovery at the apparent optimum rotation angle of each log (Fig. 4). Analogous to retrieving the simulated total value results, this was done for each combination of price list, sawing pattern type, and error type and level tested.

Effect of systematic errors.—In Figure 7A, the mean value recovery differences over all logs are plotted against the tested levels of a systematic error in knot diameter (explicit numbers given in Table A3). As can be seen, depending on price differentiation and sawing pattern type, theoretical increases in average value recovery ranged between 4 and 20 percent when no knot errors were applied.

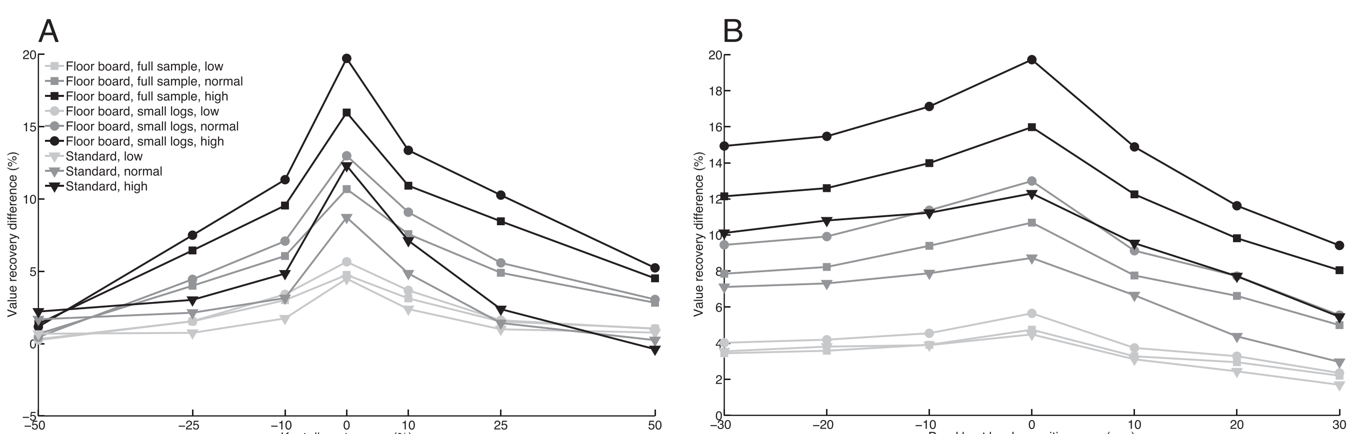

Figure 7.—Mean value recovery difference between optimization taking into account internal knottiness and conventional outer-shape–based optimization, plotted against the tested levels of (A) a systematic error in knot diameter and (B) a systematic dead knot border position error. In the legend, the simulation scenarios represented by the graphs are specified with sawing pattern type applied, sample used, and price list applied.

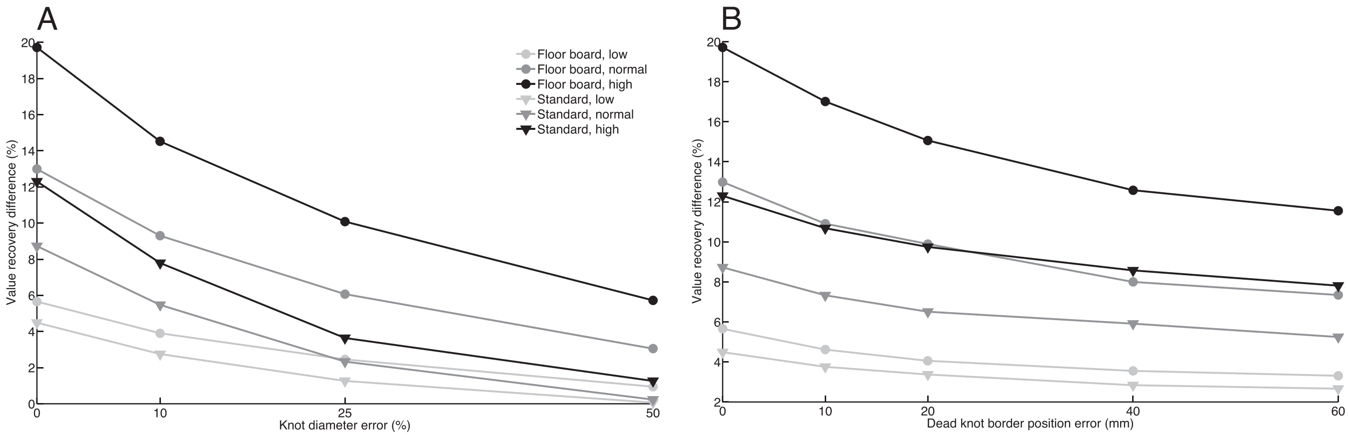

Figure 8.—Mean value recovery difference between optimization taking into account internal knottiness and conventional outer-shape–based optimization, plotted against the tested levels of (A) a random error in knot diameter and (B) a random error in dead knot border position. Note that only the subsample of small logs has been used in the random error simulations. In the legend, the simulation scenarios represented by the graphs are specified with sawing pattern type and price list applied.

When errors in knot diameter were imposed, the potential value recovery improvement was decreased to no more than about 13 percent for the combination of sawing the smaller logs with floorboard sawing patterns and enlarging knot diameter by 10 percent, and in the case of increasing knot diameter by 50 percent, even a slight loss of value recovery compared with outer-shape–based optimization of 0.4 percent could be observed. The greatest loss of value recovery compared with outer-shape–based optimization for an individual log was found to be 27 percent when knot diameter error was 50 percent and a standard sawing pattern was used under the precondition of high price differentiation.

In comparison to the systematic error in knot diameter, the tested levels of a systematic error in dead knot border position had in general less detrimental effect on the value recovery improvement obtained through adjusting log rotation with respect to internal knot structure. Even for the largest positive and negative error levels tested, the mean value recovery difference compared with conventional outer-shape–based optimization was still always positive and not reduced by more than about two-thirds of the relative value recovery improvement in the case of no error. Positive errors, i.e., an outward shift of dead knot border, showed a clearly more severe effect than negative errors on each absolute level as can be observed in Figure 7B and Table A4, respectively. For all tested levels of an error in dead knot border position, the greatest reductions in value recovery improvement for an individual log were just below 15 percent, occurring with the combination of standard sawing patterns and normal price differences as well as with floorboard sawing patterns in conjunction with high price differences, in both cases for the largest positive error.

As indicated by the results of simulated total value, the least effect could be observed for errors in rotational position of the knots. Even in the case of the largest effect—a shift of knot rotational position of ±6 degrees under the precondition of high price differentiation and applying floorboard sawing patterns to the smaller logs of the sample—the value improvement compared with conventional log rotation was not decreased by more than about 0.9 percent. When testing in combination with standard sawing patterns, the maximum levels of knot rotational position error did not cause a decrease of value improvement of more than about 0.1 and 0.2 percent, respectively. This was due to the fact that for all except three or four logs, identification of the value-maximizing rotation was not influenced by knot rotational position errors at all.

Effect of random errors.—Modifying knot diameter had the most pronounced impact in the case of random errors just as it did in the case of systematic errors. For the tested error levels, decreases in value recovery improvement from slightly below 2 to 14 percent (Table A5) could be observed. The highest value loss when compared with outer-shape optimization for a single log occurred for the combination of an error level of 50 percent, a floorboard sawing pattern, and a price list with high price differentiation and amounted to 43 percent in the random error case, which was higher than the most severe value loss of 27 percent observed in the systematic error case. While the influence of sawing pattern type and price differentiation between board grades was generally comparable to the systematic error case, the results also indicate that the effect of a random error in knot diameter of a given level seems to be more similar to the positive than to the negative corresponding systematic error level. The results for all tested cases are presented in Figure 8A and listed in Table A5.

For the random errors in dead knot border position, the differences between the potential and the materialized value improvement compared with conventional log rotation control varied between around 1 percent and just above 8 percent (Table A6). The greatest value loss for an individual log was 24 percent when the value of the products from a floorboard sawing pattern was determined by the high difference price list and when the level of the random error was 40 or 60 mm, respectively. In contrast to the error in knot diameter, for the dead knot border position error, the effects seemed to resemble those of the negative rather than the positive levels of the systematic error for the observed instances of the two lower error levels tested. Even the highest level tested, defining a standard deviation of 60 mm for the shift in dead knot border position, had a smaller effect than an outward shift of 30 mm, as can be seen in Figure 8B and Table A6.

Summarizing Discussion

The observed effects of systematic errors in the description of knot geometry on simulated total value recovery from the tested log samples were most pronounced for knot diameter with increases ranging from 2 to 53 percent and decreases from –2 to –38 percent. For dead knot border position, they were still considerable, with apparent value recovery increases in the range of 1 to 16 percent and reductions between –1 and –9 percent, whereas for knot azimuth, they were negligible. These simulation results are consistent with the findings of Grundberg and Grönlund (1999), who tested knot diameter and dead knot border position errors in their validation of the sawing simulation software and also observed a clearly larger effect for the former.

Regarding the response of simulated total value recovery to the random errors, it was noticeable that errors of the knot diameter in all cases caused a decrease in apparent total value (–0.5% to –18%), while errors of the dead knot border position led to indistinct—positive as well as negative—value changes at a much lower magnitude (below 2% in absolute values), reflecting the randomness of the error. This apparently deterministic effect of the random knot diameter error can be ascribed to its interaction with the knot rules in ''Nordic Timber,'' which set noncompensable limits for knot size, implicating that a single knot enlarged beyond the limit might decide on the grade of a board even if other knots are decreased in size by the random error so that the total knot area on the board face might stay constant or even decrease.

In general, the differences in effect on simulated total value recovery of the respective error types are reflected in the rotation optimization simulations, where the systematic or random errors in knot diameter had the largest impact as well. These errors led to reductions in realized value recovery potential between 26 and 103 percent based on the theoretical potential for the respective scenario. Systematic or random errors in dead knot border position caused corresponding decreases in realized value recovery potential from 9 to 66 percent. Here it could also be observed that increases in value recovery compared with solely outer-shape–based optimization still resulted even for considerably high error levels, such as a systematic increase or decrease of knot diameter by 25 percent or a random error causing variation of knot diameter with a standard deviation of 50 percent.

The specified price differentiation between lumber grades had a major influence on the outcome of the rotation optimization simulations, with higher price differences leading to a higher potential for value increase through optimization of log rotation with respect to internal knottiness. These observations on the small log sample used in the present study are in accordance with the findings of Berglund et al. (2013), who also noted a higher value improvement potential with higher price differences for the utilized sample of 1,465 logs from the Swedish stem bank (Grönlund et al. 1995).

Comparing the value recovery improvement figures resulting from sawing the smaller logs with standard sawing patterns with those resulting from sawing the smaller logs or the full sample of logs with floorboard sawing patterns, it can be noted that for floorboard sawing patterns, the value improvement potential through knowledge of internal log features is apparently greater. One reason for this could be that in contrast to the volume-yield–optimized standard sawing patterns, the custom floorboard sawing patterns are characterized by a considerably smaller number of dimension options available in the edging and trimming optimization (also entailing a volume yield significantly lower than that of the standard sawing patterns). A greater allowed flexibility in these controllable lumber properties thus can probably mitigate the effects of a suboptimal initial breakdown decision. The gain from knowledge of internal knottiness might therefore be larger in the case of sawn timber production with a lower number of alternative lumber dimensions.

The results of this study represent an idealized case because inaccuracy in adjusting log rotation due to the sawing machinery was not considered. As Berglund et al. (2013) observed, taking into account such an error with a standard deviation of 5 degrees can reduce the achievable value improvements considerably, in the reported case from about 13 percent to about 6 percent. Because the aim of the present study was to identify the basic effects of the individual knot error types and levels, this additional source of variation was not considered. According to Tulokas and Tannous (2010), there seems to be a large variability in the average log rotation error and its standard deviation among saw lines currently operational.

The basic intention of the present study—providing an initial and general overview of the impact of knot detection inaccuracy—was also the reason for not testing the different systematic and random error types in combination. An exhaustive investigation in principle would require a factorial test design entailing considerable effort in computation and thus time with the hardware and software available. Performing such an analysis with respect to the present findings, however, is important for a more realistic assessment of the practical implications of knot detection inaccuracy and should be undertaken as a follow-up to the present study and should incorporate a log rotation error as well.

In this context, it would also be meaningful to additionally test the effect of an inaccurate determination of knot end as observed by Johansson et al. (2013) for the knot detection algorithm evaluated.

A limitation of the present study is that, in the simulated optimization approach, of the three parameters of adjusting log position relative to the saw lines in the first saw, i.e., log rotation, parallel offset, and skew, only the first one was tested. Indeed, the individual optimization of log rotation can be assumed to have the largest single influence on the improvement in value recovery (Lundahl and Grönlund 2010). However, as the additional improvement in volume yield reported for an ''extended optimization'' that includes improved parallel offset adjustment in the first and second saw suggests, exploiting the full value recovery potential of each individual log might in many cases require applying a full log-positioning optimization, and thus the effect of knot detection inaccuracy should also be tested for such a strategy.

The Saw2003 sawing simulation software used in this study was built specifically for grading and optimizing boards according to the ''Nordic Timber'' rules. Therefore, testing the sensitivity of log rotation optimization to knot detection inaccuracy under the precondition of a different sorting standard applied was not readily possible. It can be assumed that in the case of appearance grading standards similar to ''Nordic Timber,'' such as the European standard EN 1611-1 (Anonymous 2002), the observed optimization potential and error effects would be on a comparable level. However, it would be of interest to know whether this also applied in the case of strength-grading standards with more specific sorting rules related to knots, such as those defined in the German standard DIN 4074-1 (Anonymous 2012).

Conclusions

Among the three types of knot description errors tested in this study, both systematic as well as random errors in knot diameter clearly had the most severe impact on value improvement through individual log rotation optimization. Thus, this type of knot detection inaccuracy can be expected to have the greatest implications in an application case of knot detection by CT for log breakdown control.

Systematic or random errors in the determined radial position of the dead knot border can also be expected to have a marked effect, while systematically or randomly inaccurate measurement of knot rotational position within the tested magnitudes does not seem to have any relevant influence.

Except for the most severe levels of systematic or random errors in knot diameter, even a rotation optimization based on an error-affected value-versus-rotation curve can apparently yield a true gain in value recovery.

The value improvement potential through rotation optimization might in principle be greater for sawing patterns with lower freedom in the variability of sawn products dimensions.

Apart from their limited generalizability due to the minor size of the log sample, the observations from this study also have to be treated as indicative only since they represent an idealized case of a perfectly accurate log rotation adjustment. Taking inaccuracy in log rotation due to the saw machinery into account could considerably change the outcome of the simulated optimization procedure.

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Appendix

All simulation results that are presented in graphical form in the results section are explicitly given in the subsequent tables. For the results of simulated rotation optimization, the standard deviations are indicated in addition to the mean.

Table A1.—Relative difference in simulated total value (when sawing each log in optimum rotation angle according to its outer shape) as a function of systematic error type and level.

	Relative difference (%) for both sawing patterns								
	Low price differences			Normal price differences			High price differences		
	Standard	Floorboard		Standard	Floorboard		Standard	Floorboard	
Systematic error type/level	Small logs	Small logs	All logs	Small logs	Small logs	All logs	Small logs	Small logs	All logs
Knot diameter (%)									
−50	17.16	18.26	12.38	32.83	36.80	23.03	45.51	52.58	31.32
−25	7.67	8.36	6.32	15.00	18.03	12.06	20.28	26.31	16.52
−10	3.02	2.35	2.08	5.64	5.36	3.95	7.42	8.21	5.89
10	−3.67	−2.57	−2.04	−7.38	−5.63	−4.10	−10.12	−8.28	−5.61
25	−8.73	−5.19	−4.95	−17.57	−11.69	−9.91	−24.60	−17.48	−13.43
50	−12.64	−7.75	−8.13	−26.26	−17.37	−16.38	−38.39	−28.55	−23.33
Dead knot border position (mm)									
−30	−2.94	−2.52	−2.16	−5.04	−5.77	−4.36	−6.32	−9.30	−5.97
−20	−1.76	−1.56	−1.39	−2.97	−3.52	−2.63	−3.99	−6.64	−4.07
−10	−1.12	−1.11	−0.81	−2.14	−2.63	−1.60	−2.78	−4.57	−2.42
10	1.24	1.59	0.92	1.82	3.93	1.98	2.34	5.44	2.68
20	1.88	3.34	1.91	3.56	7.01	3.67	5.04	10.96	5.46
30	3.51	4.97	2.78	6.53	10.91	5.65	9.30	16.59	8.18

Table A2.—Relative difference in simulated total value (when sawing each log in optimum rotation angle according to its outer shape) as a function of random error type and level.[a]

	Relative difference (%) for both sawing patterns					
	Low price differences		Normal price differences		High price differences	
Random error type/level	Standard	Floorboard	Standard	Floorboard	Standard	Floorboard
Knot diameter (%)						
10	−1.02	−0.54	−2.15	−0.96	−2.62	−1.42
25	−3.57	−1.19	−6.81	−2.20	−8.05	−2.97
50	−7.67	−3.46	−14.36	−6.66	−17.83	−9.84
Dead knot border position (mm)						
10	0.04	0.11	−0.06	0.30	−0.02	0.23
20	−0.05	0.06	−0.01	0.28	0.13	0.30
40	0.17	0.14	0.59	0.58	1.21	1.03
60	0.47	−0.11	1.22	0.09	1.99	0.05

[a] For both sawing pattern types, only the subsample of the 42 smaller logs was tested.

Table A3.—Relative difference between value recovery resulting from sawing in (apparent) optimum rotation angle and value recovery from sawing in rotation angle determined by outer shape for the tested levels of a systematic error in knot diameter.[a]

		Knot diameter error (%):						
Price differences	Sawing patterns	−50	−25	−10	0	10	25	50
Low	Standard	0.68 (3.78)	0.74 (4.32)	1.74 (4.13)	4.49 (3.57)	2.39 (3.82)	0.99 (4.82)	0.76 (4.08)
	Floorboard (small logs)	0.25 (3.82)	1.55 (5.51)	3.40 (4.87)	5.66 (4.77)	3.68 (4.46)	1.62 (4.68)	1.02 (4.93)
	Floorboard (all logs)	0.31 (3.35)	1.54 (4.82)	3.00 (4.33)	4.75 (4.43)	3.13 (4.00)	1.52 (4.08)	1.05 (4.27)
Normal	Standard	1.68 (5.71)	2.14 (8.14)	3.15 (7.46)	8.73 (7.00)	4.85 (8.49)	1.42 (7.31)	0.24 (7.99)
	Floorboard (small logs)	0.46 (6.09)	4.45 (10.78)	7.09 (8.95)	12.99 (9.44)	9.08 (9.00)	5.58 (10.81)	3.05 (10.21)
	Floorboard (all logs)	0.67 (5.39)	4.00 (9.42)	6.06 (8.08)	10.68 (9.08)	7.57 (8.24)	4.90 (9.45)	2.82 (8.89)
High	Standard	2.21 (6.75)	3.02 (11.29)	4.85 (9.59)	12.30 (10.24)	7.12 (11.94)	2.38 (9.92)	−0.39 (11.73)
	Floorboard (small logs)	1.17 (9.11)	7.50 (15.81)	11.33 (14.00)	19.72 (13.84)	13.37 (13.16)	10.27 (14.56)	5.23 (13.83)
	Floorboard (all logs)	1.36 (8.00)	6.44 (13.81)	9.55 (12.54)	15.98 (13.54)	10.92 (12.12)	8.46 (12.97)	4.51 (12.02)

[a] Values are means (standard deviations) reported in percentages.

Table A4.—Relative difference between value recovery resulting from sawing in (apparent) optimum rotation angle and value recovery from sawing in rotation angle determined by outer shape for the tested levels of a systematic error in dead knot border position.[a]

Price differences	Sawing patterns	Dead knot border position error (mm):						
		−30	−20	−10	0	10	20	30
Low	Standard	3.55 (3.39)	3.81 (3.68)	3.89 (3.61)	4.49 (3.57)	3.11 (3.79)	2.44 (3.80)	1.69 (3.56)
	Floorboard (small logs)	4.02 (4.70)	4.20 (4.69)	4.55 (4.91)	5.66 (4.77)	3.74 (4.66)	3.28 (4.37)	2.35 (4.72)
	Floorboard (all logs)	3.44 (4.22)	3.58 (4.23)	3.91 (4.40)	4.75 (4.43)	3.28 (4.14)	2.94 (3.87)	2.20 (4.12)
Normal	Standard	7.12 (6.57)	7.31 (6.68)	7.88 (7.03)	8.73 (7.00)	6.66 (7.57)	4.38 (6.86)	2.96 (6.62)
	Floorboard (small logs)	9.45 (9.80)	9.91 (9.57)	11.37 (9.30)	12.99 (9.44)	9.13 (8.37)	7.73 (8.17)	5.55 (8.72)
	Floorboard (all logs)	7.85 (8.93)	8.23 (8.78)	9.40 (8.75)	10.68 (9.08)	7.75 (7.67)	6.62 (7.40)	5.00 (7.67)
High	Standard	10.11 (9.28)	10.81 (10.50)	11.23 (10.28)	12.30 (10.24)	9.55 (9.26)	7.71 (10.36)	5.46 (10.29)
	Floorboard (small logs)	14.94 (13.07)	15.47 (13.60)	17.12 (13.62)	19.72 (13.84)	14.88 (13.66)	11.62 (12.59)	9.42 (14.91)
	Floorboard (all logs)	12.14 (12.28)	12.60 (12.75)	13.99 (12.92)	15.98 (13.54)	12.25 (12.64)	9.82 (11.33)	8.05 (13.08)

[a] Values are means (standard deviations) reported in percentages.

Table A5.—Relative difference between value recovery resulting from sawing in (apparent) optimum rotation angle and value recovery from sawing in rotation angle determined by outer shape for the tested levels of a random error in knot diameter.[a]

Price differences	Sawing patterns	Knot diameter error (%):			
		0	10	25	50
Low	Standard	4.49 (3.57)	2.75 (3.87)	1.26 (4.31)	0.07 (4.69)
	Floorboard	5.66 (4.77)	3.90 (4.96)	2.45 (4.83)	0.95 (4.55)
Normal	Standard	8.73 (7.00)	5.47 (7.46)	2.33 (7.59)	0.23 (8.11)
	Floorboard	12.99 (9.44)	9.30 (9.79)	6.07 (9.69)	3.05 (9.77)
High	Standard	12.30 (10.24)	7.79 (10.52)	3.64 (10.46)	1.26 (10.46)
	Floorboard	19.72 (13.84)	14.52 (14.50)	10.08 (14.29)	5.72 (14.73)

[a] For both sawing pattern types, only the subsample of the 42 smaller logs was tested. Values are means (standard deviations) reported in percentages.

Table A6.—Relative difference between value recovery resulting from sawing in (apparent) optimum rotation angle and value recovery from sawing in rotation angle determined by outer shape for the tested levels of a random error in dead knot border position.[a]

Price differences	Sawing patterns	Dead knot border position error (mm):				
		0	10	20	40	60
Low	Standard	4.49 (3.57)	3.76 (3.67)	3.37 (3.71)	2.84 (3.96)	2.66 (3.89)
	Floorboard	5.66 (4.77)	4.62 (4.81)	4.06 (4.73)	3.55 (5.07)	3.31 (4.89)
Normal	Standard	8.73 (7.00)	7.33 (7.25)	6.51 (7.25)	5.91 (7.49)	5.25 (7.54)
	Floorboard	12.99 (9.44)	10.91 (9.20)	9.89 (9.12)	8.00 (9.84)	7.35 (9.94)
High	Standard	12.30 (10.24)	10.68 (10.07)	9.75 (9.81)	8.57 (9.97)	7.81 (9.93)
	Floorboard	19.72 (13.84)	17.02 (13.50)	15.07 (14.35)	12.58 (14.38)	11.56 (14.66)

[a] For both sawing pattern types, only the subsample of the 42 smaller logs was tested. Values are means (standard deviations) reported in percentages.