Rotating *Pinus sylvestris* Sawlogs by Projecting Knots from X-ray Computed Tomography Images onto a Plane

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In this paper, a method for utilizing knot information from computed tomography (CT) scanning of Scots pine (*Pinus sylvestris* L.) logs was evaluated. A high speed industrial CT scanner is being developed, which will enable scanning of logs in sawmills at production speed. This development calls for the ability to optimize breakdown parameters in a quick manner because there are many decisions to be made and the timeframe for these production decisions is short. One of the important breakdown parameters is in which rotational position to saw a log. The presented method used CT data to create a two-dimensional projection of knot information from a log, in order to minimize the amount of data to analyze. The center of mass of the knot projection relative to the center of the sawing pattern was chosen as the rotational position of the log. The aim was to put large knots on the flat surfaces of the boards, as knots on edge surfaces have a more negative effect on board quality in the sorting rules used in this study. The method was tested by sawing simulation and was compared with the industrial praxis of sawing logs horns down. The results show an increase in board quality and value, albeit for a selected group of Scots pine logs. The method is very sensitive to positioning errors, but it has some potential if sawlog positioning accuracy is improved.

Keywords: CT scanner; Knot; Log rotation; Sawing simulation; Sawmill

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INTRODUCTION

In the sawmill industry, one longstanding goal is to be able to visualize the inside of logs and to choose how to break them down individually, based on the internal wood structure. This has to some extent been realized by X-ray technology developed for and used in sawmills (Oja *et al.* 1998; Grundberg 1999; Oja 1999). However, the X-ray scanning technology employed today is based on a limited number of scan directions, which means that the available information regarding internal wood features is restricted. One or two scan directions means that the information available is a two-dimensional image of the log, as opposed to three-dimensional information about the wood structure. Little can be said about, for instance, the position of knots, in the rotational direction, based on discrete X-ray scanning. The commercial X-ray solutions available today are mainly based on discrete X-ray scanning, such as those supplied by RemaControl (two scanning directions), Bintec (one to six directions), and Microtec (two or four directions).

Today however, other possibilities to scan saw logs in real time using X-rays are being developed, and a high-speed scanner based on a computed tomography (CT) technique is being developed and used in sawmills (Giudiceandrea *et al.* 2011). The new generation of industrial CT scanners can achieve an image quality that is on par with most medical scanners, at least when it comes to analysis of sawlogs. Various industrial prototypes for CT scanners have been described by Wei *et al.* (2011). This will enable detection of defects, such as knots and their position in logs. When this information is available, it will be possible to optimize the rotational position of a log when sawing to improve the value and quality of the sawn timber. Hodges *et al.* (1990) showed that an investment in CT scanning equipment should be profitable, at least for large sawmills, with a few percent increased value of the sawn goods, depending on various economic circumstances. Their study was conducted in hardwood mills in the southern United States.

A rotational position optimization will in most cases change the industrial praxis of today, which is to saw logs in the horns down position. “Horns down” means that the crook of the log is directed upwards during sawing. The optimal rotational position is subject to some uncertainty though, both in the detection of knots and in the precision with which it is possible to rotate a log in the sawing process. The effect of this lack of precision in the rotational position has been shown by Berglund *et al.* (2012). In their study, the value loss when failing to rotate logs properly was more than 50%. Rotational errors can therefore seriously hamper attempts to optimize the rotational position with respect to the value of the sawn timber.

It has been shown in earlier research (Lundahl and Grönlund 2010) that it is possible to increase recovery in the breakdown process of logs by several percent by choosing a rotational position that is different from horns down. For individual logs, this number is even higher. This study was made on Scots pine (*Pinus sylvestris* L.) and for Swedish sawmills and quality sorting rules. A study by Berglund *et al.* (2012) on a similar material indicates a potential value increase of about 13% when optimizing the rotational position, compared to horns down. Another study, by Todoroki and Rönnqvist (1999), indicated a potential value increase of 16% when practicing live sawing and optimizing sawing parameters. Their study was made on Radiata pine (*Pinus radiata* D. Don). Finally, Rinnhofer *et al.* (2003) show that it is possible to gain value by scanning logs using CT and making decisions on the breakdown according to the CT images. They used a manual method for choosing the breakdown strategy. Among several tools used to aid the decision of the breakdown strategy, a projection of defects onto one plane was employed.

To realize an optimal rotational position, there are other factors to consider than the scanning technology alone. Once the knots and other internal features of a log have been detected, a sawing strategy must be decided based on this information. This can involve the rotational position as well as parallel displacement of the log, skewing, and choice of sawing pattern. Furthermore, possible secondary processing operations on the sawn product could be considered in this decision making. To automatically optimize all of these parameters based on simulation alone is computationally expensive, which is a problem in an online application. Therefore, a method capable of finding an optimal or close to optimal rotational position based on internal log features, in a faster way than testing all rotational positions through simulation, would be beneficial. Such a method could save computational time, which can be used for finding the optimal parallel displacement of the log or choosing an optimal sawing pattern. Van Zyl (2011) reports on a study where several meta-heuristic algorithms of finding high value log positions when sawing has been developed and evaluated, with the aim of using a small amount of iterations to find an almost optimal position. He showed a possible value increase of

6.43% when using the best performing algorithm and after 200 iterations. That can be compared to the real optimum of 8.23 %, for ten Radiata pine logs from South Africa.

The hypothesis of the study at hand however, is that a log rotational position resulting in larger profit than horns down can be found by projecting knots and other defects onto a plane, similar to the method used by Rinnhofer *et al.* (2003). This reduces the amount of information that needs to be processed, which potentially saves computation time. However, such a method might be susceptible to positioning errors, as it is based on a smaller amount of information than in Berglund *et al.* (2012). No industrially viable solution will be developed in this study, which can be seen as a feasibility study. The study will be limited to Scots pine (*Pinus sylvestris* L.) and a production setup similar to that of Swedish sawmills.

The objectives of this study were as follows:

- Present a method of determining log rotational position in breakdown, based on CT scanned logs with detected knots, and the projection of these onto a plane.
- Investigate, using sawing simulation, whether the presented method improves quality and value recovery for sawn timber, compared to sawing all logs horns down.
- Add errors both in the rotational position of the log and in the knot detection from CT scanning and analyze the effect of the two respective errors on the presented method.

MATERIAL AND METHODS

The Swedish Pine Stem Bank

This study was based on 628 Scots pine (*Pinus sylvestris* L.) logs from the Swedish Pine Stem Bank (SPSB). The stem bank trees, from well-documented sites at different locations in Sweden, have been documented thoroughly regarding both tree properties and silvicultural treatments, felled, and bucked into logs. The logs have been scanned with a medical CT scanner (SOMATOM AR.T, Siemens AG, Forchheim, Germany) to record internal properties such as knots, pith location, and the location of the sapwood/heartwood border (Grönlund *et al.* 1995). The SPSB contains logs from the butt, middle, and top of trees. Log top diameters range from 107 to 373 mm. The knots of the SPSB are stored in a parameterized form, described further by Grönlund *et al.* (1995) and Nordmark (2005). The parameterized knot data collected by Grönlund *et al.* (1995) was the data used in this study as well.

For the purpose of analyzing macroscopic features of sawlogs, the difference in quality between a medical CT scanner and an industrial CT scanner is negligible, as shown by Giudiceandrea *et al*. (2011).

Sawing Simulation Software

The SPSB can be used for sawing simulation through the simulation software Saw2003, developed by Nordmark (2005). The CT scanned logs of the SPSB provide input. Saw2003 models a sawmill that uses cant sawing with two sawing machines, with curve sawing in the second saw, edging, and trimming. The latter two are value-optimized according to timber prices and grading criteria. Grading of the sawn boards in

Saw2003 is done according to the Nordic timber grading rules (Anonymous 1997). Boards are graded into three quality classes, A, B, or C, where A is the class with the strictest requirements. Grading in Saw2003 is based on knots and wane only because other board features such as pitch pockets and rot are not represented in the SPSB. With these grading rules, knots on edges of boards are considered more severe than knots on flat surfaces.

The sawing simulation results in virtual boards with information about knots, value, dimensions, *etc*. Saw2003 has been used extensively in earlier research (Chiorescu and Grönlund 1999; Nordmark 2005; Moberg and Nordmark 2006; Lundahl and Grönlund 2010).

Log Rotation Method with Respect to Knots

The choice of rotational position of each log was based on the azimuthal distribution of knots in the log. The parameterized knots of the SPSB log were projected onto a plane perpendicular to the longitudinal direction of the log, as seen in Fig. 1.

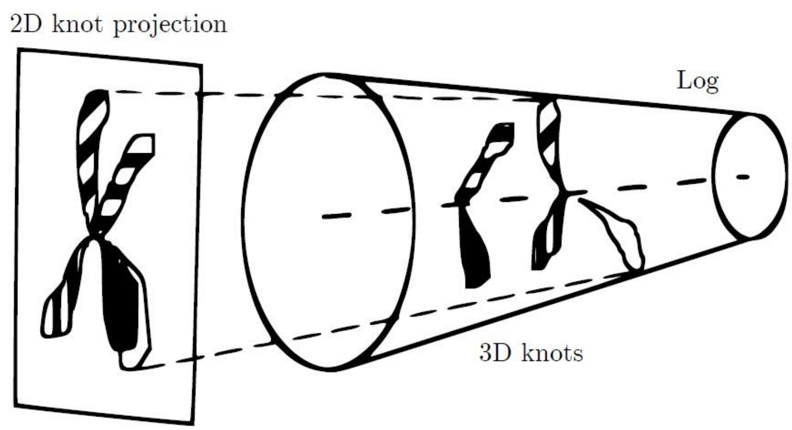

Fig. 1. Projection of knots throughout a log onto a plane perpendicular to the log in the lengthwise direction. Knots are patterned to illustrate the knot that belongs to each projection.

In a 256×256 px image representing this plane, the value of each element was the sum of knot diameters in the projection direction. Thus, large knots had a larger weight in the projection, and several knots were added together. Furthermore, a dead knot was weighted according to the Nordic timber grading rules (Anonymous 1997), by a factor of (1/0.7) = 1.4286. Thus, dead knots affect the projection to a higher degree than green knots. If a projected line from an image position through the log contained only clear wood, the element value was assigned as zero.

The final step of calculating the projection matrix was to filter out small diameter knots and knot sections. The threshold of this filter was automatically calculated individually for each log, as a linear function of the average knot diameter. This function was chosen by manually choosing a suitable knot diameter threshold for 30 of the logs, eliminating all but the six to ten largest knots. The exact number of knots that were kept depended on the size distribution of knots in the log. A linear regression function relating threshold diameter to average diameter was constructed for the 30 logs, $D_T = -8.5 + 103.4 * D_m$, where D_T = threshold knot diameter in mm, and D_m = average knot diameter in pixels. This function was used to automatically filter out knots in all logs in the SPSB.

The projection matrix can be represented as an image, such as that in Fig. 2, showing both the unfiltered and filtered matrix of one example log of the SPSB.

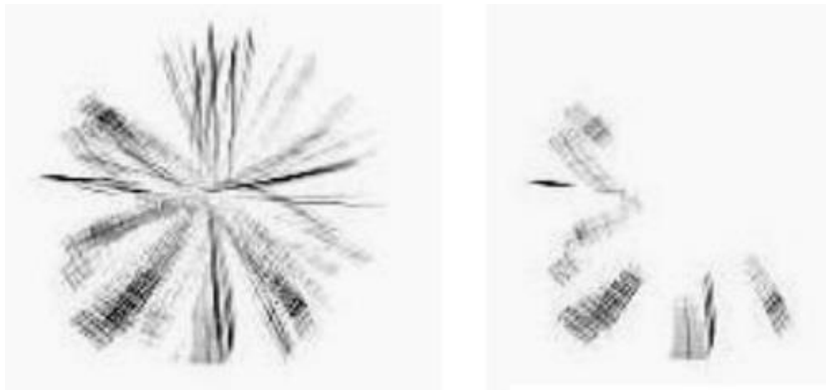

Fig. 2. Image representing projection of all knots through one log. Dark pixels represent high knot density, and light pixels represent low knot density. The left image shows a projection of all knots in a log, and the right image shows the same projection after filtering out small knots and knot sections.

To determine the direction with the largest concentration of knots, the gravitational center of the projection matrix was calculated. The direction from the center of the sawing pattern toward the gravitational center was then chosen as the rotational position of the log, in an attempt to turn the largest weight of knots towards the flat face of one of the center boards, thus avoiding large knots on edge faces.

When the knot projection method was applied on the entire SPSB and the logs were sawn using simulation, the average value change for the sawn products of the logs was close to zero compared to sawing all logs horns down. Around half of the logs had an increased value, and half of the logs had a decreased value. For this reason, logs with a bow height of less than 14 mm and a difference between sawing pattern diagonal and top diameter of more than 18 mm were selected from the SPSB. The sawing pattern diagonal is the diagonal distance between corners in the outermost center boards in the sawing pattern, as illustrated in Fig. 3.

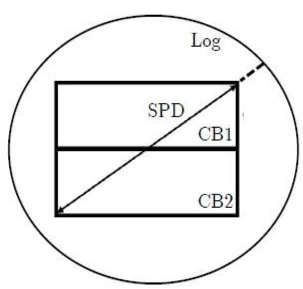

Fig. 3. The sawing pattern diagonal (SPD), which is the diagonal distance between two corners of the outermost center boards in a sawing pattern. In this case, there are only two center boards, CB1 and CB2, making these the outermost. The distance between the sawing pattern diagonal and log top diameter is used as a selection parameter in this study and is indicated by a short dashed line.

The bow height of the log is defined by the maximum distance between a line drawn through the centers of the log ends and the log mid-line, as is shown in Fig. 4. The reason for this selection was to avoid wane when rotating the logs from a different position than horns down. The limits were chosen based on an exploratory approach where the combination of these limits, giving the highest value when rotating the log off the horns down position, was chosen. The limit on crook is consistent with the findings of Lundahl and Grönlund (2010).

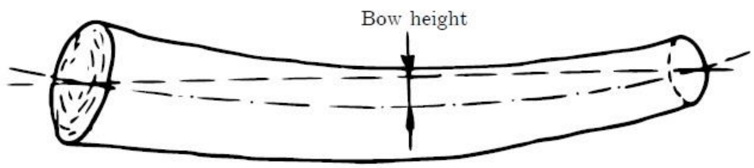

Fig. 4. The definition of log bow height used in this study.

In the study, 10 of the 105 logs were not used because it was not possible to find a rotational position with the proposed method. This was because the sawing pattern center and knot gravitational position coincided. This brought the total amount of tested logs down to 95, which is about 1/6 of the total log population in the SPSB.

Testing the Log Rotation Method through Simulations

Saw2003 was used to evaluate the method of rotating logs according to the internal knot distribution. The sawing pattern for each log was chosen according to the top diameter, in a manner typical of Swedish sawmills. The corresponding sawing patterns for different top diameters are presented in Table 1.

Table 1. Sawing Patterns Used in this Study

Lower limit (mm)	Upper limit (mm)	No. of centerboards	Width (mm)	Thickness (mm)
0	129	2	75	38
130	149	2	100	38
150	169	2	100	50
170	184	2	125	50
185	194	2	125	63
195	209	2	150	50
210	219	2	150	63
220	229	2	175	50
230	249	2	175	63
250	264	2	200	63
265	284	2	200	75
285	304	2	225	75
305	324	4	200	50
325	344	4	225	50
345	384	4	200	63
385	-	4	200	75

Lower limit = smallest top diameter allowed for logs within this sawing pattern. Upper limit = largest top diameter allowed for sawing pattern. Width = width of centerboards. Thickness = thickness of centerboards. Sideboards are edged to various sizes depending on value.

Because the sawing simulator employs value-optimized edging and trimming operations, the price of different board qualities affects the simulation result. Therefore the prices used in this study are given in Table 2.

Table 2. Pricing of the Qualities of Sawn Timber Used in Simulations, in Swedish Crowns (SEK)

Quality	A	B	C
Centerboards	1850	1600	1000
Sideboards	3000	1400	1100

The sawing simulation was performed by sawing the 95 chosen logs of the SPSB horns down. Trimming operations were performed as usual, so the board length was decided after sawing based on a value optimization. Then, the method of rotating logs toward the knot projection center of gravity was applied to the same logs, and the outcome in terms of value and quality of boards was compared between the two methods. The knot projection method was also compared to a run of 30 simulations, where the log rotational position was randomized between 0 and 360 degrees, on the 95 test logs. The distribution of the average value difference when sawing logs in a random rotational position was then compared to the value obtained when sawing according to the knot projection. A similar comparison was also made where a rotational error was introduced to both methods, an error which was normally distributed with a mean of 0° and a standard deviation of 6°. This error is at a level representative of the industrial situation. In this case, no simulations using random rotational positions were made.

Finally, an error in the representation of the knots in the sawing simulation was introduced. This was made to investigate the fact that automatic knot detection using CT scanning will not always be completely accurate. This test was made using three different levels of normally distributed, non-systematical errors to the detection of knot size, knot azimuthal direction, and fresh knot length. The last refers to the distance between the pith of the tree and the dead knot border. The sizes of the standard deviations of these errors are presented in Table 3. The error levels were chosen based on earlier experience; the levels are within the same range as reported for an automatic knot detection algorithm by Grundberg (1999). When comparing these errors, the method of common random numbers (Law 2007) was used.

Table 3. Size of Knot Detection Error*

Knot feature	Low error	Medium error	High error	Unit
Diameter	15	30	45	%
Rotational position	1	3	5	°
Fresh knot length	5	10	15	mm
*Standard deviation of the normal distribution function the errors were randomly selected from for each knot				

Simulations and comparisons of board value and quality were carried out for the three error levels, using horns down sawing as well as rotating the logs according to the knot projection. In this case, the SPSB knots were considered to be the ground truth and were used as reference.

RESULTS

For the 95 logs tested in this study, the average value change from sawing horns down compared to sawing based on the knots in the log, was +2.2%. For 60% of the logs, the value recovery was higher compared with sawing horns down. The quality distributions of the two compared methods, horns down and rotating according to knot orientation, are presented in Fig. 5.

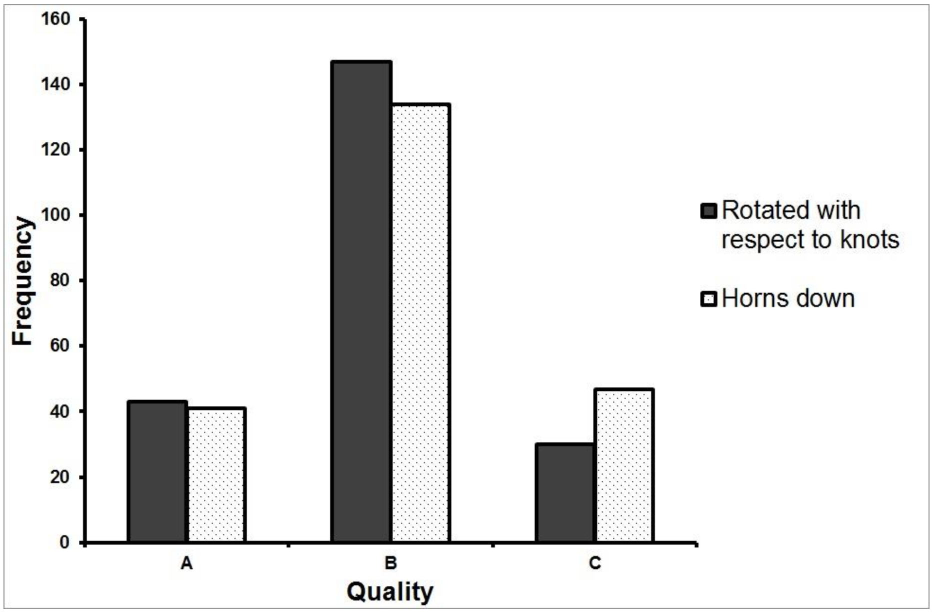

Fig. 5. Distribution of board quality when sawing logs using knot projection (filled), and sawing logs horns down (dotted).

The value potential distribution for the 30 runs when sawing in a random rotational position had a 95% confidence interval, for the mean, with a lower endpoint of 1.43% and an upper endpoint of 1.97%. Because it was 30 independent, random test runs, the central limit theorem states that the distribution will be approximately normally distributed. This confidence interval can be compared to sawing the logs according to the knot projection, which resulted in a mean of 2.2%, which is thus above the confidence interval of the random rotation value distribution. This value is located in between the 2nd and 3rd quartile of the random distribution.

When a rotational error was added to the sawing simulation of the 95 logs, the average value change was +1.3% when sawing based on the knots, compared to horns down. 55% of the logs showed an increased value recovery compared with sawing them horns down. The quality distributions for the two methods are shown in Fig. 6.

The results of using the proposed method, when the knots in the log are not properly detected, are presented in Table 4. The value recovery difference is expressed as the difference between sawing the logs horns down and sawing them according to the knot projection, divided by the value when sawing horns down. The share of logs with increased value is the amount of logs with an increase in value compared to sawing horns down, divided by the total number of logs, which in this case was 95. For all error levels, the quality distribution of the sawn timber tended toward more A and B quality, and less C quality.

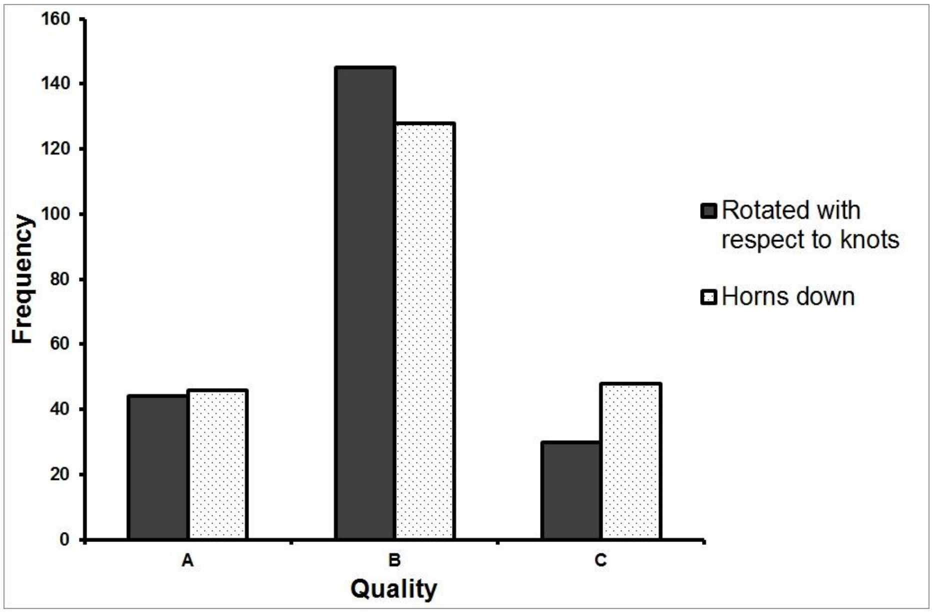

Fig. 6. When adding a rotational error: Distribution of board quality when sawing logs using knot projection (filled), and sawing logs horns down (dotted).

Table 4. Results of Method With Knot Detection Errors

Error level	Low	Medium	High
Value recovery change compared to horns down (%)	+1.9	+1.6	+1.6
Share of logs with increased val. rec. (%)	59	51	58

DISCUSSION

The proposed method improved the sawn board quality when comparing it to sawing horns down for the 95 selected logs. It could also be shown that the value yield increased, compared to sawing the logs in a random rotational position. This increase was not very large compared to the potential shown in previous work, and the reasons for this could be several. The outer shape of the log was not accounted for in this method, apart from the fact that only logs with small bow and large difference between sawing pattern diagonal and top diameter were used. Furthermore, downgrading in the Nordic timber grading rules is to a large degree affected by large knots and knots on the edge side of the board. This means that a small change in rotational position can have a severe effect on the value of the sawn timber, for instance when a large knot changes from being on the flat side of a board to the edge side. This sensitivity is shown by Berglund *et al.* (2012). The rotational position of a log in some cases needs to be chosen with high precision, something which was not the case here. The method is thus sensitive to small errors. When adding a rotational error which corresponds to the normal situation in many sawmills, the value increase was below the confidence interval of the mean when sawing in a random rotational position. When an error in the knot detection was added, this resulted in a value increase potential similar to that of introducing a rotational error in sawing.

The results show that the proposed method is not suitable for industrial use in its present shape. The sensitivity to errors is high, as shown by the simulation results. In the ideal case without errors, the quality of boards was changed to some degree toward higher quality.

The value increase of 2.2% compared to sawing horns down was, however, so small that it cannot be refuted that it was the result of pure chance. The value increase was above the confidence interval of the value distribution when sawing in a random rotational position, but still within the 2nd and 3rd quartile. It is also quite far from the potential shown by previous research (13 to 16 %). It can also be compared to van Zyls (2011) study, that showed a value potential of 6.43 % while also saving computational time.

It should be noted that the simulations in this study were made on logs that were scanned with a medical CT scanner, which uses a different scanning principle and reconstruction algorithm than the industrial high-speed scanner. The produced image stacks are, however, very similar, and the principle of the method proposed here should work on this type of data as well. The similarities are demonstrated by Giudiceandrea *et al.* (2011).

The material in this study was limited to Scots pine logs from Sweden, which means that the results should not be generalized outside this limitation. The SPSB contains logs from a large variety of growth conditions, however, and should be sufficiently varied to account for a large part of the Swedish pine forest inventory. One should also bear in mind that the method was tested on a selection of logs in the SPSB, which corresponds to about 1/6 of the entire population of logs. The reason for doing this was to reduce the effect of the outer shape of the log, as this is not accounted for in the projection method. The implication of this choice is that the results presented here are only representative for a sample of selected logs. In an industrial situation, a very restrictive log sorting would have to be done before using this projection method. A small amount of logs could be sawn by this method, and the rest sawn horns down. However, this seriously limits the practical applicability of this method.

When assessing the inner features of a log in an industrial situation, and adapting the breakdown strategy to these, there are many factors that need to be taken into account. One of the main advantages of the proposed method is that it assesses a projection of the information available in CT data, thus potentially decreasing computational time compared to a full optimization. This is important in an industrial situation, where a breakdown decision needs to be made for each individual log, in a short timeframe. The saved computational time could be used for assessing the translational position of the log, sawing patterns, or other decisions related to the breakdown procedure.

Possible future work includes adding other defect types such as rot or pitch pockets to the data. These could be projected and weighted in the same manner as the knots, and in the case of these defects, it is also desirable to turn the log so they end up on one half of the sawing pattern. The direction in which to rotate the logs could be more distinct in that case, but it is not certain. The effect of the outer shape of the log should also be included. It would also be interesting to test the method on a species with a different knot structure than Scots pine, such as radiata pine, for instance. Finally, the lengths of boards were not taken into account in any way, but that should be investigated.

For instance, knots near the log ends could possibly be disregarded, since they are normally taken away in the trimming plant at a sawmill.

CONCLUSIONS

1. The approach to automatically find a rotational sawing position from CT images using projected information about knot positions throughout a Scots pine (*Pinus sylvestris* L.) log shows some positive tendencies. For logs with an appropriate shape, it improves the quality distribution and the value of the sawn timber, compared to sawing logs horns down.
2. When testing the method using errors in knot detection and log rotation, corresponding to an industrial situation, the method showed a performance no better than chance. The sensitivity to errors is high, which indicates that the method is not feasible for industrial application in its current state.

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