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ORIGINAL ARTICLE

Optimization potential for perception-oriented appearance classification by simulated sawing of computed tomography-scanned logs of Norway spruce

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Abstract

Wood, as a natural material, has favourable properties in both technical and aesthetic aspects. Due to its inherent variability, production of high-quality sawn timber demands adequate control of log conversion, which is feasible with computed tomography (CT) log scanning. Existing appearance grading rules for sawn timber might not fully reflect people's visual perception of wood surfaces, and therefore, an alternative, more perception-oriented appearance classification could be beneficial. An appearance classification of sawn timber based on partial least squares discriminant analysis (PLS-DA) of knot-pattern variables was developed and tested. Knot-pattern variables derived from images of board faces were used in training PLS-DA models against an initial classification of the board faces previously established by aid of cluster analysis. Virtual board faces obtained from simulated breakdown of 57 CT-scanned Norway spruce logs were graded according to the developed classification. Visual assessment of the grading results indicated that the classification was largely consistent with human perception of board appearance. An initial estimation of the potential to optimize log rotation, based on CT data, for the established appearance grades was derived from the simulations. Considerable potential to increase the yield of a desired appearance grade, compared to conventional log positioning, was observed.

Keywords: *Log scanning, knots, sawing simulation, grading, partial least squares discriminant analysis*

Introduction

Wood is a natural material and the quality of sawn timber is determined to a major extent by the inherent properties of the roundwood. Thus, the production of sawn timber that meets usage requirements relies on applying an appropriate quality sorting to the sawn products, and an efficient conversion of the raw material demands best possible knowledge about the properties of the individual log. Besides its technical and environmental advantages, wood is an appreciated material also due to its natural aesthetics.

Existing appearance grading rules for softwood sawn products, such as the European standard EN 1611-1 (Anon. 2002) or *Nordic Timber* (Anon. 1997), usually comprise a rather small number of grades differentiated by the allowed characteristic,

i.e. frequency, size and type, of features on the surfaces, with a higher intensity of features implying a lower grade. While such appearance grading rules provide a feasible quality classification for a broad range of timber uses, they might not fully reflect people's aesthetic perception and preference of wood surfaces. Broman (2000) found not only that the overall blend of features on a wood surface influences people's judgement, but also that features mismatching in the pattern have an even greater effect. Furthermore, the interview studies by Broman revealed that both visual harmony and balance and some degree of visual activity, evoking the impression of naturalness, are important for a positive attitude towards a wood surface. In a study with secondary products of Alaska birch lumber, Donovan and Nicholls (2003) observed that wood surfaces

with features like knots and colour variations were preferred by the majority of the consumers interviewed, which was even reflected in a higher willingness to pay. These findings, together with indications that the judgement of a wood surface also depends on the type of final product exhibiting it (Nicholls and Barber 2010), point out that an alternative grading of sawn timber for visible use which is more oriented towards consumer perception and preference might be useful for producers of sawn timber.

Extensive research has demonstrated the suitability of computed tomography (CT) log scanning for the control of log breakdown in sawmills (e.g. Funt and Bryant 1987, Rinnhofer et al. 2003). Internal wood properties such as the position of the pith, the heartwood-sapwood border and knots can be detected with sufficient accuracy (Longuetaud et al. 2004, Longuetaud et al. 2007, Johansson et al. 2013). Recent development of purpose-built CT scanning equipment for sawmills employing high-speed cone-beam tomography has made this technology usable for industrial application (Giudiceandrea et al. 2011).

Computer simulation of the log-breakdown process has been used in several studies on log conversion in sawmills in the past decades with different types of sawing and tree species considered (e.g. Maness and Donald 1994, Chiorescu and Grönlund 2000, Pinto et al. 2005, Knapic et al. 2011, Stängle et al. 2014). Lundahl and Grönlund (2010) investigated, by aid of sawing simulations, the potential to raise volume yield in a typical Scandinavian sawmill by applying log positioning different from vertically aligning the largest crook in the first saw, the so-called horns-down position. They found that, while horns-down sawing produced good volume yield on average, the individual yield-maximizing rotation of a log most often differed from the horns-down rotation. Furthermore, they observed an increase in average volume yield of 8.6% when applying the optimal combination of rotational and lateral position to each log. Results on sawing optimization where internal wood features detected by CT log scanning, namely knots, were taken into account in the simulations indicate that adjusting the rotational position of the log to the detected knots holds some potential for improved value recovery. Berglund et al. (2013) found that value recovery for sawn products sorted according to the visual grading rules in *Nordic Timber* (Anon. 1997) could be increased by 6–13% compared to horns-down sawing when log rotational position was governed by the detected knots. In a following study, where simulated sawn products were strength graded according to the Nordic standard INSTA 142, Berglund et al. (2014)

reported potential increase in value recovery of 5–11%. In both cases, the amount of value increase found was depending on whether a rotational error of the sawing machine was simulated or not. In a study by Fredriksson (2014), individual log positioning – including not only log rotation but also lateral position and skew – governed by outer-shape and knot information from CT scans was tested against two references, horns-down positioning and optimization according to outer shape (i.e. volume optimization). A potential value recovery improvement of 13% compared to outer-shape optimization and 21% compared to horns-down sawing was observed with the simulated breakdown of 269 softwood logs, where the sawn products were graded according to *Nordic Timber* (Anon. 1997).

Against the background of the mentioned findings, it is assumed that CT-based optimization of log breakdown with grading of the sawn products according to an appearance classification as consistent as possible with human perception of wood surfaces might be a promising strategy for the production of sawn products for visible use. Thus, the objectives with this work were to develop such an appearance classification that can be applied on data available from CT scans and to assess its performance in providing a classification in agreement with human perception, as well as to give an initial estimation of the potential of optimizing log breakdown with one of the established appearance grades as target grade by means of sawing simulations.

Floorboards were chosen as an example of a sawn product for visible use. Thus, sawing of logs into boards with typical dimensions for floorboards was physically performed and simulated in this investigation.

Materials and methods

Roundwood sample, processing and data acquisition

A sample of 57 Norway spruce (*Picea abies* [L.] Karst.) logs were collected from 30 randomly selected trees that had been felled in a commercial harvest of a mature stand on the western slope of the Black Forest mountain region in south-western Germany. The sample comprised butt logs and logs from higher stem sections with top diameters ranging from 20 cm to 58 cm and lengths between 3.9 m and 4.2 m. Roundwood quality according to the European standard EN 1927-1 (Anon. 2008) was grade A for one log, grade B for 40 logs and grade C for 16 logs. The logs were scanned with a computer tomograph (MiCROTEC CT.LOG[®]). Parametrical log models (also referred to as ‘virtual logs’) representing log outer shape,

heartwood–sapwood border, pith and knots were extracted from the CT images by means of the knot-detection software developed by Johansson *et al.* (2013) and saved.

The logs were then sawn into boards with a green dimension of 30 mm × 130 mm. Thereby, sawing patterns were applied that were set up for this study to produce only boards of the specified dimension (see Figures 1 and 4 for exemplary drawings), so that a maximum number of the same product with a large variation in appearance could be obtained. In total, 810 boards were produced. After kiln-drying, profiling and surface treatment with an uncoloured oil finish, the boards which then had a face width of 101 mm and a thickness of 20 mm were scanned with an optical board scanner, and the colour images of both board faces were stored.

All boards were sorted by iteratively grouping them based on distinct visual appearance, aiming to maximize within-group homogeneity (see Breinig *et al.* 2014). The visual impression was mostly governed by the appearance of knots, orientation of the annual rings on the board face and colour variations. Boards with technical defects such as knot holes or large resin pockets precluding the use of at least a two-metre section of the board were sorted out. The sorting procedure resulted in 15 appearance classes and rejects. A sample of 20 colour images corresponding to boards of two metres length for each of the 15 appearance classes, i.e. 300 images of boards in total, were further used.

Figure 1. A cross-section view of a log showing the type of sawing pattern used and the definition of three sectors on the log cross section ('log-sector classes').

Knots and pith streaks were manually measured by aid of a purpose-built software in the images. The measurement data represented knots by their *x*- and *y*-position on the board face and their bounding box, i.e. their size in longitudinal and transversal direction of the board, and pith streaks by their length. Knot condition was defined as sound or dead. Feature data as they are available from CT log scans and sawing simulations were thus measured.

Calculation of feature-pattern variables and variable-based board classification

A set of 30 variables describing the pattern of the measured features on the board faces were calculated from the measurement data (Table I). Only knots with a bounding box area of more than four square millimetres were considered in order to avoid insecure measurements.

Table I. Variables calculated from knot and pith measurements in the board images.

Variable Number	Variable description	Variable unit
1	Number of knots	□
2	Number of sound knots	□
3	Number of black knots	□
4	Simpson index of knot type	□
5	Mean knot size	mm ²
6	Mean sound knot size	mm ²
7	Mean black knot size	mm ²
8	Standard deviation of knot size	mm ²
9	Standard deviation of sound knot size	mm ²
10	Standard deviation of black knot size	mm ²
11	Median of knot size	mm ²
12	Median of sound knot size	mm ²
13	Median of black knot size	mm ²
14	Minimum knot size	mm ²
15	Minimum sound knot size	mm ²
16	Minimum black knot size	mm ²
17	Maximum knot size	mm ²
18	Maximum sound knot size	mm ²
19	Maximum black knot size	mm ²
20	Relative total knot area	mm ² /mm ²
21	Relative total sound knot area	mm ² /mm ²
22	Relative total black knot area	mm ² /mm ²
23	Mean knot elongation	mm/mm
24	Standard deviation of knot elongation	mm/mm
25	Minimum knot elongation	mm/mm
26	Maximum knot elongation	mm/mm
27	Mean Euclidean distance to first nearest neighbour	mm
28	Standard deviation of longitudinal knot position	mm
29	Span of longitudinal knot position	mm
30	Length sum of pith	mm

Figure 2. Compositions of boards according to the classes established by log-sector pre-classification and cluster analysis. The numbers on each board composition indicate class designation (log-sector class and cluster-analysis group). The order of the boards in each composition is random.

The boards were pre-classified into three classes, referred to as ‘log-sector classes’ based on their position in one of three sectors on the log cross section. This was done since the orientation of the annual rings was an important feature for the visual appearance of the boards but was not represented in the feature-pattern variables. The sectors were therefore defined so that they corresponded to the expected orientation of the annual rings on the board faces. They were centred on the log pith and aligned with the sawing patterns applied. Two 135° sectors delimiting boards with vertical annual rings (vertical grain), two 45° sectors defining boards with horizontal annual rings (flat grain) and one circular sector on the log centre were specified as illustrated in Figure 1. Allocating the boards to the log-sector classes was feasible since their exact positions in the logs were recorded during sawing.

Hierarchical cluster analysis of the log-transformed feature-pattern variables was performed separately for each of the log-sector classes, using Ward’s minimum variance method with squared Euclidean distances. A

classification into two groups could be identified for log-sector class 1, a three-group classification was found for log-sector class 2 and log-sector class 3 was classified into two groups. By combining the log-sector classes with the groups derived from cluster analysis, a classification of the sample boards into seven classes was obtained. Figure 2 shows samples of 20 two-metre boards for each of these classes.

Apart from details on the board sorting procedure, a description of data processing, feature measurement and the explorative classification approach described can be found in the study by Breinig *et al.* (2014). An overview of the elements of the analysis is provided in Figure 3. This flow chart also outlines the analysis steps described in the subsequent paragraphs.

Development of class prediction models and final grading system

The classes derived from cluster analysis were used as group variables in partial least squares

Figure 3. Simplified flow chart of the different steps (data and analyses) involved in the study. The shaded box in the upper left corner of the chart indicates the steps performed in the study by Breinig *et al.* (2014).

discriminant analysis (PLS-DA), i.e. partial least squares (PLS) regression with the group variables encoded as dummy Y variables. Choosing PLS-DA as the method of classification was motivated by the fact that the independent variables available (the feature-pattern variables used in cluster analysis) were known to be in part highly correlated. It is assumed that variance-based projection methods like PLS are well adapted to highly collinear data (Eriksson *et al.* 2006). Analysis was done using the software SIMCA 13 (Umetrics AB 2013).

Separate analyses were conducted for each of the three log-sector classes. The same feature-pattern variables were used as in the initial classification of the sample boards, except for the length-sum-of-pith variable. Even though this variable proved to be most important for distinguishing the two groups in log-sector class 3, it had to be omitted since it was not possible to obtain data on pith streaks on the virtual boards simulated in the subsequent step of the investigation, and thus, a predictive model employing this variable was not applicable with the virtual boards. Prior to the analyses, the variables were log-transformed in order to remedy the skewed distributions that had been observed with most of them. The variables were unit-variance scaled and mean-centred. PLS-DA models for each of the log-sector classes were initially autofitted. The numbers of components were then adjusted taking into account the changing of the R^2 and Q^2 measures with added components and by comparing the classification that each model produced with the

initial classification by cluster analysis. The latter was supported by preparing composition images of the board faces according to the predicted groups which allowed for an additional visual assessment.

In PLS-DA, variable coefficients and a constant term are fitted for each of the models and provide the actual classification of the observations, i.e. boards in this case. The coefficients and constants can be re-transformed, so that they can be used together with the original, non-transformed variables for classification of new observations. Classification is performed by calculating, for each observation, so-called Y -predicted values. These are linear combinations of the variables and their respective coefficients in the form:

$$Y_{\text{pred}} = \beta_1 \times x_1 + \beta_2 \times x_2 + \dots + \beta_n \times x_n + \beta_0 \quad (1)$$

where β_i denotes the coefficient of variable x_i and β_0 the constant term. For each board, a Y -predicted value is calculated according to Equation 1 for each group. The individual PLS-DA models for each group have their specific sets of coefficients and constant term. This means that, in a two-group case, each board will get a Y -predicted value according to one group model and a corresponding Y -predicted value according to the other group model. The higher the Y -predicted value, the more certain the group belonging of a board can be assumed. The Y -predicted values for one board always sum up to 1 with the highest Y -predicted value indicating the group belonging of the board.

The possibility to obtain the Y -predicted values from the PLS-DA models allowed for fine-tuning of the classification according to visual appearance by applying thresholds for group belonging to the Y -predicted values. To this end, board composition images for each predicted group containing the boards in order of ascending Y -predicted value were examined together with the Y -predicted values of these boards.

Boards classified as group 1 in the two-group classification of log-sector class 1 that had a Y -predicted value of less than 0.65 showed not only rather small sound knots but also dead knots increasing in number with decreasing Y -predicted values. A Y -predicted value of 0.65 was thus set as threshold for the final classification, i.e. only boards with a Y -predicted value for group 1 of 0.65 or higher were retained in that group, then denoted as grade 1-1, while those with a lower Y -predicted value for group 1 were put together with the boards of group 2, forming grade 1-2.

According to the groups derived from cluster analysis, a three-group PLS-DA model was computed for log-sector class 2. Inspection of the corresponding board compositions indicated that the predicted group 1 contained both knot-free boards and boards with few, mostly small, dead knots, which also was the visual trait of the boards assigned to group 2. As it was known from previous studies that mismatching features on a wood surface are decisive for people's aesthetic perception (Broman 2000), it was decided that separating clear boards from those with minimal knot features should be prioritized, also considering that boards with minimal knot features might blend in well with boards having more or slightly larger dead or sound knots. Therefore, boards with no knots present on the face were put in a separate group. Furthermore, only for boards classified as group 3 with a Y -predicted value close to 1 classification could be considered reliable from the perspective of a characteristic visual appearance (few large sound knots visually dominating, dead knots not distinctive).

Accordingly, a threshold for classification as group 3 was set at a Y -predicted value of 0.9. The final classification of the boards in log-sector class 2 thus consisted of clear boards, denoted as grade 2-0, boards with a minimum Y -predicted value for group 3 of 0.9, now designated grade 2-2, and the remaining boards, now referred to as grade 2-1.

The PLS-DA classification of the boards in log-sector class 3 was adopted without any modifications. Visual inspection of the two groups according to the model showed that the separation of boards with exposed pith streaks and the typical pattern of knots in direct proximity to the pith (splay knots and very tight clusters of pin knots) and boards with larger sound knots was provided even without using the length-sum-of-pith variable. In accordance with the previous group designation from cluster analysis, the two grades in log-sector class 3 were denoted as 3-1 and 3-2.

No clear boards in log-sector class 1 were present in the sample of real board images. For classification of the simulated boards, however, an additional grade of knot-free boards with flat grain was introduced and denoted 1-0, in analogy to the corresponding grade in log-sector class 2. Table II gives an overview of the final grading system.

Sawing simulations

Simulation of breakdown of the logs was performed using the software Saw2003 (Nordmark 2005). This program simulates cant sawing with grading of the sawn products according to the *Nordic Timber* (Anon. 1997) grading rules on the basis of virtual logs, i.e. parametrical log descriptions extracted from CT images. Simulated sawing is controlled by settings files specifying sawing patterns, sawing machine properties, and quality definitions and prices for different board grades. When run from a Visual Basic script, the program allows writing of the knot data of all boards resulting from a simulated sawing to a text file.

Table II. Details of the PLS-DA-based grading system summarized for the defined grades.

Grade	Log-sector class	Group predicted by PLS-DA model	Threshold applied to group prediction	Fixed criterion for grade assignment	Knot size limit for rejection (mm ²)
1-0	1	2	–	knot-free	250
1-1	1	1	0.65	–	250
1-2	1	1 or 2	–	–	250
2-0	2	1	–	knot-free	250
2-1	2	1, 2 or 3	–	–	250
2-2	2	3	0.9	–	250
3-1	3	1	–	–	250
3-2	3	2	–	–	250

Sawing was simulated in 18 rotational positions for each of the 57 logs in the investigation. The known volume-maximizing rotational position of each log was used as reference, and sawing simulations of each log were successively performed with rotation increments of 10° until the log was sawn in rotational positions from 0° to 170° from the reference. Log rotational position was the only sawing parameter varied. Parallel offset and skew of the log were set to zero in both the first and second saws, i.e. logs and cants were always centred and longitudinally aligned with the direction of feeding. Curve sawing was activated in the second saw.

In the quality definitions, no limits on knot size or frequency were set, but wane was not allowed on the boards. The allowed board lengths were 2–4 m in intervals of 0.5 m. Thus, boards were not trimmed shorter than 4 m due to knots; only boards with wane (or those from logs with a length less than 4 m) were trimmed to the next possible length. The set target board dimension was 32 mm $\times$ 130 mm, and the same type of sawing patterns, shown in Figure 4, as with the real sawing was applied.

Data of the knots on either face were exported for each board simulated. Consistent with the feature measurements on the board images, these data comprised x - and y -positions of the knots, their bounding boxes and knot condition indicated as sound or dead.

The knot data of all simulated boards were imported to MATLAB, version 7.5.0 (MathWorks 2007). Classification of the boards according to log-sector class was done by assigning all boards from the outer cants (in the case of the larger logs sawn

with three cants) to log-sector class 2 and by differentiating between log-sector classes 1 and 3 based on the position of the board in the centre cant (see Figure 4). Those three boards that were located in the middle of the stack of boards in the centre cant were allocated to log-sector class 3, all other boards from the centre cant to log-sector class 1. Sideboards (boards from the first saw) were always allocated to log-sector class 1 as well. For every simulated board, the knot data on two-metre sections of the inner face (towards the pith) were taken for further analysis. The first section always extended over 2 m from the butt end of the board, and, if a board had a length of 4 m, the adjacent two-metre section was taken as well. In total, 17,448 board sections were obtained from the simulations. For each of these virtual boards, the knot variables were calculated from the extracted knot data, and a graphical representation of the knot pattern on the board was produced to allow for visually assessing the classification of the virtual boards.

Based on the calculated knot variables, the virtual boards were then graded according to the developed grading system. In contrast to the 300 real board images used in developing the grading system, the simulated boards did not stem from a sample that had undergone visual sorting and could thus also comprise individuals that should be rejected, e.g. due to knot holes. A size limit of 250 mm² was therefore introduced for dead knots, corresponding to a diameter of approximately 16 mm. Any board with larger dead knots was classified as reject since large dead knots generally have a high risk of loosening and are an unwanted visual feature.

Figure 4. Examples of the sawing patterns used both with physical sawing of the logs and in the sawing simulations. The left drawing shows a sawing pattern with a single cant for logs with top diameters of 320–355 mm, while the sawing pattern in the right drawing comprises three cants and was applied to logs with top diameters between 500 mm and 535 mm. The stacks of horizontally oriented boards constitute the cants cut in the first saw. Grey value indicates log-sector class. Boards of log-sector class 1 are light grey, boards of log-sector class 2 are medium grey and boards of log-sector class 3 are dark grey.

Figure 5. Flow chart illustrating the procedures of the two different optimization strategies tested.

The grade of each virtual board was saved. This formed the basis for estimating the potential in optimizing the yield of boards with a certain visual appearance by adjustment of log rotational position.

Estimation of optimization potential

For the tested optimization scenarios, the results of two basic strategies were retrieved. The first strategy, deemed ‘overall-optimization strategy’, consisted of first finding, for each log, the rotational position yielding the highest total amount of accepted boards. If more than one yield-maximizing rotational position was found for a log, the position that also produced the highest absolute count of boards for the desired grade was taken. This procedure was reversed with the second strategy, referred to as ‘grade-optimization strategy’, i.e. first, the rotational position with the highest board-section count for the target grade was searched, and then, in case of ambiguity, the position also yielding the highest total count of accepted boards was chosen. The procedures of both strategies are illustrated in Figure 5.

Results

Visual impression of real boards composed according to the developed grading system

During the development of the PLS-DA-based grading system, composition images of the boards were produced to assess whether the classification

was satisfactory, i.e. in line with the visual impression of the board faces. Composition images of the boards according to the final grading system are shown in Figure 6. This classification was judged as acceptable, with the groups of boards being sufficiently homogenous within and at the same time distinct from each other. Thus, the final grading system was adopted for the simulated boards.

Visual impression of simulated boards composed according to the developed grading system

Also for the simulated boards, composition images were produced to judge whether the developed grading system provided a satisfactory appearance classification for these as well. Graphical illustrations of simulated boards for each of the defined appearance grades, generated from knot data of the first two-metre section (seen from the butt end) of each simulated board, are shown in Figures 7 and 8. The virtual boards in Figure 7 originated from sawing simulations with each log sawn in its reference rotational position. The virtual boards shown in Figure 8 for comparison were obtained from simulated sawing of the logs rotated 60° from their reference positions.

As observed with the images of real boards shown in Figure 6, visual assessment of these samples indicated that the grading system produced distinct groups with sufficient within-group homogeneity. When comparing samples of the same grade for

Figure 6. Board compositions according to the PLS-DA-based grading system. The numbers on each board composition indicate grade designation. As in Figure 2, 20 boards are shown in each composition with the exception of grades 2-0 and 2-2 that comprised only 19 and 10 boards, respectively. The order of the boards in each composition is random.

different log rotation variants, such as in Figures 7 and 8, a high similarity could be noted as well, with certain characteristics of the knot pattern being present in all samples of a grade. These were e.g. large oval sound knots in the case of grade 2-2 or small to medium-sized, rather evenly distributed dead knots with grade 1-2. It was thus concluded that classification of the simulated boards by means of the developed appearance grading approach was adequate, so that an estimation of optimization potential based on such a classification could be considered meaningful.

Estimation of optimization potential with different target grades

To estimate the potential in maximizing the yield of a particular grade, the relative change in the number of boards obtained for that grade when applying either of the two optimization strategies was

considered. The shares of total board count for each grade resulting from conventional outer-shape optimized sawing, i.e. sawing each log in its reference (volume-maximizing) rotational position, are presented in Figure 9. In total, the 57 logs yielded 1007 boards of two-metre length. The noticeable high share of rejects, amounting to almost half of the boards, was a result of the rather strict size limit for black knots and also indicated that the quality of the sample logs was not above average. Furthermore, it might to some extent be ascribed to the simplified trimming approach with a fixed cutting location after the first two metres of the board. Boards of log-sector class 1 had the largest share among the accepted boards with about 21%, while boards of log-sector classes 2 and 3 accounted for 19% and 11%, respectively.

Clear boards with vertical annual rings (corresponding to grade 2-0) are usually considered the best quality, from both a technical and an

Figure 7. Graphical illustrations of virtual boards resulting from simulated sawing of the logs in individual reference rotation (0°), composed according to the grading system. The designation of grade on each composition is consistent with Figure 6, and each composition comprises 20 virtual boards in randomized order. Sound and dead knots are pictured by light and dark brown ellipses, respectively. The apparently oversized knots in the sample of grade 3-1 are caused by the simplified drawing method and actually represent tilted splay knots.

appearance perspective. Optimization with this quality as target grade therefore was the first case tested. Sawing the logs in their reference rotations, 43 boards of grade 2-0, or 4.3% of the total yield, were obtained (see Figure 9). When optimizing for this grade but prioritizing the yield of accepted boards, i.e. applying the overall-optimization strategy, the yield of grade 2-0 could be increased by 20.9% (from 43 to 52 boards in absolute numbers), with the share of rejects decreased by 23.7% (from 493 to 376 boards). Figure 10a shows the relative changes in yield for all grades with this optimization case. When the yield of grade 2-0 was prioritized over the total yield (grade-optimization strategy), it could be raised by 81.4% to a count of 78 boards.

However, in this case, the number of rejected boards was only reduced by 20.1%, and the total count of boards was lower than in the case of the overall-optimization strategy (978 compared to 991), as can be seen in Figure 10b. In any case when the overall-optimization strategy was applied, a total of 615 accepted boards could be obtained with the given log sample.

Regarding the boards in log-sector class 1, board grade 1-1 was considered the most interesting target grade for optimization since this grade most likely had the preferred visual appearance of the flat-grain boards. Applying the overall-optimization strategy, the number of boards of this grade could be raised by 37% compared to conventional sawing which

Figure 8. Graphical illustrations of virtual boards resulting from simulated sawing of the logs in a rotation of 60° from individual reference, composed according to the grading system. Each composition comprises 20 virtual boards in random order. Compositions of virtual boards for grades 1-0 and 2-0 have been omitted since the clear surfaces would have the same appearance as in Figure 7.

corresponded to an increase from 73 to 100 boards. The number of rejects was reduced by 24.1%. The relative changes in yield for all grades resulting from the overall-optimization strategy with grade 1-1 as target grade are presented in Figure 10c, while those resulting from the grade-optimization strategy are shown in Figure 10d. As can be seen, the yield of grade 1-1 could be increased by 78.1% in this case, but at the same time the number of rejected boards was only lowered by 16%, while the total board count was reduced to 978.

Since the boards classified as grade 3-2 were similar in knot pattern to the boards of grade 1-1, they were also considered for an estimation of

optimization potential. For both optimization strategies, high increases of yield were observed. In the case of the overall-optimization strategy, a yield of 118 boards corresponded to an increase of 84.4% compared to conventional sawing which yielded 64 boards (Figure 10e). In the case of the grade-optimization strategy, 145 boards were produced, representing an increase of 126.6% (Figure 10f). The counts of rejected boards were reduced by 23.5% and 18.1% and total board counts were 992 and 974, respectively.

The shares of the total board count and the absolute numbers of boards for all of the grades when using each grade as target grade are summarized in Table III for the overall-optimization strategy and in Table IV for the grade-optimization strategy, respectively. It can be noted that for both optimization strategies the shares of rejected boards were decreased considerably in comparison to conventional sawing. For the overall-optimization strategy, the shares of rejects were closely around 38% for any case of target grade, while for the grade-optimization strategy, they were between 39% and 43.6%.

Considering Tables III and IV, it can also be noted that grades 1-2 and 2-1, i.e. the boards mainly characterized by small dead knots, had rather high yields in all three optimization cases presented. Although they were not the target grades in any of the cases, the shares of both of them always exceeded 10% when the overall-optimization strategy was applied. Boards of grade 1-0, 2-2 and 3-1, on the other hand, never reached shares of more than 6% in the presented cases, neither with the overall-optimization strategy nor with the grade-optimization strategy.

Discussion

The objective with the described approach of a grading system was to develop a classification for sawn timber that is consistent with the visual perception of wood surfaces by human observers and therefore allows to supply product grades that meet diverse aesthetic preferences of consumers.

Appearance classes established through pre-grouping and cluster analysis were chosen as basis for the PLS-DA models used in the grading system. Using a classification derived from the available knot-pattern data itself as starting point was considered important. It was assumed that this would result in a higher accuracy and reproducibility of the grading system than an attempt to use a board classification derived directly from studies on consumer perception.

Board classification provided by the PLS-DA-based grading system was judged as satisfactory in that homogeneity of the boards within a grade and

Figure 9. Share of the total board count for each grade when the logs are sawn in their individual reference rotations, i.e. the volume-maximizing rotational positions. This is referred to as 'conventional sawing'. Total board count is the total number of two-metre board sections obtained from the 57 logs.

clear distinctness between the grades was recognizable. The validity of this judgement, however, is somewhat limited as it was only based on subjective visual assessment by a limited number of people. No means of quantitative evaluation, such as e.g. a classification table, were applicable since no reference classification – i.e. a classification according to perceived appearance or preference by potential customers – was available.

In general, the results of the simulations indicated that there could be considerable potential to raise both the total yield of accepted boards when applying the overall-optimization strategy and the yield of individual grades when applying the grade-optimization strategy, compared to the current practice of volume optimization. This estimation, however, was only based on a comparison of yield expressed in board counts. The optimization potential in terms of value could not be investigated within the scope of this study as there was no information about consumers' willingness to pay for the different appearance grades that could be distinguished with the developed grading system. Possible price differences between the different grades (target grade vs. other grades vs. off-grade) also pertain to the question which of the two optimization strategies to choose. If one of the defined appearance grades was priced considerably higher than the other ones and the price reduction for off-grade boards was marginal, the grade-optimization strategy might be preferred, whereas the overall-optimization strategy might be favourable in the opposite case, i.e. a high price reduction for off-grade boards and small price differences between the appearance grades.

As mentioned, the high share of rejected boards was probably caused to some extent by the simplified trimming approach used in the simulations, where always the first and – if available – the adjacent two-metre section were taken from a board. With a more flexible trimming with variable board-section lengths and positions, the share of rejected boards would have been reduced. This trimming method would also allow for calculating the optimization potential based on board length or volume yield instead of board counts only which would also make any estimation of potential value increase more meaningful. However, implementation of a more refined trimming method would have caused considerable effort. The aim of the present work was to test the developed grading system on simulated boards and provide an initial estimation of the potential in optimizing for a particular appearance grade rather than conducting a comprehensive quantitative study on optimization potential. Therefore, a simplified trimming simulation was chosen, even being aware of the limitation it entailed.

The same reasons also motivated the other limitation with the log-breakdown simulations performed, namely rotation of the logs in 10° intervals instead of rotation increments of 1°. It can be assumed that adjusting log rotational position with 1° increments would allow for higher increases in the share of target-grade boards. When investigating the potential to increase value and volume yield by adjusting log rotational positioning to detected knots, Berglund *et al.* (2013) found that this potential decreased with increased rotation intervals.

As discussed by Fredriksson (2014), there are two general aspects to be observed when attempting to

Figure 10. Relative differences of the board counts for each of the grades, compared to conventional sawing, when applying the overall-optimization strategy with grade 2-0 as target grade (a), the grade-optimization strategy with grade 2-0 as target grade (b), the overall-optimization strategy with grade 1-1 as target grade (c), the grade-optimization strategy with grade 1-1 as target grade (d), the overall-optimization strategy with grade 3-2 as target grade (e) and the grade-optimization strategy with grade 3-2 as target grade (f). The column of the respective target grade is marked with light grey fill.

translate results of sawing simulations into applicable sawing optimization systems: the log positioning error of the sawing machine and the computing time required for optimization. Research on the log positioning accuracy of existing sawmill equipment indicates that the average error in log rotation is more than 5° , with a standard deviation of more than 10° (Tulokas and Tannous 2010). A positioning error of such magnitude must be taken into account by an optimization algorithm, e.g. by only accepting

maximum-value rotations with sufficient safety margins to value minima. Since in a real application there is only limited time for the optimization system to find the best positioning settings for each log, algorithms that are faster than an evaluation of every possible combination of log rotation, trimming positions, etc. are probably required, even with the high computation capacity available today.

Comprising eight different grades, the presented grading approach might be too detailed for practical

Table III. Shares of total board counts for the different grades and rejected boards when applying the *overall-optimization* strategy with all possible target grades.

Target grade	Share of grade, % (board count)									Total count
	1-0	1-1	1-2	2-0	2-1	2-2	3-1	3-2	Reject	
1-0	<i>6.0 (60)</i>	8.7 (86)	10.5 (104)	4.4 (44)	11.0 (109)	5.8 (58)	5.5 (55)	10.0 (99)	38.1 (378)	993
1-1	5.3 (52)	<i>10.1 (100)</i>	10.5 (104)	5.1 (50)	10.3 (102)	5.8 (57)	5.3 (52)	9.9 (98)	37.8 (374)	989
1-2	5.1 (51)	9.0 (89)	<i>11.8 (117)</i>	4.7 (47)	10.0 (99)	6.2 (62)	5.6 (56)	9.4 (94)	38.2 (380)	995
2-0	5.2 (52)	9.2 (91)	10.9 (108)	5.2 (52)	10.2 (101)	5.9 (58)	5.6 (55)	9.9 (98)	37.9 (376)	991
2-1	5.6 (55)	8.9 (88)	10.7 (106)	4.7 (46)	<i>11.3 (112)</i>	5.7 (56)	5.2 (51)	10.2 (101)	37.9 (375)	990
2-2	5.1 (51)	9.0 (89)	11.3 (112)	4.6 (46)	10.1 (100)	<i>6.4 (64)</i>	5.7 (57)	9.7 (96)	38.1 (379)	994
3-1	5.3 (53)	8.9 (88)	10.7 (106)	4.8 (48)	10.2 (101)	6.2 (62)	<i>6.9 (69)</i>	8.9 (88)	38.1 (379)	994
3-2	5.5 (55)	8.9 (88)	10.4 (103)	4.8 (48)	10.6 (105)	5.9 (58)	4.0 (40)	<i>11.9 (118)</i>	38.0 (377)	992

Absolute board counts for each grade are indicated in parentheses. Share and board count of the respective target grade are marked with italic font.

application, where a smaller number of different grades could be favoured for production efficiency and logistics reasons. Earlier studies on the perception of wood surfaces indicate that knots, if they are present, dominate the visual impression of the surface, so that other features such as the pattern of annual rings become less important (Broman 2000). As boards of grades 1-1 and 3-2 show a rather similar knot pattern and are mostly differentiated by their patterns of annual rings (boards of grade 3-2 tend to have less flattened annual rings as their origin in the log is closer to the pith), they might thus be treated as a single grade and also marketed together. Depending on the customers' sensitivity to the visual appearance of a wood product such as floorboards, it might even be possible to mix other grades. Still, being able to distinguish a rather large set of grades could be of advantage as it would preserve flexibility to react to changing customer preferences. Considering the question of the sensitivity of people's visual perception of wood surfaces and the lack of a reference classification already

mentioned, it would be interesting to conduct complementary surveys in which images of real boards or graphical illustrations of virtual boards would be presented to respondents. On the one hand, respondents could be asked to sort a set of virtual boards into different groups, and the outcome could be compared to the developed classification. On the other hand, the preference for wood surface samples with mixed grades of boards could be compared to the preference for samples comprising only boards of one grade. Willingness to pay for the different appearance grades distinguishable should also be investigated in such surveys as this knowledge is a prerequisite for any further investigation on value improvement potential with the proposed grading system.

Comprising only one board dimension and thus entailing low volume recovery, the sawing patterns used for production of the test boards and applied in the simulations did not correspond to industrial practice. Such sawing patterns would only be feasible if the appearance-graded boards, including off-

Table IV. Shares of total board counts for the different grades and rejected boards when applying the *grade-optimization* strategy with all possible target grades.

Target grade	Share of grade, % (board count)									Total count
	1-0	1-1	1-2	2-0	2-1	2-2	3-1	3-2	Reject	
1-0	<i>8.4 (84)</i>	7.4 (74)	8.3 (83)	4.0 (40)	8.4 (84)	6.0 (60)	5.5 (55)	9.7 (96)	42.1 (419)	995
1-1	4.8 (47)	<i>13.3 (130)</i>	8.2 (80)	4.8 (47)	8.7 (85)	5.0 (49)	5.1 (50)	7.8 (76)	42.3 (414)	978
1-2	3.7 (36)	7.0 (69)	<i>14.5 (142)</i>	4.0 (39)	8.5 (83)	6.5 (64)	5.2 (51)	9.2 (90)	41.5 (407)	981
2-0	4.7 (46)	8.4 (82)	9.9 (97)	<i>8.0 (78)</i>	7.3 (71)	5.9 (58)	5.5 (54)	10.0 (98)	40.3 (394)	978
2-1	5.1 (51)	7.9 (78)	10.7 (106)	3.7 (37)	<i>13.3 (132)</i>	5.1 (51)	5.3 (53)	9.9 (98)	39.0 (387)	993
2-2	5.3 (52)	8.0 (78)	9.6 (94)	3.7 (36)	6.6 (65)	<i>9.9 (97)</i>	5.7 (56)	9.3 (91)	41.9 (411)	980
3-1	4.4 (43)	7.6 (74)	9.2 (89)	4.5 (44)	8.9 (86)	6.2 (60)	<i>10.5 (102)</i>	5.2 (50)	43.6 (423)	971
3-2	4.6 (45)	7.4 (72)	10.0 (97)	3.7 (36)	10.1 (98)	5.7 (55)	2.3 (22)	<i>14.9 (145)</i>	41.5 (404)	974

Absolute board counts for each grade are indicated in parentheses. Share and board count of the respective target grade are marked with italic font.

grade boards, could realise sufficiently high prices, so that the loss of volume recovery would be compensated, compared to other sawn products. In principle, the grading system would also be applicable with sawing patterns comprising variable board dimensions, provided that the boards to be graded have rather small dimensions. With larger board dimensions, knot appearance on the board face would become too variable to be handled by the current classification, and proper assignment to log-sector classes would no longer be possible. A feasible option for the choice of sawn products and sawing pattern could be a mixed production strategy, i.e. the production of boards graded according to the proposed classification together with other sawn products of different dimensions that are graded according to another grading system, such as *Nordic Timber* (Anon. 1997).

In the context of dimension of the sawn products, it should be mentioned that a certain restriction also applies to their length. The homogeneity of the knot pattern on a board decreases with its length as the probability of the occurrence of mismatching knots increases.

It has to be noted that the presented results, both the assessment of the grading approach and the estimated optimization potential, are based on a rather small sample of logs which implies that they cannot be readily generalized. If an optimization system using such a grading approach was implemented in a real application where it faced a continuous throughput of logs with possibly varying characteristics, constant control of the output and recalibration of the PLS-DA models as required would be necessary.

Conclusions

- In the scope of this exploratory work, an approach of an appearance grading system for sawn timber based on PLS-DA was developed, and an initial estimation of optimization potential was given.
- The classification provided by the grading system could be deemed largely in accordance with the perceived appearance of wood surfaces.
- The simulations performed indicated that there is good potential to raise both the total yield of accepted boards and the yield of individual target grades compared to the current practice of volume optimization. The real value-optimization potential, however, depends on the price differences between the different board grades.
- As optimization potential with log breakdown increases with an increasing number of options

in the sawing parameters such as log rotational position in the first saw and allowed trimming lengths, higher potential for maximizing both the yield of target-grade boards and the total yield of accepted boards than with the simplified approach tested in the simulations can be expected for a more sophisticated optimization approach.

- From a practical perspective, distinction of eight different grades might not be necessary. Still, a rather finely graduated classification might be beneficial as it preserves flexibility for adjusting production.
- Further research on the response of potential customers to the proposed appearance classification is needed in order to assess its feasibility and to estimate willingness to pay for the different appearance grades. The latter is a requirement for any further study on value-optimization potential with such a grading system.

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