DOCTORAL THESIS

The Measurement of Compression Wood and Other Wood Features and the Prediction of Their Impact on Wood Products

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by

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ABSTRACT

Wood is a complex and highly variable biological material formed to give the tree best possible conditions for sustaining life. Thus every piece of wood is possessed of unique qualities. The great challenge in the process of manufacturing wood products has always been to select pieces of wood with properties that fulfil requirements for the product. The importance of selecting the right piece of wood will increase along with demands from customers for products with specific properties, such as moisture content, warp, strength, biological and aesthetic features. In order to supply customers with the products they request, a considerably improved selection of the raw material is needed. The earlier an accurate selection can be done, the better. To improve this selection or pregrading process, knowledge of the relationships between different features and different aspects of quality, as well as methods for measuring external and internal features, must be developed.

The main objective of this work was to contribute to improved predictability of the quality of dried sawn products using the features both of logs and of sawn green products as input. This work was divided into two parts:

Part one focused on the possibility of learning how to predict the quality grades of centre planks by manually inspecting longitudinal radiograph images (LRI) that depict the density variation within a log. In a survey respondents were interviewed regarding their interpretations of the density related features visible in the LRIs of Scots pine logs (Pinus silvestris L). The purpose was to be able to use these interpretations in predicting the final quality of planks sawn from the logs. The LRIs were reconstructed with the aid of an X-ray CT scanner.

Part two focused on the relationship between compression wood (CW) in foremost butt logs of Norway spruce (Picea abies (L.) Karst) and the warp of the sawn products, on how to detect CW and on how to predict warp. The logs used in the study were chosen among logs delivered to and sawn at commercial sawmills located in the northern part of Sweden in order to assure that conditions in the study match those extant in commercial sawmills.
The most important findings in this thesis are:

- Longitudinal radiograph images of the density variation within a log can be a powerful aid in manual grading of logs with respect to the quality of the resulting sawn products.
- The shape of the sawn, but not dried, centre planks is an indicator of both the amount and distribution of compression wood.
- Basing the cutting of planks on their shapes while still green can considerably increase the total length of acceptably straight dried products. This improvement is achieved through the elimination of compression wood.

**Keywords:** Bow, compression wood, crook, defects, density, external shape, knot, lumber, measuring, Norway spruce, Picea abies, prediction, grading, sawn products, scanning, sorting, spring, straightness, studs, sweep, twist warp, wood, X-ray.
PREFACE

The work presented in this thesis was carried out at the Division of Wood Technology, Luleå University of Technology, under supervision of Professor Anders Grönlund.

At this moment at the end of my education to be a scientist, I could spend some minutes reflecting on the past years of work. A lot of my work could have been done differently, probably better and definitely faster. Another reflection is the fact that the hardest part of the work to achieve a PhD is found neither in the difficulty of the objective nor in revealing hidden relationships, but in putting words to my accumulated thoughts and ideas in a foreign language. The work has, however, been interesting, stimulating, challenging and simply fun, with one exception—"the English". In long hours of work when a PhD exam seemed to be an insuperable task and I forgot about the fun, I often thought of my mother and her consoling words of wisdom:

"En komm fram han som tjool vä oxn å...

And my father’s quick reply, which better expressed my true feelings:

...men et gick hä fort, saa’n."

Nevertheless, today I've finally reached the destination, feeling great joy and satisfaction. I would like to thank the financiers of my work, the Swedish Council for Forestry and Agricultural Research, the former Swedish National Boards for Industrial and Technical Development (NUTEK) and The Swedish Forest Products Industry which supported part one of the work reported in this thesis, and the syndicate behind Trävision Norr 2000 and EU Program Objective 1 which supported part two.

Special thanks to Professor Anders Grönlund for supervision and keeping "things" simple, to Kjell Karlsson for splendid co-operation and support, to Ms Nordlund for bringing "order" and to all my colleagues for advice, ideas, inspiration and finally, for making the atmosphere at work so pleasant. Thanks also to Mr Brian Reedy for correcting my English and making it readable for other people.

Last but not least, I would like to thank my beloved family, Karin for her belief in me and for her support, and my sons Elias, William and Erik.

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LIST OF PAPERS

1 Öhman M. 1998:
Grade Prediction of Scots Pine Logs with the Aid of a Radiograph Image of the Log.

2 Öhman M. 1999:
Plank Grade Indicators in Radiograph Images of Scots Pine Logs.

3 Öhman M. 1998:
Correspondences between manually estimated compression wood in
Norway Spruce and the warp of the sawn timber.

4 Öhman, M. 2001:
Methods for Avoiding the Negative Effects of Compression Wood,

5 Öhman, M. 1999:
Modelling compression wood in sawn timber of Scots pine and Norway spruce.
IUFRO WP S5.01-04. Third Workshop, Connection between Silviculture and
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6 Öhman, M., Nyström, J. 2001:
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INTRODUCTION

1.1 Background

Wood is a biological material with great variability formed by the purpose to give the best possible living conditions at the site for the tree throughout its whole life. The wood in a tree has to provide the whole tree with strength, ability to transport water and nutrients, store nutrients, maintain an upright growth direction, forming a micro biological defence etc. By forming a minimum of components a perfect designed construction is formed by the tree, indeed a highly admirable ability. The consequence is that every piece of wood is unique due to the function it is designed to fulfil in the tree. This large variety in wood causes problems to us when we try to turn trees into homogeneous standard products useful in our reality. The great challenge in the manufacturing of wood products has always been to select pieces of wood with properties that fulfil the requirements of large number of different products. In earlier days, skilled craftsmen with long experience, and of course, a lot of time to select the right tree for each product carried out the selection process. When the manufacturing process gradually became more and more industrialised, the time available for selection of logs and sawn products with the required feature profile decreased. The process turned to be focused on high productivity in volume per hour and a high volume recovery. This progress has resulted in perhaps as much as 50% of what a sawmill of today produces are products not totally correspond to the customers expectations and needs. The customer's eager to buy the product is thereby reduced. Thus the total value of the produced products will be low. Grönlund (1992) calls this "the sawmill paradox". The sawmill paradox is due to the fact that the sawmills of today, by the strategy of sawing they use cannot control variation in the raw material. By Deming (1986) is the variation the root of all "evil" and is the major cause of costs for poor quality.

Quality is a word of many meanings. A number of more or less different definitions can be found in the literature. Examples of such definitions are "fitness for use" by Juran (1951), "conformance to requirements" by Crosby (1979) or by the International Standard, ISO 8402 "quality is the totality of characteristics of an entity that bear on its ability to satisfy stated or implied needs". As soon as there is a relation between two parts, consumer and provider of products, service, experiences etc. the process can be described in terms of quality. Quality is everything from describing the property of a product to how well the customer is satisfied, and can often be related to costs, (Garvin, 1984). In the wood industry the word quality is very strongly related to the properties of the sawn products or the raw material, and the dividing in well defined standardised quality-grades.

The current principle for production of sawn products is focused on a volume recovery of standard dimensions from the log. By the hypothesis, the larger volume of the
log that can be sawn to a product the better it is. A common strategy among the sawmills is to group the logs by the top-diameter in batches to fit a specific sawing pattern of combined standard dimensions. The number of dimensions is by this strategy limited and consequently more easy to handle physical and logistical. The sawn products are then grouped by dimension, dried and finally graded with respect to geometry and wood features. This concept describes the simplest sawing concept in use today, a batch sawing focused at a volume recovery of standard dimensions, an understandable strategy which makes the process less complex. A concept, which well corresponds to an older paradigm of supply an unknown end-user with, standardised products through a number of middlemens. By tradition the sawmill industry has been weak in market orientation and customer contacts. A concept associated with some major drawbacks. The customers can not buy a product, which exactly fit their needs of function. The customer satisfaction is low and the sawmill is more exposed to competition. If the sawmill is trying to improve the customer satisfaction other problems arises. If a product of a standard dimension is drained on planks showing specific properties, or qualities, to fulfil the demands of one customer only, the saleability of the remaining products could be negatively affected due to a skewed property structure and thereby less profitable. An even larger risk is taken if the sawmill decides to deliver a customer unique dimension of a highly specified quality. The more specified the quality demands are the larger amount of pieces not reaching the tolerances will be achieved, which could affect the saleability and profit of the rejected products. To minimise these negative drawbacks more knowledge must be achieved of how to grade and saw logs to achieve best possible value recovery. The truth is as Grönlund concluded 1995, "without any doubt the fact that the raw material is not efficiently utilised is the largest cost for poor quality".

Sawmill people have by time become more aware of the potential profits that can be achieved by better characterisation of the logs. An awareness, closely related to the change of paradigm from the older described above to an increased market orientation with closer contact between the sawmills and the consuming customers of sawn products. A change demanding, to be successful, an increased customer satisfaction, there one important part is to deliver products showing a quality better adjusted to the customers demands of function etc.

What lacking are the tools for characterisation of the logs as well as green sawn products that can control the conversion process in a more optimal way. Lönn (1989) pointed out the large economical potential in better utilisation of high quality logs if both the external and internal properties were concidered. Johansson and Liljeblad (1988) showed in a simulated sawing of 51 stems of Scots pine (Pinus sylvestris L.) that with full knowledge of the internal knots and outer shape of the log, the value of the sawn products could be increased by 10%. Results obtained by only one degree of freedom, the rotational position of the log during sawing. Also Björklund and Julin (1998) showed that knowledge of the internal knot structure creates a great potential for increased value recovery. It can be concluded the better the log can be described the potential to find a better end-products for the log increases and thereby the value.
Many sawmills are though trying to grade the raw material by more than the top-diameter of the log to achieve more homogeneous end products. The logs can be divided in a better or a worse quality-grade by the outer shape features and some sawmills are even grading the green sawn products. Most common is a grading of logs by use of optical scanners. From consecutive-diameter values or cross-sections, outer log features such as taper, butt taper, bumpiness, log sweep and degree of oval-shape can be turned to useful variables. By the aid of these variables statistical classification algorithms can be developed. (Nylander, 1990; Grace, 1994; Jäppinen and Nylander, 1997; Andersson, 1997; Jakobsson, 1998; Oja et al., 1999).

Grundberg et al. (1997) have shown the possibility of grading logs by detecting some of the inner features of a log by a 2-directional X-ray log scanner. Compared to the methods based on the outer shape of the logs this log scanner adds information concerning the density variation within the log as well, by other words a considerably better description of knots and heart wood/sap wood relations. Other techniques, such as NMR scanners, X-ray CT scanners and ultrasound are capable of detecting inner defects as well but much development are still needed for these methods before it can be used in sawmills. (Benson-Cooper et al. 1982; Taylor et al. 1984; Asplund and Johansson 1984; Roder et al. 1989; Davis and Wells 1992; Grundberg 1994; Chang et al. 1989; Soest 1996; Han 1991; Han and Birkeland 1992; Sandoz 1996)

When the end-products are more homogeneous in feature variation the costs of poor quality decreases by decreasing number of pieces not reaching the grading tolerances or customer satisfaction, and by improved utilisation of the production capacity.

The reason why not more grading is done, in spite of decreased costs of poor quality can partly be found in: A, tradition. B, lack of knowledge about the relation between the log and the sawn products features and the customer demands. C, equipment and methods for improved grading is not yet developed.

Efficient utilisation of the raw material can only be reached through optimisation based on knowledge of both the properties of the raw material and the demands of the customers. Each step of increased pre-grading of the raw material that can be done is an improvement. The opportunity of satisfying the customer increases if the batches of sawn products can be made more homogeneous and the costs of poor quality decreases. Fewer rejects can be expected as well as an improved utilisation of the production capacity.

The ambition of my work was to contribute to the development to a more efficient utilisation of the raw material as Grönlund (1995) concluded. It means, moving from a strategy of batch sawing logs to standardise end-products focused on the volume recovery towards a strategy focused on an optimised value recovery of each individual saw log. If the value recovery of each log is going to be truly optimised, a 3-dimensional description of the of the entire log features must be achieved to fulfil the customers needs and demands of products with special properties regarding dimension, moisture content, warp and last but not least biological or aesthetically features (Lönner, 1989).
No single technique of today is capable of this, by combining several different techniques it is though technically possible to get considerably closer to the optimum than today. But during a considerably foresight the sawmills are reduced to a second best strategy, concentrating logs and sawn products by the structure of quality related features.

1.2 Outline of the thesis

My work has foremost been focused on studies for an increased possibility to pre-grade saw-logs and sawn green products by the purpose to concentrate the quality of the batches of sawn products to a higher extent than is possible, or done, today. A work concentrated on finding features that are indicating the final grade, or properties, of the sawn products.

The work is divided in two parts by the focus of the studies. Part 1 is focused on grading saw-logs of Scots pine (Pinus silvestris L.) with respect to the quality grade of the sawn products, by the aid of longitudinal radiograph images. Foremost described by the knots in the sawn product and measured directly or by secondary features related in some extent to the knots.

In part two the impact of compression wood (CW) in Norway spruce, (Picea abies (L.) Karst.) on the sawn products is studied. Part two also includes how to detect CW and how to avoid CW causing a problem and how to avoid problems caused by CW.

1.3 Part one, grading by the aid of LRI's

Part one is focused in the opportunity to manually predict the true quality grade of the centre planks before sawing by features visual in longitudinal radiograph images of the saw-logs, paper 1 and 2. The differences in density within the log can be made visually and thereby can features describing the structure of knots and heartwood/sapwood relation be interpreted and combined with the outer shape of the log. A reliable detection of the inner features of a log is an example of how a homogenisation of the sawn products quality can be achieved by avoiding logs showing features not suitable for a specific sawn-product. The grading of logs by this method is one step toward a focus on the value recovery by the concentration of more equal logs. This grading is still in a batch perspective, but fewer logs are needed to produce an order of a specific product compared to a grouping by the top-diameter only.

The idea is to utilise the superb ability human has to process images. The more abstract interpreting needed the more superior we are compared to automated imaging processing systems. However it soon become clear that it was possible to achieve a reliable prediction by the machine system as well (Grundberg et al., 1997). Since an automated system has some important advantages over a manually based grading method such as the processing speed, the stability in measuring over time (a machine don't get tired, sick or bored) and very often lowered costs, no further research in the subject was done.
1.4 Part two, compression wood

This part is as mentioned above focused on CW in Norway spruce. The impact on the quality of the sawn products in terms of the magnitude of warp, methods for measuring and the possibilities to avoid products being rejected because of CW are studied. All by the purpose to identify and take action against harmful CW as early as possible in the sawing process. The earlier this can be done the more alternatives there is to find best possible end-product for each log and sawn product.

Compression wood: what it is and why it is a problem

CW is a type of wood formed by the tree as a response to an asymmetric load by the purpose to maintain an upright growth direction. Coniferous species such as Norway spruce rearrange the design of the cells, to be shorter, more thick walled and showing a larger angle between the micro-fibril bundles within the cell wall of CW than the normal wood cell (Wloch, 1975; Boyd, 1977; Harris, 1977; Cave, 1972). As a consequence the swelling/shrinking properties related to a change of the moisture content are different between the two type of wood. Largest difference is found in the longitudinal swelling/shrinking where the CW can have up to ten times larger by the same change in moisture content (Schultz et al., 1984).

CW is not a problem by it self but in an interaction with normal wood large forces are achieved (Watanabe, 1965; Alhasani, 1999). Dependent of how symmetrical the two wood types are distributed, the impact on the piece of wood can be everything in between a considerably magnitude of warp or none at all by the same amount of CW (Pillow and Luxford, 1937; du Toit, 1963; Ormarsson, 1999). CW is though a severe problem only when it affects the function defined by the customers. The straightness is one such important function, if the magnitude of warp become too large the piece of wood must be adjusted to fulfil the planned function or rejected both alternatives results in an increased cost. Jointing is another important function, which can be negatively affected by CW since CW is harder and more brittle than normal wood. In this work is though only the impact by CW on straightness regarded.
How to measure CW

If the exact position of CW within the sawn product could be determined before sawing, all problem related to CW could be avoided. Examples of such techniques are X-rays and gamma radiation, nuclear magnetic resonance and microwaves. X-ray technique or gamma-radiation both are capable of depicting the internal density variation rather well (Grundberg, 1999; Lindgren, 1992). But the unknown amount and distribution of water makes it impossible to identify areas of CW by the accuracy needed. Nuclear magnetic resonance is a method, which foremost is measuring the water content above the fibre saturation point, and is thereby not capable at all to detect CW (Chang et al., 1989). By microwaves it is possible to separate moisture content and wood density apart. In samples of the size of a log the damping of the signal is large and the ability to detect any density variations small (Kaestner and Bååth, 1998).

Since a reliable depiction of the true CW distribution within a log not is possible of today (2001), the second best strategy is to concentrate the logs in classes by the risk of large amount of CW. By using secondary features related to CW, a rough indication of the amount of CW can be achieved, examples of such indicators are the magnitude of log sweep, oval-shape and amount of visible CW in the butt-end cut of the log (CW-log) (Hagman, 1996). One example of the use of these features in a manual based grading can be found in the regulations for measuring of roundwood recommended by the Swedish Timber Measurement Council (Anon, 1997a). Features possible to measure by optical scanners or manually estimated but with the drawback of a poor accuracy.

On green planks could the microwave technique be of interest in depicting the amount of and distribution of CW within a plank. The method is though suffering from restricted penetration/damping but for most plank dimensions, at least up to 50 mm, the method is sufficient enough to depict the inner structure (Johansson, 2001). Theoretical it would be possible to detect CW when the local moisture content could be separated from the wood density, but not yet investigated.

The amount and distribution of CW can as well be depicted on the surfaces of the planks both manually and by different surface scanning applications (Hagman, 1996; Nyström, 1999; Nyström, 2000).

In common for all methods is that the true amount and distribution of CW is not exactly predicted. The measurements can though in many cases be sufficient enough to concentrate the material in more homogeneous classes regarding both amount of CW and the risk for large deformations. But in common for these methods are that a considerably development still are needed to achieve a commercial grading system for CW in green planks.
Outline of part two

The relation between CW and the warp of the sawn products is not yet described by such accuracy that a measured amount of CW could be used in a prediction of the warp. Neither is any method developed capable of depicting the true distribution of CW in 3 dimensions when green. Still considerably advantages can be achieved by a pre-grading procedure of both logs and green products focused in concentrating the raw material by the risk of CW-related warping. By a pre-grading the variety in the raw material will be decreased and a better adapted raw material can be selected for each specific product. The costs for poor quality decreases when both the amount of rejected products decreases and the utilisation of the sawmills production capacity can be increased.

This work was foremost oriented in studying the relation between measurable features related to CW on a sawmill on both logs and sawn but not yet dried planks and the shape of the dried final products in order to make a pre-grading possible. Together the studies gave an indication of how well the CW and CW related warp could be predicted and what degree of concentration could be achieved by a pre-grading procedure on logs as well on the sawn green planks.

A more detailed description of each paper included in the studies related to CW is shown below:

- Paper 3 is a study of the relation between the methods of measuring CW in use today and the warp of sawn products. On logs the Swedish Timber Measuring Councils' definition of the amount of CW visible in the butt-end cut was studied, (Anon, 1997a). On planks the amount of CW visible on the surface of the sawn planks, defined by the grading rules of the Nordic Timber was used (Anon, 1997b).

- Paper 4 is a study of; How well the amount of CW in the sawn products could be predicted by CW-related log features. How well the warp of wall studs could be predicted by both the CW-related log features and the amount of CW on the planks. Which concentration could be achieved by a pre-grading procedure based on the features studied? The possibilities to decrease the magnitudes of warp by different sawing strategies.

- Paper 5 and 6 were studies of the relation between the shape of the green central planks and the presence of CW.
1 OBJECTIVES AND LIMITATIONS
The main objective of my work was to find methods to improve the characterisation of the raw material, sawlogs and sawn products, as early as possible in order to predict the quality grade of the end products. My work is, however, divided into two parts by the focus of the studies.

2.1 Objectives part 1
Part 1 focuses on how to use longitudinal radiograph images (LRIs) of logs in the grading process.

More specifically:
• How to utilise the possibilities of LRIs in manual grading of logs with respect to the quality of the sawn products, Paper 1.
• Identify features, manually interpreted, that are of importance in the explanation of variety in observed plank quality grades, Paper 2.

2.2 Objectives part 2
In part 2 the focus was on one specific feature, compression wood (CW), and its relationship to the straightness of the sawn products.

The work can be divided into three major areas of inquiry:
• How to predict the amount of CW in the sawn products by CW-related log features and features of the sawn products before drying, Papers 3, 4, 5 and 6.
• How well the warp of the sawn products can be predicted by the amount of CW in the sawn products and other CW-related features in logs and in sawn products, Papers 3, 4 and 6.
• What can be done to avoid problems caused by CW? Papers 4 and 6.
2.3 Limitations

One limitation common to all the studies included in this work is the limited number of observations they were based on. The results shown in the papers cannot be regarded as exact truths, but as more or less good indications of the relationships shown.

The largest limitations of the work done in this thesis were though:

• In part 1 only 20 logs were included and ≤ 35 respondents were interviewed. Another limitation is found in the selection of logs. In order to decrease the complexity of the study, only logs yielding centre planks of the same quality grade were included. A larger study including logs yielding centre planks of different quality grades is needed before a final conclusion about the reliability and validity of the LRI method can be drawn.

• In part 2, the test material was selected in order to study the phenomenon of CW, primarily in butt logs. Therefore, no conclusion about the magnitude of the CW-related problems in terms of frequencies or costs can be drawn from these studies.
3 MATERIALS AND METHODS

3.1 Part 1, LRI based grading

Papers 1 and 2 were based on the manual impression of ten different log features visible in longitudinal radiograph images (LRI) and the quality grade of the centre planks when sawn.

In total, 20 logs from the Swedish Stem Bank were included in the survey. The Swedish Stem Bank is a database containing information such as silvicultural data, manually estimated log grades, computer tomography images (CT), test sawing results, grading results of sawn timber and scanned images of the centre planks of 200 Scots pine (Pinus sylvestris L.) trees (Grundberg et al., 1995). The logs included in the survey had to fulfil two criteria to be selected:

- An unquestioned quality grade of the selected plank.
- Both centre planks of one log had to be of the same quality grade.

The first criterion was fulfilled by selecting only planks graded equally by two professional sawmill graders acting independently. The second criterion was defined to reduce complexity in the grading process and in the analyses of the results. The logs were of three different centre plank grades: US, Fifth and Sixth, in accordance to the grading rules defined in the Guiding Principles for Grading of Swedish Sawn Timber (Anon, 1982).

The LRIs are grey-scale images representing the variation in green density inside a log, mainly the distribution of water and cell wall tissue (figure 1). The LRIs were calculated from the attenuation of the X-ray beam when it passed through the log. In this study, however, the LRIs were simulated out of a stack of CT images depicting 10-mm sections of the log length, and were also pathway compensated (the length the X-ray beam travels through the log) (Grundberg & Grönlund, 1991). The LRIs presented to the respondents were paper printouts of the dimensions 65 mm x ≤ 260 mm with a resolution of 53 halftone dots per square inch in 256 grey-scale levels.

In paper 1, 35 respondents, and in paper 2, 30 respondents, were interviewed, all familiar in one way or another with sawn products. In paper 1 the respondents were asked to estimate the quality grade of the planks sawn out of the log. In paper 2 they were asked to give their impression of 10 different features visible in the LRI of the log by putting a mark on a scaled line between two opposite words. The opposite words and the position of the mark described the respondents' impressions of the feature impact.
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The examined wood features were:

A. *Whorl distance*, the variation of the distance between the whorls.
B. *Knot angle*, mean fluctuation in the bearing of the knot's angle.
C. *Knot size*, mean size of the knots over the length of the log.
D. *Whorl knot size*, mean fluctuation of the knot size in the whorls.
E. *Heartwood fr*, fraction of heartwood in the log.
F. *Heartwood irr*, magnitude of diameter irregularities of the heartwood cylinder.
G. *Diameter irr*, magnitude of the diameter irregularity of the log mantle.
H. *Log sweep*, magnitude of.
I. *Log taper*, magnitude of.
J. *Butt swell*, magnitude of.

Partial least square regression (PLS) was used to identify the features indicating the final grade of the centre plank. PLS is a method based on the assumption that the x-variables are correlated, that there is noise in the data and that there can be structures in the residuals (Lindgren, 1994). Because of these assumptions, PLS was a tool well suited to adaptation to wood features, in consideration of bias in manual judgements and the possibility of correlated features. The PLS analysis was carried out with aid of SIMCA-S software (Anon, 1996). In a PLS model, the covariance between the features (x-variables) is maximised to the linear combination of one, or many, y-variables (Marten & Naes, 1989). In this study, three y-variables were used, one for each plank grade. By using three y-variables, the PLS model generates the probability of the log’s belonging to each one of the specific grades. The y-variable demonstrating the largest probability of the three was then chosen as the predicted grade of the log.
3.2 Part 2, Compression wood

In general, focus was on the relationship between compression wood (CW), features related to CW and the shape of the sawn products studied in papers 3 to 6. Norway spruce logs from the northern part of Sweden were the primary subjects studied, with the exception of paper 5 where Scots pine logs was included in the study as well.
The Measurement of Compression Wood and Other Wood Features
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Logs

Paper 3 was based on a total of 200 butt logs, 160 with varying fractions of CW and 40 free from CW, from four different regions in the northern part of Sweden, Ånge, Vilhelmina, Skellefteå and Piteå. Paper 4 was based on 90 butt-end logs from the region around Luleå. Paper 5 was based on 64 Norway spruce logs and 51 Scots pine logs, also originating from the northern part of Sweden (see paper 3). Paper 6 was based on 21 butt logs from the region of Skellefteå. In all studies were the selected logs of a lower quality than can be found in a normal distribution of butt logs. In all papers, reduced log quality was caused mainly by a considerable amount of CW present in the butt-end cuts and/or by large log sweep.

In papers 3, 4 and 5 some CW-related log features were measured. In all three papers, the magnitude of log sweep, oval shape and amount of CW visible in the but end of the log were measured by professional inspectors from the Swedish Timber Measurement Society according to the regulations developed by the same organisation (figure 2) (Anon, 1997a). In the material of paper 3, the displacement of the pith in the butt-end cut was measured, as well, and defined as the quotient between the distances from pith to bark on the diameter with the largest displacement, E/D in figure 2. In paper 5, the amount of juvenile wood was estimated, as well, and expressed as the diameters of the first 5, 10 and 15 annual rings.

Figure 2  To the left is the butt end of a log showing how the oval shape was measured, major and minor axis. The black area A+B is the total amount of CW, while only the area A within the treatment cylinder C is regarded in the regulations of Swedish Timber Measurement Society. D and E are the lengths that the quotient expressing the displacement of the pith was based on. To the right the principle for measuring the magnitude for log sweep is shown.
Sawn products

All logs were square sawn into planks, in papers 3, 5 and 6 to the dimensions 50 x 125 mm and in paper 4 to the dimensions 50 x 150 mm. In the material paper 3 is based on, 152 dried centre planks from 76 logs were resawn into studs of the dimensions 50 x 50 mm. The resawn planks were a representative selection within the studied material, as regards the amount of CW and warping of planks from the material of each of the 4 geographical areas listed above. In paper 4 planks were also resawn. Ninety planks were resawn green, and 90 were resawn after drying. A total of 92 planks were asymmetrically resawn to the nominal dimensions 50 x 50 mm and 50 x 100 mm while 88 were symmetrically resawn to studs of the nominal dimensions 50 x 75 mm, evenly distributed between planks resawn green and planks resawn dried.

Measuring the shape of sawn products

In the papers 3, 5 and 6, the shape of the sawn products was measured both green and dried. Before drying to indicate CW, when dried as a quality feature in terms of bow, spring and twist.

Throughout the studies the magnitude of warp was measured as the largest observed distance in mm between the piece of wood and the imaginary plane through the ends of the piece (figure 3).

Figure 3  Principles of how the magnitude of warp was measured. Bow (top) and spring (middle) as the distance between the plane through the ends of the plank and the plank. The magnitude of twist (bottom) was the distance between the plane through three of the planks corners and the fourth corner.
In paper 3 the warp of the dried planks was measured automatically with the aid of a CCD camera over a length of 4 m. The secondary warp of the studs (Plank-span) from the resawn plank, the studs’ deviation from parallel, was manually measured and expressed in mm (figure 4). In paper 4 the warp of each dried stud was measured manually over a length of 3 m, (figure 3). In paper 6 the warp of the dried planks was measured automatically in the stack of CT scans depicting the shape of the plank over a length of 297 cm.

In papers 5 and 6, the shape of the green planks was measured also. In paper 5 measurement was manual and expressed as the largest observed (Green-span) in mm between the two centre planks after sawing (figure 4). In paper 6 the shape of the single green plank’s bow was continuously measured over a length of 297 cm with the aid of a CCD camera, see Plank shape in figure 4.

Figure 4 Span shape, is an example of the principle used in two different moments; manual measurement of secondary warping of studs when resawn from a dried plank, denoted as Plank-span, and the span between the two green centre planks directly after sawing, denoted as Green-span. The plank shape shows the principle for measuring the bow of the green plank in relationship to a plane, the broad line in the figure, through the plank’s two end points.

Quality grading of sawn products

In papers 4 and 6, the features studied were related to their impact on the results when the sawn products were graded with respect to the magnitude of warp. The final products in both papers had dimensions corresponding to wall studs, a product in which one of the important qualities, or functions, is to be straight enough to build a wall with without any adjustments needed on the studs or the wall. In both papers, a grading regulation suggested by Johansson et al. (1993) developed for the grading of construction timber that will fulfil demands from the building trade was used.
Measuring CW in sawn products

The measurement of CW in the sawn products was altered throughout the papers. Papers 3 and 5 were based on the method defined in the grading rules of Nordic Timber, with the exception of the estimation of the volume of CW. In Nordic Timber the volume of the smallest box enclosing the whole volume of CW is regarded, while in papers 3 and 5 the volume of CW was estimated only (Anon, 1997b). In paper 4 only the visible area of CW on the surfaces of the sawn products was measured. In paper 6 a CT scanner was used in the estimation of the distribution and amount of CW within the sawn product, based on differences in density between CW and normal wood.

Drying

The sawn products in part 2 were all dried artificially in compartment kilns at elevated temperatures. The sawn products in papers 3 and 5 were dried to a moisture content of 12%. In paper 4 they were dried to 16% and in paper 6 to 18%. In papers 3, 4 and 5 the sawn products were all dried under restraint to prevent development of warp. In paper 6 the planks were dried and conditioned without restraints or loading to allow free development of warp. All sawn products in papers 4 and 5 and half the material in paper 3 were dried by a traditional air-drying schedule. They were heated to a wet-bulb temperature of 55°C which was then held constant. In the initial phase, a 3°C wet-bulb depression (WBD) was used which was increased to 12°C at the end. The other half of the sawn products in paper 3 were preheated by saturated steam to a wet-bulb temperature close to 100°C and then dried at a dry-bulb temperature of 110°C followed by conditioning with saturated steam for 1.5 h. In paper 6 the planks were heated by saturated steam to a wet-bulb temperature of 60°C, initially with a 6°C WBD, increased to an 18°C WBD at the end of phase one. In phase two, beneath the fibre saturation point, a WBD of 15°C was held constant for 24 h. The planks were then conditioned in a dry temperature of 75°C and a WBD of 1.5°C.

Evaluation of results

The results were evaluated by several different statistical methods. The most frequently used methods were, without ranking, partial least square regression to latent structures (PLS), regression analysis, one-way ANOVA on grouped materials and Chi² tests on observed frequencies.

The PLS-based analyses were carried out with aid of the statistical software SIMCA-S from UMETRICS. All other statistical analyses were done using the statistical software JMP version 3.1 from the SAS Institute Inc. (Anon, 1996; Anon 1994).
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4 RESULTS AND DISCUSSIONS

4.1 Part 1 grading by the aid of LRIs

The possibility of grading sawlogs of Scots pine (Pinus sylvestris L.) with the aid of longitudinal radiograph images (LRI) was studied in papers 1 and 2. Grading was performed with respect to the quality grade of the centre planks. Typical LRIs are shown in figure 5.

![LRIs of three logs](image)

Figure 5  LRIs of three logs, each representative of logs yielding two centre planks of equal grade: US, Fifth and Sixth respectively.

The results reported in paper 1 indicated a good possibility of using LRIs to concentrate logs into three classes corresponding to the quality grade of the centre planks. In table 1 the average results and a 95% confidence interval for all interviewed respondents are shown. The average respondent was able to achieve a level of 78% correctly classified logs.

Table 1  Predicted quality grades with the aid of LRIs of the logs versus observed quality grade of the planks: US, Fifth and Sixth. Based on 35 respondents’ inspection of 20 logs.

<table>
<thead>
<tr>
<th>Manual log grading with the aid of LRIs</th>
<th>US_predicted</th>
<th>Fifth_predicted</th>
<th>Sixth_predicted</th>
<th>n_observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>US_observed</td>
<td>193</td>
<td>51</td>
<td>1</td>
<td>245</td>
</tr>
<tr>
<td>Fifth_observed</td>
<td>30</td>
<td>157</td>
<td>23</td>
<td>210</td>
</tr>
<tr>
<td>Sixth_observed</td>
<td>2</td>
<td>48</td>
<td>195</td>
<td>245</td>
</tr>
<tr>
<td>n_predicted</td>
<td>225</td>
<td>256</td>
<td>219</td>
<td>700</td>
</tr>
</tbody>
</table>
The respondents were also asked to describe their impressions of 10 different features in each LRI of a log. The contribution of each feature to the explanation of the observed variety in plank quality grade was evaluated by partial least square regression (PLS). Of 10 different features tested, 8 contributed to the variation explained (table 2). Variation in the data set could not be explained in terms of the magnitude of log sweep or of the magnitude of Log taper. As the VIP values show, no single feature dominated in the prediction model. The feature ranked as the strongest was, for example, less than 1.6 times stronger than the weakest.

Table 2  Ranking of the features and cumulative variable influence (VIP). The term Separator indicates which plank grade it is possible to separate from the others: US, Fifth, Sixth or all three.

<table>
<thead>
<tr>
<th>Feature Ranking</th>
<th>VIP&lt;sub&gt;cum&lt;/sub&gt;</th>
<th>Separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Knot angle</td>
<td>1.143</td>
<td>Sixth</td>
</tr>
<tr>
<td>2: Diameter irregularity</td>
<td>1.099</td>
<td>Sixth</td>
</tr>
<tr>
<td>3: Butt swell</td>
<td>1.083</td>
<td>US</td>
</tr>
<tr>
<td>4: Knot size</td>
<td>1.058</td>
<td>All</td>
</tr>
<tr>
<td>5: Whorl knot size</td>
<td>1.015</td>
<td>Sixth</td>
</tr>
<tr>
<td>6: Whorl distance</td>
<td>0.922</td>
<td>Sixth</td>
</tr>
<tr>
<td>7: Heartwood irregularity</td>
<td>0.884</td>
<td>Sixth</td>
</tr>
<tr>
<td>8: Heartwood fraction</td>
<td>0.728</td>
<td>US</td>
</tr>
</tbody>
</table>

In figure 6 the results of grading by the PLS-based prediction model are shown. The model was based on each respondent's impression of the 10 features of each of the 20 logs included in the study. A total of 600 observations, 30 per log, were made, each observation shown as a large dot in figure 6. The prediction model showed a total accuracy of 76% correctly classified logs if divided by the "class dividing limits" shown in figure 6. The spread among the predictions was large, however, causing considerable confusion between the grades (figure 6). Beneath the large dots are smaller dots representing a prediction based on averaged impression of the 10 features, e.g. one observation per log. By using the same prediction model as before, a considerably better separation of the logs was achieved by averaging the respondents impressions.
Figure 6  Large dots represent the predicted grade index for each respondent’s impression of the log, based on 10 features. Small dots represent the predicted grade index of each log based on the mean value of each feature. Class dividing limits are examples of how a change of the threshold level can affect the grading result.

In a comparison to the grading results based on manual inspection of the logs exterior and outer shape designed by the Swedish Timber Measurement Society (VMR), the performance of the LRI method was at least as good. On the same material, VMR grading correctly classified 68% of the logs to be compared to the LRI-based results of 78% (table 1). The correspondence between the true plank grade and the VMR-based log grade was considerably higher in this study than that observed in other studies. Grönlund (1995) has shown total correspondences of approximately 40% between the log grades arrived at by VMR and the true plank grades.

The results in papers 1 and 2 indicate that the LRI method has a good ability to separate logs into three classes, which corresponds well to the grade of the centre planks. The findings in paper 2 contributed to the work done by Grundberg et al. (1997) to develop a machine grading system based on LRI (scout-view technique). The LRI method could also be a powerful aid in the VMR’s manual log grading procedure of today.

However, the results were based on a limited number of logs far from being perfectly representative for the normal distribution. For example, no logs yielding centre planks of different quality grades (half-grades) were included. Before a final conclusion can be made regarding the accuracy of the method, new tests with more logs and test persons have to be carried out, and methods for grading half-grades must be developed.
4.2 Part 2, compression wood

This part summarises the studies done on the prediction of compression wood (CW) in sawn products. The prediction was based on the relationships between log features and plank features before drying.

Predictions of compression wood in planks

One of the major objectives in this work was to find features useful for the prediction of CW in sawn timber. Going by the principle that the sooner the amount of CW can be predicted the better, a number of features were studied.

The relationships between the amount of CW in the sawn products and different log features were generally weak. The log features with the strongest correlations to the total amount of CW in both centre planks were the magnitude of log sweep and the amount of visible CW in the butt-end cut of the log (CW-log). But in neither of papers 3 or 4 did the correlations demonstrated exceed $|r|=0.60$. Other log features, such as oval-shaped top and butt ends, displacement of the pith and amount of juvenile wood, all demonstrated an even poorer correlation to the amount of CW in the two centre planks.

In a pregrading process, only the log features CW-log and log sweep could be used in a separation of the logs, in both cases into not more than two classes with significantly different group mean values (figure 7). The observed differences in the group mean values were at least a factor of 2 for both features with the threshold level used in papers 3 and 4 (figure 7). The spreads among the observations were large in all comparisons.

Paper 5 showed how the shape of the green planks of Norway spruce was a considerably better indicator of the amount of CW within the two centre planks. A convex shape was found to indicate the presence of CW, while a concave shape indicated planks free from CW (figure 8). By measuring the largest magnitude of the span formed by the green planks’ deviation from parallel, a correlation of $|r|=0.78$ was shown to the amount of CW-plank. A prediction model including CW-log and Green-span explained $R^2=0.64$ of the observed variation in the amount of CW in the planks. In paper 5 the predictability of CW within planks of Scots pine was also studied. In general, results were the same, a correlation to the Green-span of $|r|=0.71$, and the prediction model explained $R^2=0.64$ of the observed variation.

Pregrading based on the features studied above has two major drawbacks. Since CW is often concentrated very locally within the log, a large number of planks will have a small amount of CW in spite the log features’ indication of large amounts of CW. A considerable spread can be found in the amount of observed CW, which is undesirable and results in a poor concentration. The second drawback is the way the features were measured. All features studied in papers 3 to 5 were expressed by one value meant to describe the character of the whole log, a traditional procedure in manual grading. Since CW is locally distributed within the log it, become difficult to reach a good accuracy in
the estimation of the true amount of CW by using features defined to describe the whole log, such as those used in papers 3 to 5.

Figure 7 Pregrading of logs by the amount of visible CW in the butt end (CW-B.End/Grouped) to the left, and magnitude of log sweep (GrupperadKrok) to the right, with respect to the amount of CW-units within the centre planks (CW-C.Y). To the left the logs were separated by a CW-log value of 20% and to the right by logs with no measurable sweep, Straight, and those with sweep, Swept. Results can be found in paper 4.

Figure 8 Two pairs of centre planks, the upper showing a concave CW-free shape, while the lower shows a convex shape indicating a considerable amount of CW. The image shows the 50 mm edges of the planks over a length of 3 m. Denoted as Green-span in paper 3.
In paper 6 the whole plank was depicted in terms of the bow of the green plank with the aid of a CCD camera, and the amount and distribution of CW within the plank with the aid of an X-ray CT scanner.

Notable findings were:

- In a comparison of the green bow and the total volume predicted as CW in all planks included in this study, 84% was found in parts with a convex bow.
- A correlation of \( r = 0.63 \), based on 42 planks, could be observed between the total volume of CW within the planks and the magnitude of the convex green bow.
- Large magnitudes of convex green bow displaced towards the butt end of the plank indicated an increased risk of large local concentrations of CW.

In table 3 the amount of CW for planks grouped by largest observed convex bow is shown. As can be seen, the planks with a convex bow larger than 9 mm, level C, measured over 297 cm, had significantly more CW than level A and B.

Examples of the relationship between the green bow of the planks and the amount and distribution of CW within planks are shown in appendix 1.

Based on the findings in paper 6 it can be concluded that the location of CW within a single plank can be predicted by the shape of the green plank. A convex-shaped green bow is a very strong indicator of the presence of CW, and the larger the observed convex bow, the more CW can be expected, while a concave shape is as strong indicator of CW being absent. However, the total amount of CW within a plank could only be roughly predicted from the magnitude of the convex bow.

### Table 3

<table>
<thead>
<tr>
<th>Planks grouped by magnitude of convex bow</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>n</td>
<td>CW%</td>
<td>Std Dev</td>
<td>S.D CW%</td>
<td>( n_{accept} )</td>
<td>S.D accept</td>
</tr>
<tr>
<td>A</td>
<td>9</td>
<td>0.4</td>
<td>1.0</td>
<td>C</td>
<td>8</td>
<td>B, C</td>
</tr>
<tr>
<td>B:</td>
<td>23</td>
<td>2.1</td>
<td>2.5</td>
<td>C</td>
<td>14</td>
<td>A, C</td>
</tr>
<tr>
<td>C:</td>
<td>10</td>
<td>6.7</td>
<td>4.5</td>
<td>A, B</td>
<td>1</td>
<td>A, B</td>
</tr>
</tbody>
</table>
The Measurement of Compression Wood and Other Wood Features and the Prediction of Their Impact on Wood Products

The large benefit of measuring the shape of the green plank compared to the other features studied is not in the prediction of the total amount of CW, but in the ability to describe the longitudinal distribution of CW within the plank. The findings in paper 6 also indicate an opportunity to locate areas of very high concentrations of CW by combining the magnitude and location of the largest observed convex shape. This finding may be more important than improved accuracy in predicting the total amount of CW within the whole plank. The relationship between CW and the green shape of the plank is complex, and a lot of work remains to be done to further improve the reading of the green shape in order to locate CW.

An important question is how frequent logs with increased amounts of CW are. A small frequency study at a sawmill during normal conditions showed that approximately 40% of all butt logs and up to every third middle and top log of Norway spruce showed a convex Green-span between the two centre planks, based on a study of 1126 logs. Table 4 gives more detailed information about how frequent the shapes indicating CW are. The logs are divided into two diameter classes, <170 mm and 225 to 264 mm, and two log type classes, butt logs and other. The observed Green-span between the two centre planks was manually classified into 4 different shapes. Concave was the typical CW-free shape and Convex the typical shape when a considerable amount of CW could be expected (figure 8). Additionally, two intermediate shapes were included in this study, denoted as S-shaped and Parallel-shaped. The S-shaped showed a typical CW-related convex span close to the butt end which changed to a CW-free concave shape at the top, a shape typical for a concentration of CW in the butt end only. The Parallel shape indicates some CW well distributed over the entire length of the planks, but not in such amounts that a convex shape is formed.

Depending on log type, 25% to 45% of all Norway spruce planks indicated that CW was present in the planks. When CW is found in a plank the risk of large magnitudes of bow and spring is increased when dried. The shown frequency of planks indicating CW is of such magnitude that pregrading based on the planks green shape could be of interest to identify low quality planks earlier than is possible today.
Table 4  Frequency of 4 different green-bow shapes formed by the centre planks. Logs of Norway spruce of top-diameter 225 to 264 mm and of top-diameter ≤170 mm. Concave was the CW-free shape, a Convex shape indicated a considerable amount of CW, S and Parallel were two intermediate shapes indicating some CW. "n" is the number of observed logs.

<table>
<thead>
<tr>
<th>Log type</th>
<th>Concave</th>
<th>Convex</th>
<th>S-shaped</th>
<th>Parallel</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt225-264</td>
<td>56%</td>
<td>18%</td>
<td>8%</td>
<td>18%</td>
<td>434</td>
</tr>
<tr>
<td>Other225-264</td>
<td>64%</td>
<td>19%</td>
<td>2%</td>
<td>15%</td>
<td>101</td>
</tr>
<tr>
<td>Butt≤170</td>
<td>61%</td>
<td>18%</td>
<td>6%</td>
<td>14%</td>
<td>217</td>
</tr>
<tr>
<td>Other&lt;170</td>
<td>74%</td>
<td>5%</td>
<td>6%</td>
<td>14%</td>
<td>374</td>
</tr>
<tr>
<td>n_total</td>
<td>719%</td>
<td>156%</td>
<td>73%</td>
<td>178%</td>
<td>1126</td>
</tr>
</tbody>
</table>

Competition wood and the warp of the dried products

The presence of CW by itself is not a problem in sawn products. Problems arise when the forces caused by differences in shrinking properties between normal and CW result in a deformation of the sawn product both from drying and from further processing of the dried product. The possibility of identifying sawn products with increased risk of large warp was studied in papers 3, 4 and 6.

The correlation between manually measured log features and the magnitudes of warp were poor. Grading by log features was able at best to separate the logs into two groups, one with a lower risk and one with a higher risk of degradation of the sawn products due to excessive magnitudes of bow or spring. Twist was not related to the CW-related log features.

In spite of the differences between papers 3 and 4 (dimensions and methods for measuring warp), approximately the same results were found. In no study was a correlation stronger than $[r]=0.40$ observed between either of the two log features CW-log or log sweep and the magnitude of bow and spring. The correlation to twist did not exceed $[r]=0.15$.

Measurements on planks were also compared to the magnitudes of warp. The amount of CW within the sawn products was manually measured in papers 3 and 4 and had a correlation to bow and spring which did not exceed $[r]=0.50$, while to twist no correlation was shown $[r]≤0.03$.

The Green-span measured in paper 5 had a correlation of $[r]=0.56$ to the sum of the two centre planks’ magnitude of bow and $[r]=0.34$ to spring, while no correlation to twist was found, $[r]=-0.04$.

A simple measurement of the span between the two centre planks, Green-span, cannot separate the sawn products into more than two classes, one indicating a lower risk and one a higher risk of large magnitudes of bow and spring when dried (figure 8).
In table 5 can be seen how a Green-span of the single plank ≥ 15 mm implies a significantly higher risk of rejection due to excessive bow and spring than smaller Green-span does. However, it must be pointed out that the result only indicates a rapidly increased risk of large magnitudes of warp with increased Green-span. The threshold level, 15 mm, is by no means the optimum level. Further studies are needed in order to find the optimum level.

In all comparisons, the correlation between any feature and twist was extremely poor with one exception, the slope of grain. The mean slope of grain measured on the outer face of the plank in the material from paper 3 had a correlation of \( r = 0.80 \) to the magnitude of twist, based on 244 observations.

Warp becomes a problem when it no longer can be accepted in the application for which the wood product is intended. In paper 4 the study focused on a specific product, wall studs, and how well different features could be used to concentrate the yield of accepted dried wall studs in different steps of the sawing process before drying. The largest acceptable warp for this specific product is, according to Johansson et al. (1993) ≤ 6 mm for bow, ≤ 4 mm for spring and ≤ 5 mm for twist.

Table 5 Group mean values and standard deviations, Std. dev., in mm, of the observed warp of dried planks grouped by observed magnitude of Green-span between two green centre planks of each log. A, B and C on the mean values denote to which group of planks a significant difference in the group mean values could be proven. Results based on material from paper 5.

<table>
<thead>
<tr>
<th>Green-span</th>
<th>Bow</th>
<th></th>
<th>Spring</th>
<th></th>
<th>Twist</th>
<th></th>
<th>n_plank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std.dev.</td>
<td>Mean</td>
<td>Std.dev.</td>
<td>Mean</td>
<td>Std.dev.</td>
<td></td>
</tr>
<tr>
<td>A: Concave</td>
<td>6.6C</td>
<td>4.9</td>
<td>4.3C</td>
<td>3.1</td>
<td>5.2</td>
<td>5.1</td>
<td>200</td>
</tr>
<tr>
<td>B: Convex</td>
<td>7.5C</td>
<td>3.3</td>
<td>5.3C</td>
<td>3.5</td>
<td>6.1</td>
<td>5.9</td>
<td>27</td>
</tr>
<tr>
<td>&lt;15 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: Convex</td>
<td>11.6AB</td>
<td>9.0</td>
<td>8.3AB</td>
<td>11.5</td>
<td>5.3</td>
<td>5.1</td>
<td>31</td>
</tr>
<tr>
<td>≥15 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In figure 9 the impact of the magnitude of log sweep and the amount of CW in the butt end of the log (CW-log) on the yield of accepted studs is shown. The results in figure 9 show that the magnitude of log sweep was at least as useful in identifying logs giving poor yields as CW-log was, in spite of the higher correlation shown for the latter. As can be seen, the yield of accepted studs decreased dramatically as soon as a log sweep could be measured, while a minor amount of CW-log did not negatively affect the yield.
The Measurement of Compression Wood and Other Wood Features and the Prediction of Their Impact on Wood Products

Figure 9  Yield of accepted wall studs graded with respect to straightness originating from logs grouped by magnitude of log sweep and amount of CW-log. The lighter bars show the yield from the material in paper 4 when bow, spring and twist were regarded, and the darker when twist was disregarded.

When the study of paper 4 was designed, the two log features log sweep and CW-log were combined in 5 different log classes (see table 6). As can be seen, only log grade 3- (logs showing considerable amounts of CW in the butt end and a large log sweep) gave a considerably lower yield than the other groups.

Table 6  Total yield of accepted wall studs, in % of the total amount of studs in each group of log grades. Within brackets the results when only bow and spring were regarded are shown. The log grades 1, 2+, 2-, 3+ and 3- are combinations of the two log features CW-log and log sweep according to the values shown in the table.

<table>
<thead>
<tr>
<th>Yield of accepted studs (%)</th>
<th>1</th>
<th>2+</th>
<th>2-</th>
<th>3+</th>
<th>3-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield_{total} (%)</td>
<td>66 (69)</td>
<td>69 (71)</td>
<td>48 (58)</td>
<td>59 (62)</td>
<td>27 (32)</td>
</tr>
<tr>
<td>CW-log (cm²)</td>
<td>&lt;10</td>
<td>10-55</td>
<td>10-55</td>
<td>&gt;50</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Mean log sweep (cm)</td>
<td>0.2</td>
<td>0.3</td>
<td>1.3</td>
<td>0.5</td>
<td>2.9</td>
</tr>
<tr>
<td>n_{studs}</td>
<td>68</td>
<td>80</td>
<td>59</td>
<td>64</td>
<td>88</td>
</tr>
</tbody>
</table>

Based on the results shown in figure 9 and table 6, it can be concluded that a measurable log sweep is an indicator of increased risk of degradation due to excessive bow and spring, at least as good an indicator as the amount of CW-log. A high-quality log showing no sweep or CW is not by any means a guarantee of all studs being accepted. Logs with measurable sweeps should be handled with care, and sweeps larger than 3 cm should be totally avoided if the largest possible yield is to be achieved. The impact of CW-log is not as pronounced, but the larger amount, the higher risk of degradation. Consequently, pregrading based on log sweep and CW-log could only be used to identify...
logs giving a poor yield. As far as the complexity of measuring the two features in practice is concerned, only log sweep can be regarded as possible to use. An outer shape such as a sweep is much less complex to measure and less sensitive to disturbances than measurement of the fraction of CW. If the perfect logs that yield only accepted studs are to be found, other methods and features will have to be added to the prediction.

Pregrading based on the amount of visible CW on the surfaces of the green planks was only slightly better than pregrading based on log features (paper 4). Approximately three out of four studs were accepted among the planks with < 12% CW. In the interval 12% to 50%, three out of five studs were accepted, while only one out of four studs was accepted from planks with more than 50% CW.

Paper 6 showed how the shape of the green plank could be used as an indicator of the risk of degradation due to excessive warping (table 3). In spite of the small number of planks tested, the results in paper 6 indicate a very promising possibility of pregrading planks with an accuracy at least as good as a grading of the planks based on the amount of visible CW. Among the 9 planks with a convex green bow < 1 mm, planks free from CW, only 1 was rejected due to excessive bow or spring. For the 10 planks with a convex green bow > 9 mm, 9 were rejected.

When CW is mixed with normal wood, considerable forces are generated due to differences in shrinking properties. During secondary processing these internal forces can result in considerable warping of the pieces of wood (secondary warping). In order to study the possibility of predicting the risk of large secondary warping, the features studied in paper 3 were compared to the span observed between two studs resawn out of the same dried plank, denoted as Plank-span.

The results reported in paper 3 were an indication of a good opportunity to identify planks suitable for reprocessing. Both the measured deviation from being parallel of the two green centre planks, Green-span in figure 4, and the sum of visible CW on the two centre planks, CW-plank, showed a good correlation to the secondary warping of the resawn dried planks. Green-span showed a correlation $[r]=0.80$ to the magnitude of PlankSpan$_C_Y$, the sum of the both centre planks' Plank-spans, while the sum of observed CW on both centre planks reached the same correlation, $[r]=0.79$. On the single plank the observed correlation between CW-plank and Plank-span decreased to $[r]=0.60$.

The warp of the dried plank showed a surprisingly poor correlation to the magnitude of secondary warping, Plank-span, of the resawn studs: $[r]=0.55$ to bow, $[r]=0.24$ to spring and to twist none at all, $[r]=0.05$.

**Reduction of the impact of compression wood**

That CW is related to the development of both bow and spring in the dried products can be concluded from these studies as well as a number of other studies (Beard et al., 1993). The exact relationship between CW and warping has not yet been studied sufficiently to enable prediction with desirable accuracy; thus no reliable methods for detecting CW in single planks have been developed. Consequently, the opportunity to handle the
CW-related problems lies in reducing the risk of large warping. One method studied above is to avoid CW by grading of both logs and green planks and thereby reduce the number of sawn products showing too large magnitudes of warp. A strategy that could be regarded as too defensive giving a large amount of low quality products. Methods for reducing the amount of low quality products due to CW related warping would be a desirability.

In paper 6, five different cutting strategies were compared in terms of eliminating high local concentrations of CW, ≥ 30% of the cross section area. Based on the magnitude and location of the largest convex green bow, a rather efficient reduction of CW could be achieved. A reduction of CW by itself is of no importance. More interesting is how the CW-related magnitudes of bow and spring can be decreased. In figure 10 the increase of accepted plank length for two plank shapes is shown, S-shaped and the C2-shaped (Appendix 1).

The total amount of CW in S-shaped planks was found to be low. As a consequence of this, few planks were rejected. However, by only cutting planks with a convex green bow larger than 6 mm, the total length of accepted dried planks could be increased by approximately 10%. Among the C2-shaped planks a considerably higher amount of CW was found and only one third of the original, e.g. uncut, plank length met tolerances (figure 10). By adapted cutting, the accepted plank length could be doubled (figure 10).

The results shown in paper 6 indicate a possibility to increase the volume of straight (accepted) planks by using an adapted cutting strategy based on the magnitude and shape of the bow of the green planks.

In paper 4 two methods for resawing planks into wall studs were compared in terms of straightness of the dried product. Half of the planks included were resawn to wall studs after drying, while the other half was resawn out of green planks. The hypothesis was that the less the geometry of a piece of wood is changed after drying, the lower will be the magnitudes of bow and spring. The hypothesis was found to be true to some minor extent. The magnitude of both bow and spring increased with increasing amounts of CW, while the magnitude of twist was constant. The studs resawn from dried planks showed a larger increase of both bow and spring from increased amounts of CW than did the studs resawn green. The general tendency was that the larger the amount of CW present, the more beneficial was the method of resawing planks into studs in a green condition. But in no comparison was the observed difference statistically significant. Regarding magnitude of twist, the tendency was the opposite. The studs resawn green had the larger magnitudes, no matter the amount of CW. Consequently, no difference between the methods was found when all three warp types were taken into consideration.

In paper 4 the importance of how symmetrically the plank was resawn was investigated. Half of the planks were resawn symmetrically and half were resawn asymmetrically. No differences could be found that proved a statistically significant difference in magnitude of warp caused by the symmetry of the resawing pattern.
Figure 10  Increase in the yield of accepted plank length in %, for C2-shaped and S-shaped green planks using 5 different cutting strategies. The level of Tolerance shows the yield from planks with a green convex bow equal to or larger than the value shown. No Cut, denotes the magnitude of convex green bow where no planks were cut, all planks were cut at the tolerance level 0 mm.
5 CONCLUSIONS

5.1 Conclusions part 1
Conclusions regarding how to predict CW were:

- Longitudinal radiograph images reveal a great deal of the Scots pine log’s internal features and can be a powerful aid in a manual grading process.

- The results from the study of the respondents’ interpretations of log features can be used in the design of an automated grading system.

5.2 Conclusions part 2
Conclusions regarding how to predict compression wood (CW) were:

- Log features are in general poor indicators of the amount of CW within the sawn planks.

- The amount of visible CW in the butt end of a log, CW-log, and the magnitude of log sweep can be used in a minor concentration of the logs into two classes with significantly different mean amounts of CW.

- The shape of the green plank indicates the amount of CW as well as the distribution of CW within the sawn plank.

- A minor study shows that approximately 20% of the centre planks can have a CW related convex Green-span, 60% can have a CW free concave shape, while the remaining planks show intermediate shapes indicating small amounts of CW.
Conclusions regarding how to predict compression wood related warping were:

- A large magnitude of log sweep and a large amount of CW-log are indications of an increased risk of large magnitudes of bow and spring in the sawn product.

- A single high quality log, with no sweep or visible CW, is not a guarantee of a better yield of accepted products than logs with a moderate magnitude of sweep or a moderate amount of CW.

- Correlation between the amount of CW in the sawn product and the risk of large magnitudes of bow and spring when dried is poor, indicating a potential for concentration into two groups only.

- The shape of the green planks and the amount of CW visible on the plank are both good indicators of the risk for large internal forces within the sawn product giving large secondary warping when resawn.

Conclusions regarding how to avoid compression wood related problems were:

- On products where high demands are placed on straightness, pregrading before drying can result in a considerable increase in the yield of accepted products.

- Features measured on sawn green products, the shape of the plank and amount of CW, are in general more accurate than features measured on the log in their ability to indicate an increased risk of large magnitudes of bow and spring in the dried products.

- By cutting based on the shape of the green bow of the plank, a considerable increase in the total length of accepted dried products can be achieved, compared to no cutting at all.
6 REFERENCES


(In Swedish with English summary.)


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The Measurement of Compression Wood and Other Wood Features and the Prediction of Their Impact on Wood Products


APPENDIX 1

Green convex bow and compression wood distribution
Appendix 1: Green convex bow and compression wood distribution

Plots showing examples of the relation between the green bow of the planks and the volume and distribution of compression wood within the planks originated from butt-logs of Norway spruce. The blue, thin, line representing the green bow of the plank, the outer "sap-wood" surface is faced up in the plots. The red line representing the longitudinal distribution of compression wood within the plank. The length of the planks is in all plots 297 cm, the butt-end to the left. Please note that the y-axis is scaled differently in the plots. The CW, in % of the cross-cut area of the plank, is measured every 1 cm with an X-ray CT-scanner.

Plank 16U is showing a centred convex bow caused by a symmetrical distributed CW, in this case in low local concentrations.

Plank 18U and 7U are examples of displaced convex green bows. In both planks the CW was concentrated to the butt-end and in very large concentrations causing a large displaced convex bow as well. The major difference between the two planks was found in the amount of CW in the middle and top parts of the planks. Plank 18U indicate the presence of CW in the whole plank while no CW could be shown in plank 7U above 1 m from the butt-end. As an effect of no CW the upper part of plank 7U developed a concave shape.
Appendix 1: Green convex bow and compression wood distribution

Plank-18U

Plank-7U
Appendix 1: Green convex bow and compression wood distribution

Plank 12N is an example of what is denoted as an S-shape in paper 6. In relation to the elongation of the plank could both a convex and a concave part be observed. As for 18U and 7U could a concentration of CW be found in the butt-end of the plank causing a convex bow. But in plank 12N is the concentration considerably lower than in plank 18U and 7U and consequently could both a small convex shape and a concave shape be seen.

Plank 24U is an example of a plank almost totally free from CW showing the characteristic concave green shape.
Paper I
Grade Prediction of *Pinus sylvestris* Logs with the Aid of a Radiograph Image of the Log

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Today the internal structure of a log can be detected using X-ray scanning technology. The objective of this study was to investigate the potential of grading a log by visual inspection of its longitudinal radiograph image (LRI). The grading accuracy of the LRI method was compared with the accuracy of a conventional manual log grading method. The grading accuracy was expressed as the ability to predict the grade of the centre planks of a log before the log was sawn. The grading results of the LRI method were determined by interviewing respondents connected with the wood and sawmill industry. The statistics of the conventional log grading method originate from the Swedish Stem Bank. The evaluation of the results was based on conventional statistical methods, unpaired significance tests and confidence intervals for means. This study shows that it is possible to grade logs by using LRIs. The grading accuracy is equal to, or better than, conventional log grading done by skilled graders from the Measurement Society of Sweden.

Key words: centre plank, log, *Pinus sylvestris*, radiograph, timber grading.

INTRODUCTION

It would be an economic advantage to the sawmilling industry of today if the inner structure of a log were exactly known in terms of type, degree and location of internal defects. Logs unsuitable for a certain sawing pattern could thus be avoided but also a more optimal decomposition of the log could be found according to its internal features. To achieve this improvement, the internal features of the log must be revealed and appraised along with the external features (Blomqvist & Orke 1986). It has been shown that the value of sawn lumber of Scots pine (*Pinus sylvestris* L.) from each log can be increased by about 10% if the positions of internal defects are known (Johansson & Liljeblad 1988).

Until 1996 the Measurement Society (MS) in Sweden had log grading instructions that focused on predicting the grades of the centre planks. The grading was performed by visual examination of the exterior of the log. Grönlund (1995) has shown that there is a low to moderate agreement between the grading results of the MS and the sawmill grading results based on the manual *Guiding Principles for Grading of Swedish Sawn Timber* (the Green Book), the first edition of which was prepared by the Swedish Timber Grading Committee of 1958 (Anon. 1982). The agreement between the exterior of a single log and the grade of its centre planks is too low to be useful in order to control the sawing process in an optimal way.

By using X-ray scanning technology it is now possible to detect the internal structure of a log (Grundberg 1994). This information can be analysed either by a computer or visually by looking at a longitudinal radiograph image (LRI) of the log (Fig. 1).

The objective of the present study was to investigate the potential of grading logs by a visual inspection of LRIs. The questions to be answered were: How well does grading by visually examining an LRI of a Scots pine log agree with the results of the true grade? How well does the LRI method perform in comparison with the MS’s conventional log grading method? The true grade of a log is considered to be equal to the grade of the two centre planks from the log graded, after sawing, according to the Green Book.

MATERIALS AND METHODS

All material and data in the study, except for the LRI grading results, were taken from *The Swedish Stem Bank* (Grundberg et al. 1994). The Swedish Stem Bank is a database containing information such as silvicultural data, manually estimated log grades, computer tomography images (CT), test sawing re-
Fig. 1. LRIs of three logs. The logs are representatives of the true log grades of US, fifth and sixth respectively.

Interviews were carried out to determine whether the LRIs of a log can give the amount of information required in order to predict the log grade. This was done by testing 20 logs in random order showing LRIs to each one of 35 respondents, for a total of 700 observations. From the log features shown in the LRIs the respondents were asked to predict the grade of the two centre planks from each log, choosing from three different grades, unsorted (US), fifth or sixth, in accordance with the Green Book (Anon. 1982).

The Green Book is a manual, widely used throughout the European market, showing allowed size, number and appearance of defects visible in sawn timber. The sawn timber is divided into different grades according to the defects present, where the acceptance of defects is lowest for the US grade, moderate for the fifth grade and highest for the sixth grade. Furthermore, defects in sawn timber are divided into two main groups in accordance with the Green Book: (A) Defects in quality, subdivided into structure, manufacture, shakes, checks, splits and deformities. (B) Defects in condition, subdivided into moisture, blue stain and other discolorations.

The respondents were selected from four different professions; 15 were sawmill graders, 9 were sawyers, 9 were wood scientists and 2 were inspectors from The Measurement Society. The wood scientists were personnel from the Division of Wood Technology at the Luleå University of Technology while the others were from different commercial sawmills.

The interviews began with a short introduction to the purpose of the study and some brief information about how an LRI is created. The following facts about the logs were withheld from the respondents in order to prevent personal experience and knowledge from affecting the results: The dimensions of the log; type of log, for instance butt or top log; the exact positions and dimensions of the two centre planks in
the log; the true mix of grades among the logs in the test. No information about the Green Book and its grading principles was given, nor was any training in grading or any other information on the appearance of defects of vital importance given to the respondents.

The twenty test logs were chosen from six different stands in Sweden. To be selected, the test logs had to fulfil two criteria. Firstly, the two sawmill graders in the Stem Bank test must, independently of each other, have graded every single plank from each log equally. Secondly, the two centre planks from the same log must be of the same grade. The purpose of the first criterion was to ensure that the planks of a certain grade were typical of the actual grade. The purpose of the second criterion was to reduce complexity in the comparison between the true grade and the results of MS and LRI grading respectively. In Fig. 1, three LRIs are shown which fulfil the above criteria, one of each grade, US, fifth and sixth.

An LRI is a grey-scale image representing density variations inside a log (Fig. 1). An LRI can be obtained either by feeding a log continuously through the gap between an X-ray source and a detector (Fig. 2), both fixed in position, or, as in this study, by being simulated out of a stack of CT images. In the simulation case the log was represented by a stack of CT images captured by a medical CT scanner (Siemens Somatom AR.T.).

The simulated signals that build up the LRI were calculated from the attenuation of the X-ray beam when it passes through the log (Fig. 2) using the formula:

\[ I = \int_{E_1}^{E_2} I_0(E) \exp(-\mu(E)d) \, dE \]

where \( I \) = intensity of transmitted X-ray beam; \( I_0 \) = intensity of incident X-ray beam; \( E_1 \) and \( E_2 \) are the lower and upper photon energy limits for the X-ray tube; \( \mu \) = linear attenuation coefficient; and \( d \) = thickness of the object at the position where the beam passes through the object. The linear attenuation coefficient for wood has a high correlation with the density of wood (Lindgren 1991). Thus the CT images of a log can be used for these simulations, as the CT images are a chart of the density of the log. The simulated LRIs (Fig. 1) consisted of one row of pixels for every 10 mm of the log length, which is the same as one row for every CT image. The lateral resolution was 128 pixels. The grey-scale resolution of the original signal was 4096 levels. This resolution was reduced to 256 levels in the image shown (Fig. 1).

The LRIs were presented to the respondents as paper printouts with a resolution of 53 halftone dots per inch. The size of each image was 65 by 210 to 260 mm depending on the original length of each log. To improve the possibility of separating the knots in a whorl from each other, the logs in the image were tilted 20° away from the vertical axis, towards the observer.

The true grade of a log was considered to be equal to the grade of the two centre planks from the log. These grading results were obtained from the test sawing and plank grading in accordance with the Green Book in the Swedish Stem Bank project. Results, calculations and comparisons were expressed in terms of the percentage of correspondence to the true log grade of both methods.
Table 1. Comparison between true log grade and predicted log grade by the LRI and MS log grading methods separately.

Number of observations for different combinations of true log grade and predicted log grade

<table>
<thead>
<tr>
<th>True log grade</th>
<th>Predicted log grade</th>
<th>LRI method</th>
<th>MS method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US</td>
<td>Fifth</td>
<td>Sixth</td>
</tr>
<tr>
<td>US</td>
<td>193</td>
<td>51</td>
<td>1</td>
</tr>
<tr>
<td>Fifth</td>
<td>30</td>
<td>157</td>
<td>23</td>
</tr>
<tr>
<td>Sixth</td>
<td>2</td>
<td>48</td>
<td>195</td>
</tr>
<tr>
<td>n</td>
<td>225</td>
<td>256</td>
<td>219</td>
</tr>
</tbody>
</table>

Tests and comparisons were made at a significance level of 0.05 and the grading of the centre planks from one log was regarded as one observation in this study.

The grading results were expressed and analysed from two aspects. First, the ability to predict true grades—for example, if there were 100 observations of the true grade US and the LRI method classified 79 of them as US, the correspondence would be 79%—and secondly, true grades among equally graded. For example, if there were 100 observations graded as US by the LRI method, and 86 of them were true US, the resulting correspondence would be 86%.

In order to improve the reliability of the statistics of the MS method, the test set was enlarged to 120 logs, the 20 logs of the LRI test included. The statistics of those logs were taken from the Stem Bank and fulfilled the two log sampling criteria mentioned above. The logs were graded by two skilled log graders, M1 and M2, according to the guiding principles of the MS method as described in the Swedish Wood Measurement Law (Anon. 1987). This gave a total of 240 observations to be compared with the 700 of the LRI method. These graders did not participate in the LRI interview.

RESULTS

The distribution of the grading results, in terms of number of observations, is presented in Table 1 for both the LRI method and the MS method. The Table shows both the aspect of ability to predict true grades and the aspect of true grades among equally graded.

It is notable that the two extreme grades, US and sixth, very seldom were mixed up with each other.

In terms of ability to predict true grades, LRI grading gave correct grading results in 78% of the 700 observations made. A confidence interval of 95% shows that the true mean value of correspondence was in the interval 74% to 81% (Table 2). The corresponding mean result of the MS grading method was 68%, which was significantly less than the results from the LRI method (Table 3). For the US and sixth grade, the LRI method showed a higher percentage of correct log grade predictions than the MS method. For the fifth grade the MS method showed a better ability to predict true log grades (Tables 2, 3).

In the category “true grades among equally graded”, the LRI method gave a total mean result of 80% correctly graded logs (Table 2). The confidence interval (95%), gives a true mean value of correspondence between 77% and 84%. The corresponding mean value of the MS method was 76%. For the fifth and sixth grades the LRI method showed better log grade prediction than the MS method. In the case of grading US the opposite was true; the MS method gave a better prediction (Tables 2, 3).

It should be noted that the fluctuation in value of correct predictions between the three grades was considerably lower for the LRI method than for MS
Table 3. Log grade predictability (%) for the MS graders (MS1 and MS2), n = 120

<table>
<thead>
<tr>
<th>True log grade</th>
<th>No. logs</th>
<th>MS1</th>
<th>MS2</th>
<th>Mean</th>
<th>MS1</th>
<th>MS2</th>
<th>Mean</th>
<th>No. obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>55</td>
<td>62</td>
<td>60</td>
<td>61</td>
<td>97</td>
<td>92</td>
<td>94</td>
<td>71</td>
</tr>
<tr>
<td>Fifth</td>
<td>45</td>
<td>89</td>
<td>93</td>
<td>91</td>
<td>56</td>
<td>54</td>
<td>55</td>
<td>148</td>
</tr>
<tr>
<td>Sixth</td>
<td>20</td>
<td>35</td>
<td>30</td>
<td>32</td>
<td>50</td>
<td>86</td>
<td>68</td>
<td>21</td>
</tr>
<tr>
<td>Mean corr.</td>
<td></td>
<td>68</td>
<td>68</td>
<td>68</td>
<td>74</td>
<td>77</td>
<td>75</td>
<td></td>
</tr>
</tbody>
</table>

grading. It was most pronounced for the prediction of true grades but it can also be seen in the category of true grades among equally graded.

No significant differences could be found in either of the two categories (p < 0.05; Tukey's method of paired comparison procedure; Box et al. (1978)) in the results of LRI log grading by the three professions, sawyers, sawmill graders and scientists, in the result of all grades together or for each grade separately. In Fig. 4, the confidence intervals of the mean are shown for each profession and grade. It was observed that each respondent was able to predict the true grade, expressed in percentage of correct predictions per grade.

A Student's t-test, at the 95% level, was made in order to check for irregularities in the statistics of the MS grading results between the 20 logs included in the LRI test and the complementary 100 logs added to the MS results. This test showed that significant differences could not be found in grading results between the original 20 logs and the complementary 100 logs, either for all the grades together or for any separate grade (Table 4).

**DISCUSSION**

The results of this study reveal that the LRI method can reliably predict log grade and can be potentially profitable for the sawmill industry. Despite the fact that the respondents were totally inexperienced in log grading by LRIs, a high level of correct predictions was achieved. The LRI log grading method showed no significant differences between any of the three professions among the respondents. This leads to the conclusion that a great deal of the information needed to predict the log grade can be seen in the structure of the overall features in an LRI of the log.

Both the LRI and the MS grading tests were carried out without any time constraints. The MS graders also had full access to the MS grading results.
Table 4. Differences in grading results, and tests for significant differences, between the 20 original LRI test-set logs and the 100 logs added to the test set for the MS method

Expressed in correspondence (%) between the MS grading results and the true log grade. No significant differences, a = 5%, could be found either for any separate grade or for the total predicted grade.

<table>
<thead>
<tr>
<th>True log grade</th>
<th>Corr., %</th>
<th>No. obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Original logs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Fifth</td>
<td>92</td>
<td>12</td>
</tr>
<tr>
<td>Sixth</td>
<td>36</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>62</td>
<td>40</td>
</tr>
<tr>
<td>100 Complementary logs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>59</td>
<td>98</td>
</tr>
<tr>
<td>Fifth</td>
<td>91</td>
<td>76</td>
</tr>
<tr>
<td>Sixth</td>
<td>31</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td>68</td>
<td>200</td>
</tr>
</tbody>
</table>

manual. It is thereby possible to assume that the two MS graders’ results are at least as good a normal MS grading. As a result of these assumptions it is possible to compare the MS graders’ mean, per grade, to the 95% confidence intervals of the LRI method. If this is done the results clearly show a difference between the two methods. The mean values of the MS method are not included in the calculated confidence intervals of the total mean for the LRI method’s grading results (Tables 2, 3). Thus, the LRI method is at least as good as the MS method for predicting the true log grade, and in many respects even better.

The LRI method showed considerably less deviation between the three separate grades and was more successful in predicting the final grade of USs and sixths compared with the MS method (Tables 2, 3). This gives the sawmill the possibility to produce centre planks of grades US and sixth in dimensions specified by the customer without the risk of ending up with a large unsaleable stock-in-trade of centre planks of odd combinations of dimensions and grades.

The MS method showed the opposite pattern. The amount of fifth grades was greatly overestimated, thus making it difficult to find logs giving centre planks of US and sixth grade since many of them were classified as fifths. This can be seen by studying the group of true sixths, where almost two-thirds of them were graded as fifths (Table 1).

Since the LRI log grading method has not yet been totally developed, it seems reasonable to assume that there will be improvements in the accuracy of the LRI log grading method. No such improvements can be expected in the MS method since the test results were obtained under the best possible conditions. The MS graders were experienced and had no time limits during the test grading.

These findings and conclusions were, however, based on results from a study which was a simplification of reality, as the two centre planks in each log were of unambiguous grade. Under normal manual grading conditions the amount of logs with features in-between two grades will increase. This is a problem in all grading procedures, the LRI method being no exception. Further studies are necessary in order to determine how these in-betweens will affect the level of accuracy and the potential of the LRI method as a profitable pregrading technique.

ACKNOWLEDGEMENTS

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Grundberg, S. & Grönlund, A. 1997. Simulated grading of logs with an X-ray logscanner-grading accuracy...

It is possible today to detect the internal structure of a log by using X-ray scanning technology. By visual inspection of a longitudinal radiograph image (LRI) of a log, it is possible to manually predict the coming grade of the centre planks. The objective of this study was to identify the features of Scots pine logs visible in the LRIs that were of importance in a manual grading process. The identification of useful features was determined by a survey among respondents connected to the wood and sawmill industry. The test logs originate from the Swedish stem bank and the evaluation of the results was based on the statistical method of partial least square regression (PLS). This study shows that useful indicators of the true grade of the centre planks were the knots and knot-related features as well as the butt swell and the heart wood fraction of the log.

Introduction

It would be an economical advantage for the sawmilling industry of today if the inner structure of a log were exactly known in terms of type, degree and location of internal defects. It would make it possible to adapt the best possible sawing pattern to the features of each specific log and furthermore prevent logs of too low quality from being sawn. To fully achieve this improvement in the utilization of the raw material, the internal as well as the external features of the logs must be revealed and appraised (Blomqvist and Orke 1986). It has been shown by Johansson and Liljeblad (1988) that the value of the sawn timber could be increased by about 10% if the positions of internal defects were known. It is further possible to achieve financial benefits if logs of a quality that is not suitable for the planned production can be eliminated from the production process. By so doing, production capacity could be released for more profitable production and the total value of the sawn timber could be increased by more than 10%.

By using X-ray scanning technology, it is now possible to detect the internal structure of a log (Grundberg 1994). This information can be analysed automatically or, as in this study, manually by looking at a longitudinal radiograph image (LRI) of a log (Fig. 1). It has been shown that it is possible by manual analysis of an LRI to predict the quality of the sawn timber with an accuracy of 74% to 81% (95% confidence interval of mean) (Ohman 1997).

The objective of this study was to identify which of the log features visible in the LRI could be used as indicators of the final quality of the sawn timber. This information could be of importance in improving prediction algorithms for both manual and automatic analysis.

Materials and methods

2.1 Materials

All material and data in the study, except for the LRI-based interview results, were taken from The Swedish Stem Bank (Grundberg et al. 1994). The Swedish Stem Bank is a database containing information, such as silvicultural data, manually estimated log grades, computer tomography images (CT), test sawing results, grading results of sawn timber and scanned images of the centre planks of 200 Scots pine (Pinus sylvestris L.) trees.

2.2 LRI

An LRI is a grey-scale image representing density variations inside a log (Fig. 1). An LRI can be obtained either by feeding a log continuously through the gap between an...
X-ray source and a detector (Fig. 1) both fixed in position or, as in this study, by being simulated out of a stack of CT-images. In the simulation case, the log was represented by a stack of CT-images captured by a medical CT-scanner (Siemens Somatom AR.T.).

The simulated signals that build up the LRI were calculated from the attenuation of the X-ray beam as it was passing through the log (Fig. 1) using the formula:

\[ I = \int_{E_1}^{E_2} I_0(E) \exp(-\mu(E)d) \, dE \]

where \( I \) = intensity of transmitted X-ray beam; \( I_0 \) = intensity of incident X-ray beam; \( E_1 \) and \( E_2 \) are the lower and upper photon energy limits for the X-ray tube; \( \mu \) = linear attenuation coefficient; \( d \) = thickness of the object at the position where the beam passes through the object. The linear attenuation coefficient for wood has a high correlation with the density of wood (Lindgren 1991). Thus the CT-images of a log can be used for these simulations, as the CT-images are a chart of the density of the log. The simulated LRI's (Fig. 2) consisted of one row of pixels for every 10 mm of the log length which is the same as one row for every CT-image. The lateral resolution was 128 pixels. The grey-scale resolution of the original signal was 4096 levels. This resolution was reduced to 256 levels in the image shown (Fig. 2).

The LRI's were presented to the respondents as paper printouts with a resolution of 53 halftone dots per inch. The size of each image was 65 by 120 to 260 mm depending on the original length of each log. To improve the possibility of separating the knots in a whorl from each other the logs in the image were tilted 20° away from the vertical axis, towards the observer.

2.3 Interviews

Interviews were carried out to identify which of ten log features visible in an LRI could be used as indicators of the true centre plank grade. This was done by showing LRI's of 20 logs in random order to each of 30 respondents, giving a total of 600 observations of each feature. The distribution of the logs' centre plank grades was 7 of grades US and VI respectively and 6 were of grade V according to the Guiding Principles for Grading of Swedish Sawn Timber (Green Book) (Anon. 1982). The Green Book is a manual, widely used throughout the European market, showing allowed size, number and appearance of defects visible in sawn timber. The sawn timber are divided into different grades according to the defects present, where the acceptance of defects is lowest for the US grade, moderate for the V grade and highest for the VI grade.

The respondents came from four different professions; 15 were sawmill graders, 9 were sawyers, 4 wood scientists and 2 inspectors from the Timber Measurement Councils. The wood scientists were personnel from the Division of Wood Technology at the Luleå University of Technology while the others were from different commercial sawmills.

The data in this study are based on manual judgements measured by a descriptive test were each respondent expressed his opinion about each feature's appearance in the LRI of each log. The opinions about the log features were subsequently connected to the observed centre plank grades US, V and VI expressing good, moderate and bad quality respectively. For each log a total of ten different features was examined. The respondents were asked to put a mark on a scaled line between two opposite concepts. The opposite concepts and the position of the mark described the respondents' impressions of the feature impact (Fig. 3).

2.4 True grade

The true grade of the log was considered to be equal to the grade of the two centre planks from the log. These grading results were obtained from the test sawing and plank grading according to the Green Book.

To ensure that the logs showed the typical features for each specific class, two sawmill graders had to classify
The heart wood fraction of the log are?

small  X  large

2.5 Variables

The variables were designed to express the total mean impression of the whole log. Single defects which affect the plank’s final grade were not taken into consideration by this test. The ten variables expressing the overall features of a log’s appearance in an LRI were:

- A. Whorl distance, the variation of the distance between the whorls.
- B. Knot angle, mean fluctuation in the bearing of the knot’s angle.
- C. Knot size, mean size of the knots over the length of the log.
- D. Whorl knot size, mean fluctuation of the knot size in the whorls.
- E. Heartwood fr, fraction of heartwood in the log.
- F. Heartwood irr, magnitude of the diameter irregularity of the heartwood cylinder.
- G. Diameter irr, magnitude of the diameter irregularity of the log mantle.
- H. Log sweep, magnitude of.
- I. Log taper, magnitude of.
- J. Butt swell, magnitude of.

The impressions of the features were then translated to a numerical form by dividing the length of the scale line into 14 sections. The number of the section where the mark was located was then used as the measured value in the subsequent statistical analyses.

2.6 Analysis

Partial least square regression (PLS) has been used to identify the features which can be used as indicators of the final grade of the centre plank. PLS is a method which is based on the assumption that the x-variables are correlated, that there is noise in the data and that there can be structures in the residuals (Lindgren 1994). Because of these assumptions, PLS was a well suited tool to adapt to the features of this study, in consideration of bias in manual judgements and possibilities of correlated features. The PLS analysis was carried out by aid of the software SIMCA-S (Anon. 1996).

In a PLS model the covariance between the features (x-variables) is maximised to the linear combination of one, or many, y-variables (Marten and Naes 1989a). In this study three y-variables were used. Each y-variable separates logs of one grade class from the other two. By using three y-variables the PLS model generates the probability for the logs belonging to each one of the specific grades. The class, y-variable, showing the largest probability of the three was then chosen as the predicted grade of the log.

The analysis of the model was done in two steps. First, the features of importance for explaining the variance in the data set were identified with regard to four parameters. They were \( R^2_p \), \( R^2_X \), \( Q^2 \) and VIP. The coefficient of determination, \( R^2_p \), represents the proportion of the variation in the present set of y-values that is explained by the model (Mendenhall and Sincich 1992). \( R^2_X \) is the corresponding proportion of the variation in the present set of x-values explained by the model. However, \( R^2_p \) does not warn if the model explains random relations, model overfitting or the true relations between x- and y-variables.

An alternative is to use cross validation (Marten and Naes 1989b). When cross-validating, N models are built, each time excluding an Nth part of the observations and thereby creating a training set. Each model is then tested on the excluded observations (the test set). The software SIMCA-S expresses the result of the cross validation as \( Q^2 \), which is a measure of the model’s ability to predict future observations, i.e. observations which were not included in the model, and represent the proportion of the variation of y-values in the test sets that is explained by the model.

A model which explains random variations in the training set will fail when tested with new observations and hence \( Q^2 \) will be low for such a model (Marten and Naes 1989b). Consequently a model showing significantly higher \( R^2_X \) than \( Q^2 \) indicates modelling of random variation in the data, i.e. noise, while equal values describe true relations between the x- and y-variables.

VIP, variable importance, is another term used by the software SIMCA-S and expresses the sum over all model dimensions of the variable influence (VIN) contributions. For a given PLS dimension, \( a \), \( (VIN)^2_a \) is equal to the squared PLS weight \( w_{ak}^2 \) of that term, multiplied by the percent of the residual sum of squares (SS) explained by that PLS dimension. If A is the number of PLS-dimensions and \( p \) is the number of features (x-variables) then the accumulated test quantity (overall PLS-dimension) is divided by the total percent of SS explained by the PLS model and multiplied by the number of terms in the model.

\[
[k = 1, 2, \ldots, p, a = 1, 2, \ldots, A]
\]

The squared sum of all VIP’s is equal to the number of x-terms in the model due to the centering and scaling effect. The larger the VIP-value, the better the x-variable contributes to the explanation of the variation of the y-variables (SIMCA-S, 1996).

By using back propagation in finding the best PLS model, features showing low VIP-values were eliminated one by one, until the \( Q^2 \) value was as high as possible and still showing an acceptable small difference from the \( R^2_X \) value. The remaining features in the PLS model were then regarded as important indicators of the centre-plank grades.

The second step was to identify each important feature’s ability to separate specific grades from each other by
studying the difference between each feature's regression coefficients in the calculation of probability of the log's belonging to each specific grade. A large difference indicates large difference in the specific feature's appearance in the two compared grades and vice versa. For example, for the ability to separate logs of the grade US from grade VI, Butt swell (J) shows a regression coefficient of 0.354 in the calculation of probability to belong to the US grade. The corresponding coefficient for the VI grade is 0.128, which gives a difference of 0.48 (Table 3).

3 Results

Best predictability was found for a model containing eight of the ten tested features. Feature H, Log sweep and I, Log taper showed no ability to explain the variation in the data set. Of the remaining 8 features, Knot angle (B) is the most important, followed by Diameterr ir. (G), Butt swell (J), Knot size (C), Whorl knot size (D), Whorl distance (A), Heart wood ir. (F) and Heart wood fr. (E). The difference in VIP-values between the features was nevertheless small. For example, the value for Knot angle is only 1.57 times larger than the value for Heart wood fr. (Table 1).

The model explained a fraction, $Q^2 = 0.378$, of the total variation of $y$, which can be regarded as rather weak. In a strong model $Q^2$ should exceed 0.5. The coefficient of determination of the $y$-variables, $R^2_{y}$, is equal to 0.42 and the corresponding value of $R^2_x$ is 0.58. The small difference between $Q^2$ and $R^2_x$ indicates that the risk of an overfitted model can be regarded as low.

The model's ability to correctly predict the true grades included in the test set can be seen in Table 2. Altogether, 76% of the logs were correctly classified. The agreement between the predicted and true grade of the logs was 88% for the US's, 44% for the V's and 92% for the VI's. In Table 2 the total distribution of predicted grades is shown. Notable is that the confusion between US and VI was of a low rate, 2% of the true VI's were predicted as US and 3% of the US's were predicted as VI, while the grade prediction of V's was more often incorrect.

Table 1. Regression coefficients of each feature in the calculations of probability of belonging to each separate class, and each features cumulative variable influence (VIP)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VIP (cum)</td>
</tr>
<tr>
<td>Knot angle</td>
<td>1.143</td>
</tr>
<tr>
<td>Diameter ir.</td>
<td>1.099</td>
</tr>
<tr>
<td>Butt swell</td>
<td>1.083</td>
</tr>
<tr>
<td>Knot size</td>
<td>1.015</td>
</tr>
<tr>
<td>Whorl knot size</td>
<td>1.015</td>
</tr>
<tr>
<td>Whorl distance</td>
<td>0.922</td>
</tr>
<tr>
<td>Heartwood ir.</td>
<td>0.884</td>
</tr>
<tr>
<td>Heartwood fr.</td>
<td>0.728</td>
</tr>
</tbody>
</table>

In Table 3 it can be noted that the features separate the logs of different grades differently to some extent. Most important to separating logs of the grades US and V were Butt swell (J) and Heart wood fr. (E) and to some extent Butt swell (J) and Heart wood fr. (E), contribute almost equally to the separation of V's and VI's. Finally, all features were used to separate US's from VI's where Butt swell (J) contributed most to the separation of the logs.

4 Discussion and conclusions

This study shows that knowledge of a log's inner structure as revealed in an LRI provides enough information to separate logs into three different classes which correspond to centre planks of quality US, V and VI in accordance with the Green book (Anon. 1982). Especially the separation of US from VI showed a low rate of confusion, less than 5%.

Of the tested features visible in an LRI of a log, 8 showed qualities that contributed to the separation of logs, by a prediction model, into three classes. It is possible to predict the observed quality of the centre planks with a total accuracy of circa 75%. This is on a level which agrees well with a study of the possibility to manually predict the lumber quality by using LRIs (74% to 81% by a 95% confidence interval of mean) (Öhman 1997). Both studies

Table 2. The distribution of the predicted quality by the PLS model in percent of observed quality and number of observations

<table>
<thead>
<tr>
<th>Observed quality</th>
<th>Predicted quality class</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>V</td>
</tr>
<tr>
<td>88%</td>
<td>8%</td>
</tr>
<tr>
<td>34%</td>
<td>44%</td>
</tr>
<tr>
<td>2%</td>
<td>6%</td>
</tr>
<tr>
<td>n (true)</td>
<td></td>
</tr>
<tr>
<td>249</td>
<td>108</td>
</tr>
</tbody>
</table>

Table 3. Differences between the regression coefficients of each feature which indicate how important the feature is to separate two specific grades apart

<table>
<thead>
<tr>
<th>Feature</th>
<th>Differences in regression coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(US-V)</td>
</tr>
<tr>
<td>Knot angle</td>
<td>0.02</td>
</tr>
<tr>
<td>Diameter ir.</td>
<td>-0.01</td>
</tr>
<tr>
<td>Butt swell</td>
<td>-0.59</td>
</tr>
<tr>
<td>Knot size</td>
<td>-0.13</td>
</tr>
<tr>
<td>Whorl knot size</td>
<td>0.03</td>
</tr>
<tr>
<td>Whorl distance</td>
<td>-0.01</td>
</tr>
<tr>
<td>Heartwood ir.</td>
<td>0.05</td>
</tr>
<tr>
<td>Heartwood fr.</td>
<td>-0.35</td>
</tr>
</tbody>
</table>
were based on the same set of logs. Further comparisons, quality by quality, showed that the prediction model gave up to 19 percentage points higher accuracy in prediction of US's and VI's than the manual estimation. The predictability of the V's by the predicting model, however, showed a large confusion with the other two classes, the grading accuracy was only 44% compared to the manual estimations 75%.

The differences between the two studies indicate that the accuracy of the manual estimation method could be improved by training in interpreting the 8 features found to be of importance in the prediction model of this study to identify true US's and VT's. Moreover the results indicates that the 10 studied features were not capable to entirely describe the differences between true V's from the other two grades as well as the manual estimation did. Some improvements can be done by describing and measure the 8 studied features more precisely. But to reach the accuracy of the manual estimation of 75%, it seems necessary to find new features capturing more information from the LRI than the prediction model based on 8 features did. These new features are not only a matter of finding ways of measuring sizes and distances, but also features describing order and harmony of the log structure, visible in the LRI, appear to be very important. The latter could be a matter of measuring and expressing continuous changes over the length as well as local disturbances.

However, the data used in this study were affected by a human related bias caused by a lack of training in interpreting the structures of the features. If this bias could be reduced by measuring the features automatically or by training of the respondents' ability to interpret the features, it would cause some changes in the proportions between the regression coefficients. The strength of the model would increase and might thereby result in improved prediction accuracy.

These results were based on a small number of logs, not covering the whole range of natural variations in a log's appearance. However, the way the test logs were chosen guaranteed that they were typical of each class. In consideration of this, the 8 features in an LRI of a log identified as important indicators of the resulting quality of the sawn timber should be of importance in the prediction of any log. Although the correct proportion between the correlation coefficients is not yet identified, at least it is possible to achieve a good separation between the US and VI class.

References
Johansson LG, Liljeblad A (1988) Some Applications within the Project “Quality Simulation of Sawn Logs” Trätek rapport I 8806050, ISSN 02834654 (In Swedish)
Correspondences between manually estimated compression wood in Norway spruce and the warp of the sawn timber

M. Öhman

Compression wood is regarded as a serious defect which affects the warp and machinability of sawn timber. To handle these problems, different regulations have been developed regarding grading of sawlogs and of sawn timber. This study is an attempt to clarify the relation between the amount of visible compression wood in Norway spruce (Picea abies L.) and the warping of the sawn timber in terms of bow, spring and twist as well as further deformation after ripping of the dried products. The amount of compression wood was defined and measured on logs according to the methods of the Swedish Timber Measurement Council (Regulations for measuring of round wood) and on the sawn timber according to the Nordic Timber. The impact of two different drying schedules was also investigated. The study shows that visible compression wood in both the butt end of the log and within the sawn timber was a rather poor indicator of the warp of the dried sawn timber. In no comparison did the correlation coefficient, r, exceed 0.3. In contrast to this, the correlation between the amount of compression wood and the warp of secondary products was fair, r = 0.79. This means that it should be possible to identify sawn timber less suitable for secondary processing by the amount of compression wood. The corresponding correlation between compression wood in both the butt end of the log and the warp of the secondary products was r = 0.46. No significant differences could be shown in the degree of warp, as related to compression wood, between sawn timber or secondary products, dried at a wet-bulb temperature of 55 °C/117 h, LT-schedule, and a dry-bulb temperature of 110 °C/24 h, HT-schedule, respectively.

Zusammenhang zwischen visuell geschätztem Druckholzanteil und Verwerfung nach dem Trocknen von Fichtenholz


Introduction

Compression wood in Norway spruce has been considered the cause of considerable problems during processing at the sawmill as well as in sawn timber. As a response to these problems, rules and regulations have been developed for sawn timber in the Scandinavian countries. By the definition of the Nordic Timber the compression wood is disregarded if it is less than one third of the width of the annual ring, and if the compression wood is judged not to affect the straightness of the sawn product. Overall, the amount of compression wood is divided into four tolerance levels, one for each of four grades. (Anon 1997a).

Corresponding rules have also been developed by the Swedish Timber Measurement Council (Regulations for measuring of round wood) to be used in quality grading of sawlogs. In this case, it is a matter of the allowable amount of visible dense compression wood in the butt end of the log. Compression wood is regarded as dense if it exceeds half the width of an annual ring and the assessment of each single log should result in a grade that corresponds to a specific area of use of the sawn timber (Anon 1997b).

The problems are mainly related to a greater longitudinal shrinkage than in normal wood. Schulz and Bellman (1982) have found that the longitudinal swelling of compression wood was up to 10 times greater than normal wood in Norway spruce. The amount of longitudinal shrinkage of compression wood has been shown to be

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positively correlated to changes in the thickness of the tracheid wall and microfibril angle within the S2 layer of the wall. In compression wood the microfibril angle is considerably higher than in normal wood, with the consequence that longitudinal shrinkage is greater as well (Wloch 1975; Boyd 1977; Harris 1977; Schulz and Bellman 1982; Schulz et al. 1984).

Beard et al. (1993) have shown that the fraction of compression wood in Southern Pine timber shows a low explained variation in warp. Pillow et al. (1937) and Du Toit (1963) have shown that the position of the compression wood within the sawn timber greatly affects the degree of warp.

Several studies have shown that the warp on the sawn timber can be related to the drying temperature and to applied top-load restraint. Morén and Sehlstedt-Persson (1990) have shown that the warp of sawn timber of Norway spruce can be reduced by applying a top-load restraint during high temperature drying. A study of the effect of kiln schedule on warp in Douglas fir shows that differences in drying temperature, 114 °C and 140 °C, do not affect the degree of warp if top-loaded during the drying process (Milota 1992). A study by Arganbright et al. (1978) showed that a top load reduces warp in Ponderosa pine when air dried, dried by conventional schedule at a wet-bulb temperature of 47–60 °C and by high temperature schedule at 100-110 °C. None of these studies were designed to study the relation between compression wood and the warp of the sawn timber or how the drying conditions affect the results.

Compression wood is a wood property which is hard to identify and estimate visually; it varies over a wide range from very mild to very dense, as well as in distribution from parts of one annual ring to many annual rings in a tree. Consequently, it becomes difficult to consider all these variations in practise under ordinary manual grading conditions. In addition, the effect of compression wood in terms of warp of the sawn timber might be affected by the drying process. To evaluate the accuracy of the visually based methods for grade sorting, according to amount of compression wood, this study had three objectives:

- To examine the correspondence between the manual estimation of compression wood on sawlogs and the manual estimation of compression wood on sawn timber.
- To investigate the relationships between the estimated amount of compression wood and the warp of the dried sawn timber and secondary products.
- To study whether the drying conditions affect the straightness of planks and secondary products containing varying amounts of compression wood.

2 Materials and methods
This study is based on Norway spruce (Picea abies L.) butt logs from four different locations in northern Sweden. A total of 200 butt logs were selected, 160 of them showing varying fractions of dense compression wood in the butt end and 40 logs were free from visible compression wood as well as showing good quality in other respects. The sawlogs were selected and examined according to the Swedish Timber Measurement Council’s Regulations for measuring of round wood (Anon 1997b) by two of their inspectors.

These inspectors marked the areas of dense compression wood in the butt end of the logs. The butt ends of the logs were photographed and the amount of compression wood was then measured with the aid of image processing and expressed as a fraction of the butt end area, CW-log, (Fig. 1).

The selected saw logs were divided into equal groups for the purpose of studying the influence of drying schedules on the degree of warp of the sawn timber.

All logs were cant-sawn, and the results based only on the two centre planks with the dimensions 50 × 125 mm. Half of the centre planks were dried by a conventional air drying schedule at a wet-bulb temperature of 55 °C, LT-schedule (Fig. 2). The other half were dried in a 3-step process. First the planks were preheated with saturated steam until a wet-bulb temperature of close to 100° was reached. Then the planks were dried at a dry-bulb temperature of 110°. Finally, when the planks had cooled to
The high temperature drying schedule. T-dry is the dry-bulb temperature and T-wet is the wet-bulb temperature. A is the pre-heating phase, B is the drying phase, C is the cooling phase of the timber and D is the conditioning phase.

Two professional graders estimated the volume of an imagined box that encloses the compression wood in accordance to the definitions of the grading rules of Nordic Timber (1997a). They also estimated the percentage of compression wood of an imagined box within the plank.

The study of the relation between compression wood and the warp of secondary products was based on 152 centre planks, from 76 logs, stored outdoors under cover for 10 to 12 months. The 152 test planks were chosen to be a representative selection from each of the 4 geographical locations according to the amount of compression wood, warping of the planks and drying methods. Each plank was ripsawn into two battens of the dimensions 50 x 50 mm after removal of a 25 mm thick pit catcher. The warp arising during the ripsawing was defined as the largest measured span, in mm, between the two battens (Fig. 5).

All observations of compression wood in the planks were expressed as the sum of the compression wood in the two centre yield planks from the same log. This was done to simplify the comparison between the log parameter CW-log and the variables related to the centre planks. The relation between compression wood and the warp of the sawn products was evaluated by conventional statistical methods, such as linear regression analysis and unpaired significant tests at the 0.05 level by the Tukey-Kramer method for differences in group means (Box et al. 1978).

3 Results
In Table 1 the results from the linear regression analyses on the single log level are shown. The correspondence between the manual estimation of the amount of compression wood on the sawlogs, CW-log, and the estimation of compression wood in the planks, CW-plank, is rather weak: $r = 0.57$.

Table 1 also shows that the correlations between CW-log and CW-plank and the three different warp parameters, Twist, Spring and Bow, are generally very low.

If both CW-plank and PlankSpan are expressed as the sum of the two centre yield planks from each compared log, a correlation of 0.79 can be shown.

Fig. 3. The pattern of the ripsawn plank, and methods for measuring the warp of the battens.

Bild 5. Einschnittmuster und Bestimmen der Verwerfung der Kanten.

$X_{ij}$ ($X_i / X_j$). There were a total of 8 batches of 50 planks each.

$X_{ij}$ ($X_i / X_j$). There were a total of 8 batches of 50 planks each.
Table 1. Results from linear regression analyses where (n), is the number of observations, (r), is the shown correlation, CW-log, is the visible fraction of dense compression wood in the butt end of the log, CW-plank, is the fraction of CW within the plank. PlankSpan is the sum of the warp arising as a result of the rip-sawing of the dried plank. Twist, Bow, Spring and CW-plank are expressed as total sum of the two centre yield planks with the exception of PlankSpan*, which are based on each plank individually.

Tabelle 1. Ergebnisse der linearen Regressionsanalysen; n = Anzahl der Beobachtungen; r = Korrelationskoefizient; CW-log = sichtbarer Anteil des Druckholzes (CW) am Stammende; CW-plank = Druckholzanteil im Brett; die verschiedenen Holzfehler sind als Gesamtsumme von zwei Mittelbrettern zur Be­rechnung verwendet worden, außer bei PlankSpan* wobei die Werte der einzelnen Bretter ausgewertet wurden.

<table>
<thead>
<tr>
<th>Compared variables</th>
<th>r</th>
<th>N</th>
<th>Signif. prob. correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW-log</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CW-plank</td>
<td>0.57</td>
<td>103</td>
<td>Yes</td>
</tr>
<tr>
<td>Bow</td>
<td>0.20</td>
<td>163</td>
<td>Yes</td>
</tr>
<tr>
<td>Twist</td>
<td>-0.06</td>
<td>160</td>
<td>No</td>
</tr>
<tr>
<td>Spring</td>
<td>0.18</td>
<td>161</td>
<td>Yes</td>
</tr>
<tr>
<td>PlankSpan</td>
<td>0.46</td>
<td>74</td>
<td>Yes</td>
</tr>
<tr>
<td>CW-plank*</td>
<td>0.60</td>
<td>79</td>
<td>Yes</td>
</tr>
</tbody>
</table>

In a corresponding comparison based on the value CW-plank and PlankSpan of each single plank, the correlation decreases to \( r = 0.60 \).

This comparison and all other comparisons including those for the CW-plank were only based on planks dried at a wet-bulb temperature of 55 °C. The planks dried at the temperature of 110 °C were discoloured, darkened to such an extent that the difference in colour between normal and compression wood became so low that it was impossible to manually identify areas of compression wood.

In Table 2 the observations are divided into 4 groups according to the fraction of compression wood in the butt end of the logs (CW-log): group A: <5%, B: 5% to <20%, C: 20% to <35% and D: >35%. Table 2 shows that planks from logs in groups A and B have significantly lower volumes of compression wood than planks from groups C and D, with 95% confidence intervals for means.

Table 2 also shows that the amount of compression wood has no influence on the twist of the planks, while spring and bow are clearly affected only if the logs show a large amount of compression wood, CW-log ≥ 35%. This can be seen in the mean values of the groups and in the standard deviation of the groups, where only minor differences could be seen between groups A, B and C while group D is considerably larger.

The correlation, on a single-log level, between CW-log and the warp of the battens is poor; \( r = 0.46 \) (Table 1).

While grouped at the 95% level, it is possible to show a significant difference in group mean value between logs with a high fraction of compression wood, CW-log ≥ 20%, and logs with CW-log ≤ 20% (Table 2).

Table 2. Comparisons based on observations grouped by the amount of CW-log, where the number of observations (n), Mean, Standard deviation, Median and possible Significant difference to the other groups are shown per group. In all comparisons, CW-log was grouped as A <5%, B 5% to <20%, C 20% to <35%, D >35% and CD*, >20%. All variables, except CW-log, are expressed as the sum of the log's two centre planks.

Tabelle 2. Vergleich verschiedener Gruppen anhand des Anteils an Druckholz (CW) mit n = Anzahl der Beobachtungen. Mittelwerte, Standardabweichung und mögliche signifikante Unterschiede zu den anderen Gruppen sind angegeben. Die CW-log-Gruppen sind: A <5%, B 5% to <20%, C 20% to <35%, D >35% und CD*, >20%. Alle Variablen beruhen auf der Summe aus den zwei Mittelbrettern eines Stammabschnitts.

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Mean</th>
<th>Std. dev.</th>
<th>Median</th>
<th>Sign. diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>A</td>
<td>45</td>
<td>0.84</td>
<td>0.58</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>41</td>
<td>0.85</td>
<td>0.52</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>49</td>
<td>0.79</td>
<td>0.74</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>34</td>
<td>1.37</td>
<td>1.64</td>
<td>0.78</td>
</tr>
<tr>
<td>Bow</td>
<td>A</td>
<td>45</td>
<td>1.15</td>
<td>0.69</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>43</td>
<td>1.15</td>
<td>0.46</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>49</td>
<td>1.17</td>
<td>0.74</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>34</td>
<td>1.90</td>
<td>2.19</td>
<td>1.06</td>
</tr>
<tr>
<td>Twist</td>
<td>A</td>
<td>45</td>
<td>1.49</td>
<td>1.30</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>42</td>
<td>1.27</td>
<td>0.80</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>49</td>
<td>1.65</td>
<td>1.05</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>32</td>
<td>1.16</td>
<td>0.94</td>
<td>0.88</td>
</tr>
<tr>
<td>CW-plank</td>
<td>A</td>
<td>27</td>
<td>4</td>
<td>4.6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>30</td>
<td>6</td>
<td>6.8</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>37</td>
<td>13</td>
<td>10.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>16</td>
<td>19</td>
<td>11.0</td>
<td>18</td>
</tr>
<tr>
<td>PlankSpan</td>
<td>A</td>
<td>29</td>
<td>13.7</td>
<td>8.6</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>21</td>
<td>21.5</td>
<td>22.3</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>CD*</td>
<td>24</td>
<td>38.8</td>
<td>33.3</td>
<td>23</td>
</tr>
</tbody>
</table>
No significant differences could be shown between the two drying schedules regarding either total warp of the dried planks or the warp of the battens. Comparisons were made with unpaired significant tests, 95% confidence intervals for means (Box et al. 1978).

4 Discussion
The results of this study show that compression wood expressed as CW-log is a rather poor indicator of the quality of the sawn products in terms of the degree of warp. Despite the significance of the correlation, the demonstrated correspondences between CW-log and the warp of the dried centre planks were not of such magnitude that a useful prediction of bow, twist or spring could be achieved. This agrees well with results found in other studies, (Forsberg 1997; Warensjö et al. 1998).

It is, however, possible to use the amount of CW-log as a rough indicator of both the risk of large amounts of warping of the secondary products (PlankSpan) and the risk of large amounts of compression wood within the plank (CW-plank). If logs with large amounts of compression wood, CW-log ≥ 20%, can be separated from those with moderate or no compression wood, fewer products will need to be rejected due to warp. The relation between warp and compression wood is more pronounced among secondary products than for dried sawn timber. However, to divide sawlogs into more than 2 grade classes according to the amount of compression wood cannot be justified due to the poor correlation shown between visible compression wood in the butt end of the log and the warp of the sawn products.

The results of this study show that the manually estimated fraction of compression wood on planks, CW-plank, is a poor indicator of the warp of the dried plank (Table 1). Consequently, it is not possible to use the fraction of compression wood, estimated on green sawn timber, in an attempt to predict the magnitude of the bow, spring or twist when dried. These results agree well with results found in other studies (Beard et al. 1993; Forsberg 1997).

Nevertheless, the amount of CW-plank clearly corresponds to the magnitude of the warp of the ripsawn battens (PlankSpan). The correspondence is fairly good, if the results of each log’s whole centre yield is regarded, between the sum of compression wood and the sum of warp of the battens (CW-plank & PlankSpan in Table 1). While the corresponding correlation on single planks is considerably lower (CW-plank & PlankSpan* in Table 1). In spite of relatively few observations of the former case, the tendency is still such that it is better to base a prediction of the warp of the battens upon the amount of compression wood within the whole centre yield than on single green planks.

In Fig. 6, it is possible to study the accuracy of trying to estimate the warp of the battens, PlankSpan, by the fraction of compression wood of each single plank. Notable is that the spread of observed warp among planks free from compression wood is of the same magnitude as planks containing up to 30% compression wood. Nordic Timber stipulates 4 levels of tolerances, 0%, 10%, 20% and 50% compression wood of the volume of the piece (Anon 1997a). If the intention of the compression wood tolerances is to agree with the warp of secondary products in general, it does not seem relevant, based on the information in Fig. 6, to use four levels of compression wood tolerance in the grading of sawn timber.

The shape of sawn timber is highly dependent on the magnitude and distribution of stresses acting within the same. High levels of stresses do not necessarily result in a large warp of the dried and sawn timber. For example, if the stresses are symmetrically distributed within the crosscut, no net stress (moment of force) arises and the plank will remain in shape. The origins of the stresses in wood are highly related to moisture content and the conditions during the drying process. Examples of properties that result in stresses are anisotropic shrinking properties in the tangential, radial and longitudinal direction of the annual ring of all types of wood. Furthermore, there are large differences in shrinking properties between different types of wood, e.g. juvenile, compression and normal wood. Finally, the stress levels and degree of warp are affected by preparation for and conditions during the drying process, such as how well the sawn timber is stacked and how restrained, by other planks in the stack or by external loads, each plank is from responding to stresses by warping.

A plausible explanation of why the amount of CW-plank alone fails to explain the magnitude of the warp of the dried sawn timber is that the location of the compression wood over the full length of a piece of wood must be taken into consideration before the degree and type of warp can be predicted, (Pillow et al. 1937; du Toit 1963). If the different types of wood are unevenly distributed within the crosscut of the sawn timber, the differences in shrinking properties give rise to a moment of force (torque) which will result in a warp of the plank. This torque is
dependent on the amount, density and distribution within the plank of compression wood and on the moisture content. If the warp is a response to a torque, this explains why the amount of compression wood alone cannot indicate the warp of the dried sawn timber.

That the correlation between the fraction of compression wood within the plank (CW-plank) and the warp of the battens is considerably stronger than between CW-plank and the warp of the planks could plausibly be explained by the change in geometry and the release of internal stresses.

5 Conclusions and future work

There was no proof found in this study that an increase of the wet-bulb temperature from 55 to 100 °C affects the longitudinal internal stresses related to compression wood and thereby the magnitude of the warp of the sawn timber and secondary products of Norway spruce. It can therefore be concluded that the internal stresses, caused by differences in shrinking properties between normal and compression wood, do not respond to the differences in drying conditions (high-temperature short drying time versus low-temperature long drying time).

The visible dense compression wood in the butt end is generally a poor indicator of the warp of the dried planks (r < 0.20), of the warp of the rip sawn battens (r = 0.46) and of the amount of compression wood within the planks (r = 0.57). The use of the amount of compression wood in the butt end of the log might still be useful in some applications. If logs showing high amounts of compression wood (>20%) can be separated from those with no or very little visible compression wood, then fewer products sawn from the latter category will need to be rejected due to warp, a relation which is more pronounced among secondary products than in sawn timber.

The manually estimated amount of compression wood within the sawn timber, CW-plank, must be regarded as a poor indicator of the warp of the dried sawn timber due to a rather poor correlation of r = 0.33. The possibility of using the estimated amount of compression wood within a single plank as an indicator of the warp of secondary products is limited due to a low correlation (r = 0.60). If the compression wood and the warp of the secondary products are expressed as the sum of the whole centre yield, the correlation increases to r = 0.79. Consequently, it seems more adequate to use the latter to indicate the dried sawn timber's suitability for refined secondary products.

Further studies are planned to investigate the relation between the warp of the sawn timber and the position of the compression wood on the four faces as well as within the sawn timber.

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Methods for Avoiding the Negative Effects of Compression Wood

By

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ABSTRACT

This is a study of how the selection of raw material and sawing methods affects the magnitude of bow, spring and twist as well as the yield of accepted wall studs when graded with respect to straightness. The focus was on the relation between compression wood in butt logs of Norway spruce (*Picea abies* (L.) Karst) and the straightness of wall studs, in order to improve the sawmills ability to satisfy the customer demands by straighter sawn products. The following aspects of compression wood in the production process were examined:

- How logs can be pregraded with respect to features related to compression wood: log sweep and visible compression wood in the butt end of the log.
- How green planks can be graded with respect to the amount of visible compression wood.
- The impact of when, before or after drying, a piece of wood finally is resawn into wall studs and how compression wood affects the outcome of the chosen method.
- How the symmetry of the resawing pattern affects the magnitude of warp.

A total of 90 logs with a top diameter of 19-21 cm were square sawn to centre planks of the dimensions 50 x 150 mm. One half of the logs were resawn to the final stud dimension before drying, while the other half were resawn after drying. Three different wall stud dimensions were sawn: 176 of the nominal dimensions 50 x 75 mm and 92 studs each of the dimensions 50 x 50 mm and 50 x 100 mm.

The results showed that the yield of accepted wall studs could be affected by the pregrading of sawlogs and planks. A measurable log sweep ≥ 1 cm is an indication of a decreased yield, and logs showing sweeps ≥ 4 cm should be avoided in the production of wall studs. Regarding compression wood visible on logs, smaller amounts up to approximately 40 cm² can be acceptable, while logs with amounts exceeding 100 cm² should be avoided. Still, high log quality (no measurable log sweep and very little visible compression wood) does not guarantee a high yield of accepted studs. Approximately one fifth of such logs can be expected to give a yield of ≤ 1 accepted wall stud out of 4 possible, as in this study.
In the grading of green planks the tendency is that the less compression wood visible, the higher the yield of accepted wall studs that can be expected. However, up to approximately 10% visible compression wood can be accepted without any tendency towards decreased yield, while amounts ≥ 33% show a considerable reduction in the yield of accepted studs.

As to sawing methods, the method of resawing dried planks into wall studs showed greater sensitivity to the amount of compression wood than did the method of resawing green planks. If a large amount of compression wood is present, the plank should be resawn to wall studs before drying. Planks with small amounts of compression wood, however, give a higher yield of accepted wall studs if they are resawn when dried.

It can be concluded that the symmetry of the resawing pattern does not affect the yield of accepted wall studs. No differences in magnitude of warp could be proven to exist between the three dimensions compared.
5 CONCLUSIONS

6 ACKNOWLEDGEMENTS

7 REFERENCES

APPENDICES A to D
1 INTRODUCTION

This study is an investigation of what sawmills can do to lower the risk of producing wall studs with excessive warp, foremost due to compression wood in butt logs of Norway spruce (*Picea abies* (L.) Karst). It is a matter of satisfying the customer by delivering a better product and of improving the quality of the sawmilling process by avoiding raw material that would result in large amounts of rejected products being sawn. In other words, this study investigates what can be done at the sawmill to establish a win-win concept: greater customer satisfaction and decreased costs for poor quality by avoiding products that do not meet customer tolerances.

1.1 The impetus for this study

This study is an investigation into the possibility of producing wall studs with lower magnitudes of warp by an adaptation of the grading of logs and planks and of resawing methods. The reason for doing this is the building trade’s increasing demands for improved quality and function of all components involved in the process of building. As in all other businesses, an overriding goal is to decrease the cost of production. One way of doing so is to do everything faster than before. The construction trade is no exception; here the competitive edge is the ability to build houses faster.

As a consequence, the work done at a construction site increasingly consists of the assembly of prefinished components. The old-time carpenter is on the way to becoming an assembler that has no time to choose and adapt an imperfect piece of wood to function acceptably as a stud in a wall. Today’s requirement is that the wall stud the assembler lays his hand on should fit without adjustment at the intended location and be so straight that the wall will be plane. Demands on function have thus increased, and one important function of studs is their degree of straightness (Johansson et al. 1994). Individual adjustment of studs in order to make a proper wall is no longer acceptable. The sawmill industry has not been able to fulfil the functional demands for straightness building constructors require at the prices they are prepared to pay. Consequently, wooden wall studs have been losing market shares, mainly to studs of steel. In order to not entirely lose this market, the sawmills must guarantee the functionality of the wall studs. This means meeting demands for straightness, correct dimensions, correct moisture content, correct length, timely delivery and not least prices the builder can’t resist. An effect of such guarantees will be an increase in the number of pieces of wood rejected for not meeting the demands for straightness of a wall stud. This will be costly in many respects; utilisation of the raw material as well as utilisation of capacity will be decreased. To put it briefly, the cost of poor quality will increase. Therefore sawmills should be interested in reducing the amount of studs rejected due to excessive warp. In this study, two aspects of such possible reductions were investigated. One aspect is the possibility of selecting raw material better suited to the demands placed on the final product, and the other is the
impact of different methods of sawing logs on efforts to minimise the warp of the studs.

1.2 Causes of warp

There are many reasons why a piece of wood becomes deformed. The origin of warp can both be found in anatomy of the wood as well as outer reasons like bad sawing equipment and drying routines. In the latter case, to few stickers, a not perfectly plane bedding for the drying packages in the kilns, too low loading weight during drying, moisture content of the dried product etc. Regarding warp explained by the anatomy of wood two major causes could be identified, direction of grain in relation to the sawn product and differences in shrinking/swelling properties between different types of wood or combinations of these two. Examples of features are: Juvenile wood, which shows a different, shrinking behaviour than normal wood. The knots, the larger the knot become the larger the risk of warp is, due to both disturbances in grain and presence of compression wood. A top-rupture is the most extreme case of a bad knot structure. Curly grain and spiral grain, which show a direction of the wooden cell, which is not parallel to the shape of the plank. However, there are two properties that are responsible for a very large part of the degradation: spiral grain and compression wood. Spiral grain, the angle between wood cells and the log’s longitudinal axis, correlates to the magnitude of twist in the sawn product: the greater the angle, the larger the twist (Tshaye & Walker 1995). One of the common causes of excessive bow and spring in Norway spruce is the occurrence of compression wood (Öhman 1998). Thus this study therefore focuses primarily on the impact of compression wood, and foremost compression wood not related to knots.

The differences in swelling and shrinking properties between normal and compression wood contribute to the occurrence of bow and/or spring. On the whole, though, the volume shrinkage in compression wood is less than or equal to that of normal wood. If the impact of specific gravity is eliminated, compression wood shrinks up to 2.5 times less than normal wood, a difference rather constant over a large number of coniferous species (Verall 1928, Perem 1960). However, the proportions between the longitudinal, radial and tangential shrinkage are different. Visible compression wood displays a considerably larger degree of longitudinal shrinkage or swelling than normal wood with the same change of moisture content and consequently smaller shrinkage in the other two directions. Studies done on Norway spruce showed a 5 to 11 times higher longitudinal shrinkage for compression wood than for normal wood (Rak 1957, Ollinmaa 1959). The large difference might be caused by differences in the severity of the compression wood. Boutelje (1966, 1972) showed a longitudinal shrinkage of 6% for compression wood taken from Norway spruce branches. Normal wood shows a normal longitudinal shrinkage of 0.1 to 0.3% for a moisture content change between fibre saturation and oven dry. Approximately the same rates are found for swelling. Studies have shown that compression wood in Norway spruce swells up to 10 times more than normal wood when remoisturized (Schultz and Bellman 1982; Schultz et al. 1984).

It is the large differences in shrinkage/swelling properties between the two wood types during changes in moisture content that result in large stresses within the wood, green as
well as dried. When the log is sawn the equilibrium of forces acting on the material is disturbed. The remaining residual forces in each new piece of wood must come into balance and one way to reach balance is through deformation (Watanabe 1965, Alhasani 1999). This can be seen even during sawing; compression wood present in a piece of wood can be recognised by the shape of the piece, which clearly differs from the shape attained when only normal wood is present (Jacobs 1965, Öhman 1999).

During the drying process the water molecules are removed from the micro-fibril structure in the cell wall. The material shrinks, and this results in a change in the equilibrium of forces. When green, in the trunk as well as in the sawn product, compression wood causes a tensile stress on the surrounding normal wood, and during drying this effect changes to a compressive stress. The piece of wood must always establish equilibrium of all external and internal forces acting on the material, and the deformation that occurs is only one of several possible ways to establish this equilibrium. This means that each piece of wood is continually re-establishing equilibrium of force as a response to changing conditions such as temperature, external loading, alteration of geometry, changes in moisture content, chemical and biological effects etc. One of the largest changes of conditions is the process of drying from green to lower moisture contents. The decrease of moisture content combined with heat and external loading can cause a severe deformation of the piece of wood.

The degree of deformation, or warp, is dependent on the size and distribution of local stress gradients. If compression wood is present along with normal wood in the piece of wood, larger stress gradients will be acting on the material than if only one wood type is present. A study made by duToit (1963) showed that planks with an amount of 40% to 70% compression wood had the largest magnitudes of warp, though the location of compression wood was not regarded.

The amount of compression wood visible on the surface of a plank is, however, a poor indicator of the amount of warp likely to be present when dried. The amount of compression wood can only be used as an indicator of the risk of a large warp (Warensjö et al. 1998, Öhman 1998). To be able to predict the type and magnitude of warp, the distribution, amount and severity of compression wood in each part of the piece of wood must be described. Pillow and Luxford (1937) reported a relation between the location of the compression wood and the warp of the piece of wood. This can be explained by how symmetrical the distribution of compression wood is. If the compression wood is symmetrically distributed, the forces are symmetrical as well, and no deformation of the piece of wood is needed to establish a force equilibrium. But if the compression wood is asymmetrically distributed, as Pillow and Luxford observed, the piece of wood is forced to warp in order to establish equilibrium (Figure 1). To predict a warp from the amount, distribution and severity of compression wood together with all other wood features that cause warp, numerous calculations are needed. Still, in the beginning of the year 2001 many problems remain to be solved before a good prediction can be made. Ormarsson (1999) has, however, shown some promising progress in predicting the deformation of planks by using finite element modelling.
Methods for Avoiding the Negative Effects of Compression Wood

End Views  Face Views

Figure 1: Distribution of compression wood, symmetric and asymmetric, within pieces of wood and possible deformations caused by difference in longitudinal shrinkage. Dark areas denote compression wood.

1.3 Production of wall studs

A large number of wall studs are sawn from sawlogs of relatively small diameters. These studs are mostly of the dimensions $45 \times 95$ mm or wider and furthermore have a symmetrical structure and centred pith. Another common method of producing wall studs, which this study is focused on, is to resaw dried planks to more slender studs with widths $< 100$ mm.

By the latter method the equilibrium of forces established during drying in the original piece is dramatically changed. Each new piece of wood must establish its own equilibrium by deformation as a response to the residual stresses still acting on the material. The deformation of the resawn wall stud is not only caused by the residual stresses from the plank caused by compression wood. With traditional drying, a moisture gradient can be expected in a dried plank, where the inner parts most often show slightly higher moisture contents than the outer (see A in figure 2). When resawn, each new piece of wood will have an asymmetrical moisture gradient (see B in figure 2). The resawn face will in time reach the same moisture content as the other faces of the piece of wood (C in figure 2). Since the surfaces will shrink/swell differently, due to differences in moisture content, when a new equilibrium with the surrounding humidity is established, an asymmetrical force will occur which most probably will warp the piece of wood. If compression wood is present the change in shape will be more pronounced.
Methods for Avoiding the Negative Effects of Compression Wood

Figure 2: The change of the moisture gradient in a piece of wood, from being symmetrical when dried, A, to asymmetrical when resawn, B, to symmetrical when the resawn surface has established a moisture equilibrium with the surrounding humidity, C. A plausible deformation of the stud when the moisture content once again is symmetrical is shown in C, as well.
2 OBJECTIVES
In order to improve the straightness of studs, asymmetrical stress gradients must be avoided. Two causes of such stress gradients are the presence and distribution of compression wood and moisture gradients. Since these two gradients are difficult to measure on-line and evaluate today (2001) in an ordinary sawmill, it is important to find methods for decreasing the risk of large deformations. The focus of this study was to evaluate the possibilities of decreasing the magnitude of warp and increasing the yield of accepted studs, resawn from planks originated from butt-logs showing an increased amount of compression wood.

Four different aspects were studied:

- Improvements by an adapted log grading, primarily grading with respect to magnitude of log sweep and visible compression wood in the butt end of the log.
- Improvements by grading the planks by the amount of visible compression wood.
- Improvements by resawing methods. Wall studs resawn out of dried planks were compared to studs sawn to the final dimension before drying.
- Symmetry of the resawing pattern. The warp of studs from planks resawn symmetrically was compared to that of studs asymmetrically resawn.

The first two aspects, adapted log grading and grading of planks by the amount of compression wood, focused on how much of each feature can be accepted before the yield of accepted wall studs decreases too much. The comparison of the resawing methods is based on the hypothesis that the less the established equilibrium of forces is disturbed after drying, the better. It is expected that the more equal the local amounts of compression wood and normal wood is, the larger internal forces acting on the material will be. The purpose of the fourth aspect is to evaluate if differences can be seen between how symmetrically the planks are resawn to wall studs.
3 MATERIALS AND METHODS

Selection of saw logs: The study was based on 90 butt logs of Norway spruce (Picea abies (L.) Karst) with a top diameter in the range from 19 cm to 21 cm. The logs included in this study were selected to correspond to one of totally five different classes, denoted as five-grade, according to the amount of visible compression wood in the logs' butt ends and the magnitude of log sweep, according to the criteria's shown in figure 3.

Please observe that the logs were selected by the objective of studying the relation between compression wood in butt-logs and the straightness of sawn wall studs. Thereby a considerably higher amount of compression wood was shown in this material than in the normal frequency of compression wood.

The amount of visible compression wood in the butt end, in cm², and the magnitude of sweep, in cm, were estimated on each log. The measuring of log sweep and compression wood were done according to the definitions in the regulations, For the piece by piece measurement of coniferous sawlogs of the Swedish Timber Measuring Council (VMR), (Anon 1997a). Magnitude of sweep is the largest distance found from a straight line through the end centres of the logs to the centre of the log (Figure 4). The measurement of the amount of compression wood, however, is defined differently in this study, compared to the regulations of VMR. In figure 5 the butt end of a log is shown. The dark area represents compression wood. In this study, the whole area, A + B, was regarded and expressed in cm². In the regulations of VMR only area A is regarded and expressed as a percentage of a circle defined as the top diameter of the log minus 1 cm (circle C in figure 5).
Figure 3  Grouping in 5 different classes by the features log sweep, butt-end compression wood, CW, and by method of resawing the wall studs, Dry and Green.
Figure 4: The log sweep is defined as the largest distance between the centre of the log and a straight line through the centres of the two ends of the log. Expressed in cm.

Figure 5: Measuring of the amount of compression wood visible in the butt end of the log. A and B represent the area of compression wood, C represents a cylinder with the diameter equal to the log’s top diameter minus 10 mm. In this study the amount of compression wood, A and B, was manually estimated and expressed in cm².

A general quality grading of the logs according to VMR’s measuring regulations was done as well (Anon 1997a). The quality grading by the method of VMR resulted in 51 logs of the quality grade 3, denoted as III in the report, and 39 logs of the quality grade 4, denoted as IV (Figure 9). The logs in grade IV were primarily degraded because of excessive visible compression wood and log sweep.
**Methods for Avoiding the Negative Effects of Compression Wood**

**Sawing:** The logs were curve-sawn up to 1.75 cm/m, using the pattern shown in figure 6, to two centre planks of the nominal dimensions 50 x 150 mm. The planks were then resawn into 2 wall studs each. 45 logs were sawn into studs before drying and the remaining 45 were resawn into wall studs after drying (figure 6).

Of these 180 planks, 88 were symmetrically resawn into 176 studs of the nominal dimensions 50 x 75 mm and 92 planks were asymmetrically resawn to the nominal stud dimensions 50 x 50 mm and 50 x 100 mm (figure 6). In an ordinary situation, the wall studs would have been planed to a dimension 5 mm smaller than the nominal dimension shown above. In this study, however, no such planning was done.

The observant reader will notice that studs are missing in the results compared to the number of studs sawn. This lack of observations was caused by losses in process from the manually measuring of both warp and amount of compression wood. One wall stud was lost during the measuring of warp. Totally 8 studs were missed when the compression wood was measured, e.g. if one wall stud was missed during the estimation of compression wood, the plank or the whole log was excluded from the specific comparison.

90 Butt Logs of Norway spruce, top-diameter 19-21 cm  
Logs Curve-Sawn, 1.75cm/m, to two Center Boards 50 by 150 mm  
Asymmetric Resawn Studs 50 by 50 and 50 by 100 mm, 92 studs each  
176 Symmetric Resawn Studs 50 by 75 mm,  

![Figure 6: Schematic picture of how the logs were sawn into planks and then resawn to three different dimensions of wall studs.](image)

**Drying:** Planks and studs were stacked in a 6 m long drying package with 9 stickers per layer. They were dried to a moisture content of 16% by a regime of a wet-bulb temperature of 55°C and a dry-bulb temperature of 58°C in the first phase of the drying process and increased to 67°C in the second phase. No artificial conditioning of the sawn products were done.

During the drying process the planks and studs were loaded with a weight of two drying packages. In order to follow normal production procedure, the dried planks and studs were stored outdoors, covered, for more than a month. Then the planks were resawn into studs, and magnitude of bow, spring and twist were measured.
Methods for Avoiding the Negative Effects of Compression Wood

**Warp:** The wall studs were then graded with respect to observed straightness by the grading rules for wall studs suggested by Johansson et al. (1993). In order to fulfil building contractors’ requirements for straightness, the maximum acceptable magnitude of bow is 6 mm, of spring 4 mm and of twist 4% of the width or at least 5 mm, measured over a length of 3 m (Figure 7). The nominal dimensions of the studs have been used in this report. Please observe that the actual width of the wall studs was approximately 2 mm less than the nominal width after the resawing operation.

![Figure 7: Principles of measuring the magnitude of warp. Bow (top) and spring (middle) is the distance between the plane through the ends of the plank and the plank. The magnitude of twist (bottom) is the distance between the plane through three of the planks corners and the fourth corner. Expressed in mm and measured over a length of 3 m.](image)

**Compression wood in sawn products:** In this study compression wood is regarded as present in significant amounts when 50% or more of the annual ring shows the characteristic dark red colour typical of compression wood in combination with increased annual ring width. It should be emphasised that the estimation of compression wood done in this study is only an estimation of visible compression wood on the faces of the studs.

A visual estimation of the amount of compression wood was done on studs of the dimensions 50 x 75 mm, a total of 168 studs from 44 logs. Each stud was divided into 180 zones. The two edges of the stud form one 50 mm wide zone each. The inside and the outside faces of the stud are divided into two zones each. The length of all zones is 100 mm (figure 8).

The amount of compression wood in each zone was visually estimated and expressed in one of 4 different classes. If no compression wood was observable in the zone, the zone was given the index 0. If less than one third of the zone area was recognised as compression wood, the zone was given the index 1. If more than one third but less than two thirds of the area was recognised as compression wood, the zone was
given the index 2. Finally, if more than two thirds was recognised as compression wood, the zone was given the index 3. The amount of compression wood in a stud was then expressed as the sum of the zone indexes, denoted as CW units. If the whole stud were to consist of only compression wood, the observed amount of compression wood would be 540 CW units (3x180). In figure 8 an example of how the stud was divided into zones is shown. Two sides are shown. No visible compression wood can be seen in zones A and B, and these zones are therefore each given the index 0. In zone C, however, compression wood can be seen, exemplified as extremely thick lines, and covers between 1/3 and 2/3 of the zone’s total area and is thus given the index 2.

Figure 8: The principle for the measurement of compression wood on the surface of the studs of the dimensions 50 x 75 mm. Each stud was divided into 180 zones. The two faces were divided into two zones, A and B, approximately 37.5 x 100 mm each, while the edges, C, are one 50 x 100 mm zone each, making for a total of 180 zones. The amount of compression wood was manually estimated for each zone and expressed in 4 grades, no compression wood, < 1/3, ≥ 13 and > 2/3 and ≥ 2/3.

Evaluation of results: The results are based to a large degree on statistical comparisons of observed differences between different groupings made on the material. The definition of each grouping and the results of the groupings can be found in appendix A to D. When differences in observed mean value of the groups are compared, Tukey-Kramer’s Honestly Significant Test is the principal method used. In those cases where a frequency distribution was compared, for instance when differences in levels of acceptable studs were compared between different groupings, a Chi² test was used. Depending on the number of degrees of freedom, either Fisher’s Exact Chi² test or Pearson’s Chi² test was used. When the differences in magnitude of warp between the two asymmetrically resawn studs from the same plank are compared, a paired Student’s t-test was used when the assumption of a normal distribution was proven, and if not, a Signed-Rank test was used. All comparisons were done at a level of significance, or alpha level, of 0.05. All statistical analyses were done with the aid of the software program JMP, a product from SAS Institute Inc. (Anon 1994).
4 RESULTS AND DISCUSSION

This study is highly focused on compression wood and the warp of one specific product, wall studs resawn out of planks originated from butt logs and the warp of the wall studs.

4.1 Summery of results

The most important findings of the study are shown below. Detailed results of the study are presented in Appendices A to D.

Summary of Appendix A, Why the wall studs were degraded:

- No difference between the two resawing methods, Dry and Green, regarding the yield of accepted studs could be shown.
- Excessive spring was the largest cause of degradation, no matter the resawing method used. Only a minor difference in the number of studs degraded due to spring could be shown between the resawing methods. Studs resawn green showed a larger degradation due to twist and a lower degradation due to bow than studs resawn dried did.
- Studs degraded due to bow and spring showed considerably higher amounts of compression wood than accepted studs and studs degraded only due to twist did.
- The larger the log sweep and/or amount of compression wood, the larger the risk is of degradation due to excessive bow and spring, regardless of resawing method.

Summary of Appendix B, The impact of log features and resawing methods on the yield of accepted wall studs:

- The log-grading method of VMR can be used for separating logs suitable for wall stud production from those that are not. Logs of quality grade 3 give a considerably higher yield of accepted wall studs than logs of quality grade 4.
- The tolerances of acceptable log sweep and amount of compression wood visible in the butt end of the log in the regulations of VMR can be adjusted to be more efficient than the regulations of today in identifying logs that will give both acceptable yields and extremely poor yields.
- If possible, only logs showing no measurable log sweep should be resawn into wall studs.
- Minor amounts of compression wood can be accepted in sawlogs. An amount up to 40 cm² did not affect the yield of accepted wall studs.
• The choice of resawing method, dry or green, does not affect the yield of accepted wall studs from sawlogs of good quality.

• Among the high quality sawlogs showing either no compression wood or no log sweep, only 35% yielded 4 accepted wall studs out of 4 possible.

Summary of Appendix C, Relationship between the amount of compression wood in sawn products and the magnitude of warp:

• Only planks showing low amounts of compression wood, up to 10%, are suitable for wall stud production and should be resawn when dried to achieve highest possible yield of accepted wall studs.

• Planks showing high amounts of compression wood (>50%) are not suitable for wall stud production no matter what resawing method is used. However, considerably fewer studs resawn dry were accepted than resawn green, 18%, compared to 35%.

Summary of Appendix D, Comparison of differences in the yield of accepted studs for different resawing patterns:

• The quality of the sawlog had a greater impact on the magnitude of warp than did the symmetry of the resawing pattern. No differences in the yield of accepted studs were found between studs asymmetrically and studs symmetrically resawn out of planks originating from the same log quality.

• In a pairwise comparison of the warp of the two studs from asymmetrically resawn planks showed: No differences in magnitude of bow, the narrower dimension showed on average a significantly larger magnitude of spring, while the wider studs tended to have a larger magnitude of twist.
4.2 Why the wall studs were degraded

According to Johansson et al. (1993) the building contractors finds wall studs with a bow larger than 6 mm, a spring larger than 4 mm or a twist larger than 5 mm measured over a length of 3 m unacceptable in wall construction. These requirements result in spring being the largest cause of degradation due to excessive warp in this study, (figure 9).

The amount of compression wood observed in the studs rejected only because of excessive spring or bow was 1.6 times larger than in the accepted studs. Wall studs rejected both for excessive bow and spring showed a mean amount of compression wood twice as high as the accepted studs. The accepted studs and those rejected only because of twist did not show any differences in the mean amount of compression wood. It can be concluded that compression wood is a cause of bow and spring and that the risk of rejection increases with increasing amount of compression wood within the piece of wood.
4.3 Log features

A purpose-driven selection of sawlogs can improve the yield of studs meeting the building constructors requirements for straightness. The magnitude of log sweep and the amount of compression wood in the log’s butt end can be used in order to predict the risk of excessive deformation in the wall studs cut from the log. The magnitude of log sweep is, however, the better indicator of the two log features studied. A notable decrease in the amount of accepted studs could be shown as soon as a log sweep, \( \geq 1 \text{ cm} \), could be observed, while a minor amount of compression wood, up to 35 to 40 cm\(^2\), approximately 10\% to 15\% of the top-end area, could be present before the yield decreased. A comparison of very large log sweeps, \( \geq 4 \text{ cm} \), and high amounts of compression wood, \( > 33\% \), shows the same trend; logs with large log sweeps gave the poorer yield of accepted studs.

A straight log of good quality has the best chances of giving a high yield of acceptable wall studs. Approximately two thirds of the studs from these high quality logs were accepted. Among these high quality logs, spring was the greatest cause of degradation. The lower the observed log quality was, the more dominant was spring as the single most common cause of degradation.

If the results were expressed as a yield per log of accepted studs, it could be noted that only 35\% of the high quality logs, with no sweep and no compression wood, gave a yield of 4 out of 4 possible accepted studs, while 20\% yielded \( \leq 1 \) accepted stud. Among logs showing a large sweep, \( \geq 3 \text{ cm} \) or 1\% of the log length, no logs gave 4 accepted studs, while 64\% of the logs gave \( \leq 1 \) accepted stud, Figure 10.

![Figure 10](image-url)

Figure 10: Yield per log of wall studs graded with respect to straightness, expressed as percentage of logs giving 4 out of 4 possible studs, "4", 2 or 3 out of 4, "2-3" and 0 or 1 out of 4, "0-1", for each grade in the five-grade classification.
In this study two methods of classifying logs by their features were compared. A general quality grading of the sawlogs was done in accordance with the VMR, where the logs were classified as grade 3 or grade 4, (Figure 11). Using the five-grade method, a division of the logs into 5 grades more focused on the observed magnitude of log sweep and the amount of compression wood within the butt end of the log was done, (Figure 12). The results showed the possibility of both methods for increasing the yield of accepted studs by preventing sawlogs of poorer quality from being used in the production of wall studs, as compared to no pregrading at all. The five-grade method was found to be more efficient in identifying logs that will give a poor yield of accepted studs, but resulted in the same yield as VMR for high quality logs, compare figure 11 and 12.

Figure 11: Schematic picture of the distribution of the logs in VMR quality grades 3 and 4 and the method of resawing into studs, resawn green and resawn dry. The number of logs and studs in each group is shown, as well as some results such as yield of accepted studs and the mean warp of each group.
## 90 Butt Logs of Norway spruce

### Five-Grade System

<table>
<thead>
<tr>
<th>Grade</th>
<th>Dry/Green</th>
<th>Logs:</th>
<th>Studs:</th>
<th>Bow:</th>
<th>Spring:</th>
<th>Twist:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 1</td>
<td>8/9</td>
<td>32/36</td>
<td>3.4/2.0</td>
<td>4.0/3.3</td>
<td>0.5/1.5</td>
<td></td>
</tr>
<tr>
<td>Grade 2+</td>
<td>11/9</td>
<td>44/36</td>
<td>3.1/3.1</td>
<td>3.1/3.6</td>
<td>0.8/1.7</td>
<td></td>
</tr>
<tr>
<td>Grade 2-</td>
<td>7/8</td>
<td>27/32</td>
<td>3.8/3.9</td>
<td>3.9/3.9</td>
<td>1.0/4.1</td>
<td></td>
</tr>
<tr>
<td>Grade 3+</td>
<td>7/9</td>
<td>28/36</td>
<td>4.6/2.4</td>
<td>4.3/3.1</td>
<td>1.4/1.5</td>
<td></td>
</tr>
<tr>
<td>Grade 3-</td>
<td>12/10</td>
<td>48/40</td>
<td>7.5/4.6</td>
<td>7.8/6.2</td>
<td>1.2/1.7</td>
<td></td>
</tr>
</tbody>
</table>

**Log Grade:**

<table>
<thead>
<tr>
<th>Dry/Green</th>
<th>Number of Studs:</th>
<th>Yield of Accepted Studs:</th>
</tr>
</thead>
<tbody>
<tr>
<td>123+</td>
<td>104/108</td>
<td>63% / 67%</td>
</tr>
<tr>
<td>2-</td>
<td>27/32</td>
<td>57% / 41%</td>
</tr>
<tr>
<td>3-</td>
<td>48/40</td>
<td>25% / 30%</td>
</tr>
</tbody>
</table>

Figure 12: Sawlogs divided into 5 classes according to amount of compression wood and magnitude of log sweep. The number of logs and studs per log grade and resawing method, dry or green, is shown, as well as the mean magnitudes of bow, spring and twist for each group. The yield of accepted studs is shown for 3 groups, group 1, 2+ and 3+ are united into the new group 123+, while the groups 2- and 3- are untouched.
4.4 Compression wood in planks and resawing method

If the goal is to achieve highest possible amount of accepted studs, only planks free from compression wood should be resawn. If the differences caused by resawing method were disregarded, the planks with less than 12% compression wood gave on average a yield of 77%. Among studs resawn from planks with an amount of visible compression wood exceeding 50%, on average only 26% were accepted. The remaining planks gave on average a yield of 59%. The differences between the resawing methods were not statistically significant in any comparison. A general tendency could be noticed in the results of a relation between amount of compression wood and the choice of resawing method. For planks showing low amounts of compression wood the method of resawing dry tends to be more beneficial, (p=0.23). This tendency changes in favour of the resawing green method when the amount of compression wood increases, (p=0.30 for planks showing more than 50%). For planks with an amount of compression wood in between these two levels, no difference in the yield of accepted studs was found (Figure 13).

The magnitudes of bow and spring increased with increasing amounts of compression wood and were affected by the choice of resawing method. The studs in these comparisons were divided into 3 groups according to the amount of compression wood in the planks: CW-Low < 12%, CW-Medium 12% to 50% and CW-High > 50%. The observed mean magnitude of bow was lower for studs resawn green than for studs resawn dry, a difference that increased with increasing amounts of compression wood. Compared to the largest acceptable bow of 6 mm, suggested by Johansson et al. (1993), the smallest margin between the mean bow and the tolerance was found for studs resawn dry from planks with large amounts of compression wood. Regarding spring, the tolerance is closer; only a spring ≤ 4 mm is accepted. This resulted in all groups, except studs resawn dry from CW-group low, having mean values dangerously close to 4 mm and exceeding this value when the amount of compression wood was > 50%. The observed mean values of twist were had a good margin to the tolerance of 5 mm (Figure 13).

Comparing the two resawing methods, the resaw dry method tends to be more sensitive to the amount of compression wood than the resaw green method. This can be seen in figure 11 in the development of bow and spring. By way of contrast, the magnitudes of twist were not affected by the amount of compression wood at all.

Spring was the single most common cause of degradation among these wall studs in all classes. Among the studs resawn dry in CW group Low, spring was the only cause of rejection, and among the studs resawn green, as many studs were rejected due to spring as to bow and twist together. With increasing amounts of compression wood, spring strengthens its position as the major cause of degradation. There was no difference in the yield of accepted wall studs when only spring was regarded for amounts of compression wood > 12%. The differences in the total yield of accepted studs between the two resawing methods shown in table 11 were mainly a consequence of differences in bow.
### Methods for Avoiding the Negative Effects of Compression Wood

**84 Planks, 50 x 150 mm**

Resawn into **168 Wall Studs, 50 x 75 mm**

**Grouped by Resawing Method**

- **Resawn Dry**
  - 41 Planks
  - 82 Wall Studs

- **Resawn Green**
  - 43 Planks
  - 86 Wall Studs

**Grouped by the Planks’ Amount of Measured Compression Wood into:**

<table>
<thead>
<tr>
<th>CW-Group Dry</th>
<th>CW-Group Green</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low</strong></td>
<td><strong>Medium</strong></td>
</tr>
<tr>
<td>Planks:</td>
<td>6</td>
</tr>
<tr>
<td>Studs:</td>
<td>12</td>
</tr>
</tbody>
</table>

**Mean Warp of the Studs in mm**

- **Bow:**
  - Dry Low: 2.9
  - Dry Medium: 4.2
  - Dry High: 5.6
  - Green Low: 1.8
  - Green Medium: 3.2
  - Green High: 3.4

- **Spring:**
  - Dry Low: 1.5
  - Dry Medium: 3.8
  - Dry High: 7.5
  - Green Low: 3.1
  - Green Medium: 5.1
  - Green High: 3.1

- **Twist:**
  - Dry Low: 0.7
  - Dry Medium: 1.1
  - Dry High: 0.6
  - Green Low: 1.7
  - Green Medium: 2.1
  - Green High: 2.5

**Yield of Accepted Studs:**

- Dry Low: 92%
- Dry Medium: 58%
- Dry High: 18%
- Green Low: 70%
- Green Medium: 61%
- Green High: 35%

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Figure 13: Schematic picture of how the planks were divided into three groups according to amount of compression wood and resawing method. Some results, such as number of planks, number of studs, mean warp, bow, spring and twist, and yield of accepted wall studs, are shown as well.
4.5 Asymmetry
An asymmetrical or symmetrical resawing of the planks did not affect the yield of acceptable studs to any great extent. There was in this study, however, a tendency for an asymmetrical pattern to be preferable when planks from high quality logs were resawn to studs. For logs of the lower quality the converse was true: a symmetrical resawing gave the higher yield. However, the observed differences were not of such magnitude as to be statistically significant.

If the two asymmetrically resawn studs from the same plank were compared, the narrower studs showed a slightly larger mean warp throughout the comparison. But in only one case was the difference large enough to be statistically significant: this difference was found in the degree of twist on studs from logs of good quality. The narrow stud of the dimensions 50 x 50 mm showed in this study a mean twist that was 0.37 mm to 1.47 mm larger than the stud of the dimensions 50 x 100 mm from the same plank. These results regarding twist were though only valid if the twist was expressed in mm only. If the magnitude of twist was expressed as an angle the opposite was found to be true, the narrower stud 50 x 50 mm showed the larger twist in average 0.5 degree, significant at an alpha-level of 0.10.

4.7 Best possible yield
The findings of the study indicate that the highest possible yield of accepted wall studs can be achieved if an adapted grading of both the logs and the sawn planks is done for the purpose of minimising the warp of the studs.

In general, only dried planks from straight logs free of compression wood should be used in the production of wall studs. This conclusion might be difficult to follow in reality. The study shows, however, that the straighter the log, the higher the yield that can be expected. A considerable decrease of accepted studs was shown as soon as a measurable log sweep could be observed. The amount of compression wood on the planks from straight logs had a minor impact on the yield; the lower the amount of compression wood, the better the yield. The highest yield was found for planks with less than 12% compression wood, resawn when dried. Using this strategy, a yield 9 accepted studs out of 10 possible could be obtained from planks with a minor amount of compression wood, 10%-15%. If higher amounts of compression wood are accepted, the yield decreases. When as much as 33% compression wood was present, 8 out of 10 studs were accepted. If no grading regarding the amount of compression wood of the planks is done and only logs showing no sweep are used in the production of wall studs, the total yield can be expected to be lower. In this study, two thirds of the studs resawn from dried planks were accepted.
4.7 General comments

The objective of this study was to evaluate the possibility of improving the yield of sawn wall studs meeting building contractors’ demands for straightness by:

- A grading of sawlogs adapted to the demands on the wall studs.
- A grading of planks by the amount of visible compression wood.
- An adapted resawing of the planks, before or after drying and by an asymmetric or symmetric resawing pattern.

The grading of logs focused on two features that could be related to the amount of compression wood within the log: the magnitude of log sweep and the amount of compression wood visible in the butt end of the log.

All three aspects above were evaluated by regarding the magnitudes of the observed warp and the yield of accepted wall studs when graded with respect to straightness. In this study, the studs were graded with respect to straightness according to the tolerances suggested by Johansson et al. (1993). These tolerances are based on the building trade’s requirements for the function of the wall stud. The sawmill industry in Sweden today more or less applies the grading regulations *Nordic Timber*, where acceptable magnitudes of deformations are defined (Anon 1997b). The reason why these regulations were not used in this study was the fact that they are too far from the customers’ demands on an acceptable deviation from straightness; too large magnitudes are accepted. The sawmilling industry’s traditional lack of focus on the satisfaction of customers’ demands can be exemplified by the first paragraph in the introduction of *Nordic Timber*:

*The GRADES listed in NORDIC TIMBER reflect qualities that the forest sector produces on a sustained basis and which the sawmills are able to continuously deliver to the markets.*

In such a formulation there is no evident impulse to deliver the functions the customers are asking for. The focus is rather on offering a standard product assortment that doesn’t suit any buyer exactly. On the other hand, if the studs are graded according to the standards suggested by Johansson et al. (1993) to meet the building constructor’s demands, a large amount of studs will be degraded due to excessive warp. An increase of rejected end products is an unwanted and very costly problem to solve. This study demonstrates the possibility of reducing the amount of rejected studs by an improved pregrading of logs, and even of sawn products. Clearly, if the sawmills cannot deliver the functions customers are asking for, in this case straight studs, the market share of wooden wall studs is going to decrease further and perhaps disappear altogether. Ultimately, this
is a larger and more costly problem than increased grading efforts.

The conclusion to be drawn from the results of the study is that the magnitude of bow and spring increases with increasing amounts of compression wood. A quality grading of timber according to VMR's grading rules can be used to reduce the number of rejected studs if only logs of grade 3 are used. This is achieved by preventing the worst logs with large log sweep, which is an indication of a large amount of compression wood, from being resawn into wall studs. A further reduction is possible if pregrading become more focused on detecting compression wood. The results of this study show that monitoring the magnitude of log sweep and monitoring amount of compression wood visible on the surface of the plank are two simple methods that can be used to improve the yield of accepted studs. But only using the magnitude and amount of compression wood in the pregrading process is not especially efficient. Grading based only on the amount of compression wood will result in large variations of the observed magnitudes of bow and spring. The variation, according to Deming (1986), is the root of all "evil", and the lack of knowledge of how to control the variation causes costs for poor quality. To further decrease the variation, new methods for detecting the warp of the sawn products must be developed. Methods capable of detecting the severity and distribution of compression wood within the whole piece of wood are crucial to improving the identification of sawn products that will have too large bow and spring. The sooner such predictions can be made in the sawing process, the better.

An example of an improvement that can be achieved with only minor efforts in research and development, is an improved measuring of the log sweep by regarding the growth of the log sweep over the whole length and the magnitude. From this it would be possible to improve the prediction of the amount and lengthwise distribution of compression wood within the log. An even more accurate prediction of the amount and distribution of compression wood can be made by measuring the magnitude and growth of the green plank’s deformation (Öhman 1999). It has been shown by Nyström (1999) that it is possible, as well, to detect compression wood on a fresh wood surface and thereby to predict both the amount and the distribution.

The measurement of the amount of visible compression wood in the butt end of the log does not improve grading results to any great extent compared to the magnitude of log sweep. Measurement of the feature is done manually today with highly varying accuracy. A freshly cut area is needed in order to achieve good accuracy in the manual estimation of the amount of compression wood, and the older the surface is, the poorer the contrast becomes between compression wood and normal wood. Automation of the measurement is even more difficult in an on-line process for the same reason. The conclusion is that the amount of compression wood visible in the butt end of the log is not worth the effort to measure. This feature’s ability to indicate an increased risk of large deformations on the sawn products is too poor compared to other features.
5 CONCLUSIONS

- Pregrading of sawlogs with respect to magnitude of log sweep and amount of visible compression wood increases the yield of accepted wall studs compared to no pregrading at all. A measurable log sweep $\geq 1$ cm is an indication of a decreased yield, and logs with sweeps $\geq 4$ cm should be avoided in the production of wall studs. Regarding compression, wood smaller amounts, up to approximately 40 cm$^2$, can be acceptable, but logs with amounts exceeding 100 cm$^2$ should be avoided. Still, high log quality (no measurable log sweep and very little visible compression wood) does not guarantee a high yield of accepted studs. Approximately one fifth of these logs can be expected to give a yield of $\leq 1$ accepted wall stud out of 4 possible, as in this study.

- Grading with respect to the amount of compression wood visible on a sawn product can be used as an indicator of the risk of large deformations when the lumber is dried. The less compression wood visible, the higher the yield of accepted wall studs that can be expected. An amount up to approximately 10% can be accepted without any tendency toward a decreased yield, while amounts $\geq 33\%$ result in a considerable reduction in the yield of accepted studs. To only use the amount of compression wood as a grading criterion results in large variations of the observed magnitudes of bow and spring. To reduce these variations, and the costs of poor quality, the distribution and severity of the compression wood over the entire piece of wood must be measured and evaluated, as well.

- The method of resawing dried planks to wall studs is more sensitive to the amount of compression wood than is the method of resawing green. As the amount of compression wood increases, the yield of accepted studs decreases more, and larger magnitudes of bow and spring can be observed among the studs resawn dry. Planks with small amounts of compression wood, however, give a higher yield of accepted wall studs if they are resawn when dried. This difference is due solely to the magnitude of spring. If a large amount of compression wood is present, the plank should be resawn to wall studs before drying.

- How symmetrically a plank is resawn does not affect the yield of accepted wall studs. No differences could be found between studs symmetrically resawn (2 studs of the nominal dimensions 50 x 75 mm) and those which were asymmetrically resawn (1 stud of the nominal dimensions 50 x 50 mm and 1 stud 50 x 100 mm) out of planks of the nominal dimensions 50 x 150 mm from the centre of the log. No systematic difference in magnitude of warp could be found between two wall stud dimensions asymmetrically resawn from the same plank.
6 ACKNOWLEDGEMENTS

I would like to thank: EU Program Objective 1 and the syndicate Trävision Norr 2000 for funding, and I thank their project manager Kjell Karlsson especially for his invaluable cooperation and support and for being the initiator of this study. The BAC sawmill company for disposing equipment, personal and time for this study. My instructor professor Anders Grönlund for his patience and for his tireless efforts to force me to keep things "simple". Finally, I would like to thank my beloved family, Karin and my sons, for allowing me to spend so many late evenings and weekends with such "boring work" as a research report instead of spending the time at them.

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APPENDIX A

Cause of degradation
A.1 Purpose
The purposes of the comparisons made in this appendix are:

• To study what causes the degradation of wall studs; bow, spring or twist.
• To study the differences in log sweep and amount of compression wood in the butt end of logs when grouped according to cause of degradation.
• To study differences in the amount of compression wood in wall studs grouped according cause of degradation.
• To study the impact of dry and green resawing methods on the distribution of degraded studs.

A.2 Major findings
The major findings of the comparison shown in this appendix are:

• Excessive spring was the largest cause of degradation, no matter which resawing method was used. Only a minor difference in the number of studs degraded due to spring could be shown between the two resawing methods. Studs resawn green showed more degradation due to twist and less due to bow than studs resawn dried.
• The larger the log sweep and/or amount of compression wood, the larger the risk is of degradation due to excessive bow and spring, regardless of resawing method.
• Studs degraded due to bow and spring showed considerably higher amounts of compression wood than accepted studs and studs degraded due only to twist.
A.3 Results

In figure A.1 the distribution of the causes of degraded wall studs is shown for each resawing method. The studs were grouped by cause of degradation, denoted as B for bow, S for spring and T for twist, or a combination of these three letters if there was more than one cause. That is, all studs which could be rejected because of both excessive bow and excessive spring were denoted as BS, and so on.

A total of 359 wall studs were included study. Fifty-two percent of the studs resawn dry and 54% of those resawn green were accepted. The difference in result between the two methods was remarkably small. Larger differences were found when the causes of degradation were compared.

A total of 80% of the degraded studs resawn dry and 75% of the degraded studs resawn green could be degraded due to excessive spring. Excessive bow could be cited as cause for degradation for 50% of the degraded studs resawn dry and for 25% of the degraded studs resawn green. The lowest figures were shown for twist: the total rate for the degraded studs resawn green was 26% and was 6% for degraded studs resawn dry. Among the studs resawn green, 24% of the rejected studs could be degraded for more than one type of warp. The corresponding value for studs resawn dry was 35%.

The results shown in figure A.1 are based on material of a lower mean quality than the normal distribution of butt logs. This means that only the proportions between resawing methods can be compared. The observed levels of accepted/rejected studs cannot be regarded as normal proportions between the amounts of accepted and rejected studs.

In table A.1 to A.4 the results are shown for the relation between cause of degradation and the log features sweep and compression wood, as well as the amount of compression wood within the sawn products. In all four tables the number of observations was low for the degradation categories ST, BST and BT, making these results less reliable than the others.

Table A.1 shows how the log’s magnitude of log sweep varies between the different categories of degradation. The differences shown were foremost a matter of a difference between accepted studs and rejected studs. A large log sweep did not guarantee that wall studs would be rejected. Thus the standard deviation of the classes of degradation was too large. In general, however, the risk of degradation increases with increased log sweep.
Figure A.1: Distribution of rejected wall studs grouped by the cause of degradation and resawing method expressed as the percentage of all rejected studs from each resawing method. S is degradation due to excessive spring, B to excessive bow and T to excessive twist.

Table A.1: Mean value and standard deviation of observed log sweep, in cm, for wall studs grouped by cause of degradation. Tests for statistically significant differences, S.D, between the groups at an alpha level of 0.05. The degradation categories are S for spring, B for bow, T for twist and combinations of these; * denotes a low number of observations, n is the number of studs.
Table A.2 shows the amount of visible compression wood in the butt-end of the logs for each cause of degradation. As expected, the accepted studs show the lowest mean amount of compression wood, followed by T, twist, and S, spring. The largest amount of compression wood was found among studs rejected due to excessive bow, B, and combinations including bow and spring.

It can be concluded that an increase of compression wood increases the risk of studs being degraded due to excessive bow.

Table A.2: Mean value and standard deviation of amount of visible compression wood in the log's butt end, in cm², for wall studs grouped by cause of degradation. Tests for statistically significant differences, S.D, between the groups at an alpha level of 0.05. The degradation categories are S for spring, B for bow, T for twist and combinations of these; * denotes a low number of observations, n is the number of studs.

<table>
<thead>
<tr>
<th>Degradation Category</th>
<th>n</th>
<th>Mean</th>
<th>Std Dev</th>
<th>S.D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accepted</td>
<td>190</td>
<td>44.2</td>
<td>42.06</td>
<td>B, BS</td>
</tr>
<tr>
<td>S</td>
<td>82</td>
<td>63.5</td>
<td>52.19</td>
<td>BS</td>
</tr>
<tr>
<td>BS</td>
<td>39</td>
<td>99.0</td>
<td>63.34</td>
<td>Accept, S, T</td>
</tr>
<tr>
<td>T</td>
<td>16</td>
<td>52.2</td>
<td>43.40</td>
<td>BS</td>
</tr>
<tr>
<td>B</td>
<td>21</td>
<td>94.5</td>
<td>68.50</td>
<td>Accept</td>
</tr>
<tr>
<td>ST*</td>
<td>7</td>
<td>61.4</td>
<td>31.98</td>
<td>---</td>
</tr>
<tr>
<td>BST*</td>
<td>3</td>
<td>90.0</td>
<td>34.64</td>
<td>---</td>
</tr>
<tr>
<td>BT*</td>
<td>1</td>
<td>50.0</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

Table A.3 and A.4 show the results of a comparison between cause of degradation and visually estimated amount of compression wood on the stud's four faces. The comparisons were based on 160 studs of the nominal dimension 50 by 75 mm. The amount of visible compression wood in the sawn products was expressed as CW units (see materials and methods for definition).

Table A.3 shows the total sum of visible compression wood in the log, based on all 4 studs from each log. Statistically significant differences could be proven to exist between the accepted studs and those rejected due to spring, S, and the combination of spring and bow. In general, the larger amount of compression wood shown within the sawn products of the log the higher rate of rejected products could be expected. Degradation due to twist exhibited no relation to large amounts of compression wood in this comparison.
### Table A.3: Mean value and standard deviation of amount of visible compression wood expressed as CW units on all 4 studs from a log, with the material grouped according to cause of degradation of wall studs. Tests for statistically significant, S.D, differences between the groups at an alpha level of 0.05. The degradation categories are S for spring, B for bow, T for twist and combinations of these; * denotes a low number of observations, n is the number of studs

<table>
<thead>
<tr>
<th>Degradation Category</th>
<th>n</th>
<th>Mean</th>
<th>Std Dev</th>
<th>S.D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accepted</td>
<td>91</td>
<td>466</td>
<td>342.1</td>
<td>BS, S</td>
</tr>
<tr>
<td>S</td>
<td>35</td>
<td>722</td>
<td>445.7</td>
<td>Accept</td>
</tr>
<tr>
<td>BS</td>
<td>17</td>
<td>1001</td>
<td>336.0</td>
<td>Accept</td>
</tr>
<tr>
<td>T*</td>
<td>4</td>
<td>435</td>
<td>110.6</td>
<td>---</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>661</td>
<td>399.2</td>
<td>---</td>
</tr>
<tr>
<td>ST*</td>
<td>3</td>
<td>1078</td>
<td>495.4</td>
<td>---</td>
</tr>
<tr>
<td>BST*</td>
<td>1</td>
<td>1364</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>BT*</td>
<td>1</td>
<td>1364</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

In table A.4 the results are expressed for each cause of degradation as the mean amount of compression wood of each individual stud. The accepted studs and the studs degraded due to excessive twist only, T, had less compression wood than the other categories. The studs rejected due to excessive bow, B, and spring, S, exhibited equal amounts of compression wood, more than 1.5 times more than the accepted studs. The greatest mean amount of compression wood was found among studs which could be rejected due to both bow and spring (BS). The tendency toward an increased risk of rejection due to excessive bow and spring as the observed amount of compression wood increases can be seen both in table A.3 and A.4.
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Table A.4: Mean value and standard deviation of amount of visible compression wood, in CW units, on each individual stud, grouped according to the cause of degradation of the wall stud. Tests for statistically significant differences, S.D, between the groups at an alpha level of 0.05. The degradation categories are S for spring, B for bow, T for twist and combinations of these; * denotes a low number of observations, n is the number of studs.

<table>
<thead>
<tr>
<th>Degradation Category</th>
<th>n</th>
<th>Mean</th>
<th>Std Dev</th>
<th>S.D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accepted</td>
<td>93</td>
<td>147</td>
<td>127.2</td>
<td>S, BS</td>
</tr>
<tr>
<td>S</td>
<td>36</td>
<td>240</td>
<td>172.0</td>
<td>Accept</td>
</tr>
<tr>
<td>BS</td>
<td>17</td>
<td>291</td>
<td>131.8</td>
<td>Accept</td>
</tr>
<tr>
<td>T</td>
<td>6</td>
<td>139</td>
<td>94.4</td>
<td>---</td>
</tr>
<tr>
<td>B</td>
<td>11</td>
<td>235</td>
<td>122.7</td>
<td>---</td>
</tr>
<tr>
<td>ST*</td>
<td>3</td>
<td>385</td>
<td>104.9</td>
<td>---</td>
</tr>
<tr>
<td>BST*</td>
<td>1</td>
<td>460</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>BT*</td>
<td>1</td>
<td>434</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
APPENDIX B

The impact of log features and resawing methods on the amount of accepted wall studs
B.1 Purpose
The purposes of the comparisons made in this appendix were:

- To study the possibility of increasing the yield of accepted wall studs by an adapted grading of sawlogs.
- To study the relationships between the yield of accepted wall studs, log features and resawing methods.

B.2 Major findings

- The log-grading method of VMR can be used to separate logs suitable for wall stud production from those that are not. Logs of quality grade 3 give a considerably higher yield of accepted wall studs than logs of quality grade 4.

- The tolerances for acceptable log sweep and amount of compression wood visible in the butt end of the log in the regulations of VMR can be adjusted to be more efficient than the regulations of today in identifying logs that will give extremely poor yields.

- If possible, only logs with no measurable log sweep should be resawn into wall studs.

- Minor amounts of visible compression wood can be accepted in sawlogs. An amount up to 40 cm² did not affect the yield of accepted wall studs.

- The choice of resawing method, dry or green, does not affect the yield of accepted wall studs from sawlogs of good quality.

- Among the high quality sawlogs with either no compression wood or no log sweep, only 35% yielded 4 accepted wall studs out of 4 possible.
B.3 Material and methods

The study was based on 90 butt logs of Norway spruce (Picea abies L. Karst). The evaluations of the results were based on the sawlogs being grouped in several different ways:

The sawlogs were selected and divided in to 5 grades (five-grade) according to the amount of visible compression wood in the log’s butt end and magnitude of the log sweep, according to the criteria shown in figure 3 chapter 2. A general quality grading of the logs according to VMR’s measuring regulations for the piece-by-piece measurement of coniferous sawlogs was done as well (Anon 1997). Quality grading in accordance with VMR resulted in 51 logs of the quality grade 3, denoted as III in the report, and 39 logs of the quality grade 4, denoted as IV. Groupings of the logs by magnitude of log sweep and by amount of visible compression wood in the butt end of the log alone were done as well. The results of these groupings were then expressed as mean magnitudes of warp and by yield of accepted wall studs when graded with respect to observed straightness by the grading rules for wall studs suggested by Johansson et al. (1993).

The yield of accepted wall studs was also expressed in two different ways: As a yield expressed as percentage of accepted studs of all studs included in each specific group and as a yield per log of each log grade. The logs in the latter case were divided into three classes: all 4 studs, 2 to 3 studs out of 4 and finally 0 to 1 stud per log, accepted, denoted as 4, 2-3 and 0-1.

Comparisons of statistically significant differences in group mean values were done by Tukey Kramers Honestly Significant Tests. Fisher’s Exact Chi² test and Pearson Chi² test were used to analyse whether the observed differences between the grouped logs’ yields of accepted wall studs were significantly different or not. All tests were done at an alpha-level of 0.05. All statistical analyses were done with the aid of the software JMP, a product from SAS Institute Inc. (Anon 1994).
B.4 Results

B.4.1 Magnitude of warp

The observed magnitudes of warp for studs were grouped by resawing method and log quality. The logs were quality graded by two different methods, the VMR method and a five-grade method. The purpose of this comparison was to get a more detailed picture of how the logs' features affect the magnitude of warp.

In table B1 to B6 the number of observations, mean values and standard deviations of each group of studs are shown. Whether the observed mean values of each group were significantly different from any of the other groups was also tested by Tukey-Kramer HSD test.

Logs grouped by VMR quality:

In table B1 the amount of compression wood in studs of the dimensions 50 x 75 mm is shown, expressed as % of the stud area. As can be seen, the spread of observations was large in each group. Thus studs with large amounts of compression wood, as well as studs free from compression wood, could be found in each group. In general, studs from logs of grade IV had a significantly higher amount of compression wood than studs from log grade III did.

Table B.1: Amount of visible compression wood, %, seen in wall studs, grouped by resawing method, Dry and Green, and by the logs' quality grade according to VMR, III and IV. The results are shown as the numbers of observations, n, mean values, Mean, standard deviations and if significant differences were found to other groups.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mean (%)</th>
<th>Standard Deviation</th>
<th>Significantly Different from</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Dry III</td>
<td>52</td>
<td>31</td>
<td>22.0</td>
<td>C, D</td>
</tr>
<tr>
<td>B. Green III</td>
<td>46</td>
<td>23</td>
<td>27.5</td>
<td>C, D</td>
</tr>
<tr>
<td>C. Dry IV</td>
<td>30</td>
<td>49</td>
<td>27.1</td>
<td>A, B</td>
</tr>
<tr>
<td>D. Green IV</td>
<td>40</td>
<td>47</td>
<td>26.8</td>
<td>A, B</td>
</tr>
</tbody>
</table>

Table B.2 to B.4 show the impacts of each resawing method and log grades on the magnitudes of bow, spring and twist. In table B.2 the results of bow are shown. Studs that were resawn green showed a lower mean bow than studs resawn dry, regardless of log grade. The difference in bow between the two resawing methods increases with decreasing log quality. By resawing studs from logs of quality grade IV to the final dimension before drying, it was possible to decrease the mean bow and standard deviation to a level only slightly higher than studs resawn dry from logs of quality III.
Table B.2: Magnitude of Bow in mm for wall studs grouped by resawing method, *Dry* and *Green*, and by the logs' quality according to VMR. The results are shown as the number of observations, *n*, group mean values, *Mean*, standard deviations and if significant differences were found to other groups.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mean (mm)</th>
<th>Standard Deviation</th>
<th>Significantly Different from</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Dry III</td>
<td>107</td>
<td>3.4</td>
<td>2.9</td>
<td>C</td>
</tr>
<tr>
<td>B. Green III</td>
<td>96</td>
<td>2.7</td>
<td>2.3</td>
<td>C</td>
</tr>
<tr>
<td>C. Dry IV</td>
<td>72</td>
<td>6.6</td>
<td>5.8</td>
<td>A, B, D</td>
</tr>
<tr>
<td>D. Green IV</td>
<td>84</td>
<td>3.8</td>
<td>3.0</td>
<td>C</td>
</tr>
</tbody>
</table>

In table B.3 the results of spring are shown. Studs that were resawn green showed a lower mean spring than studs resawn dry, regardless of log grade. Regarding differences related to log quality, the resawn green studs showed less difference than the studs resawn dried did.

Table B.3: Magnitude of Spring in mm for wall studs grouped by resawing method, *Dry* and *Green*, and by the logs' quality according to VMR. The results are shown as the number of observations, *n*, group mean values, *Mean*, standard deviations and if significant differences were found to other groups.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mean (mm)</th>
<th>Standard Deviation</th>
<th>Significantly Different from</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Dry III</td>
<td>107</td>
<td>3.6</td>
<td>3.4</td>
<td>C</td>
</tr>
<tr>
<td>B. Green III</td>
<td>96</td>
<td>3.3</td>
<td>2.4</td>
<td>C</td>
</tr>
<tr>
<td>C. Dry IV</td>
<td>72</td>
<td>6.7</td>
<td>5.9</td>
<td>A, B, D</td>
</tr>
<tr>
<td>D. Green IV</td>
<td>84</td>
<td>5.0</td>
<td>4.4</td>
<td>C</td>
</tr>
</tbody>
</table>
Methods for Avoiding the Negative Effects of Compression Wood

In Table B.4 the results for twist are shown. No pronounced tendency toward differences between log grades regarding the mean magnitude of twist could be found. However, there was a tendency for studs resawn green to have a larger degree of twist than those resawn dry. The difference between the resawing methods was considerably smaller for the studs originating from quality grade III logs compared to the difference shown for studs from quality grade IV.

Table B.4: Magnitude of Twist in mm for wall studs grouped by resawing method, Dry and Green, and by the logs’ quality according to VMR. The results were shown as the number of observations, n, mean values, Mean, standard deviations and if a significant difference was found to other groups.

<table>
<thead>
<tr>
<th>Magnitude of Twist in Wall Studs</th>
<th>n</th>
<th>Mean (mm)</th>
<th>Standard Deviation</th>
<th>Significantly Different from</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Dry III</td>
<td>107</td>
<td>1.0</td>
<td>1.4</td>
<td>B</td>
</tr>
<tr>
<td>B. Green III</td>
<td>96</td>
<td>2.6</td>
<td>2.5</td>
<td>A, C, D</td>
</tr>
<tr>
<td>C. Dry IV</td>
<td>72</td>
<td>1.4</td>
<td>2.0</td>
<td>B</td>
</tr>
<tr>
<td>D. Green IV</td>
<td>84</td>
<td>1.7</td>
<td>2.0</td>
<td>B</td>
</tr>
</tbody>
</table>

Logs grouped by five-grade:
Tables B.5 to B.7 show the mean values, the standard deviations, number of observations and whether significant differences can be shown between the groups of logs divided according to five-grade grading and resawing method.

In Table B.5 the results of how the magnitude of bow varies between the grades are shown. As can be seen, approximately the same levels were shown for both resawing methods. The difference between the resawing methods was most pronounced among studs from poor quality logs of grade 3+ and 3-. Most beneficial for these log grades was to resaw to the final dimension before drying, the resaw green method. Based on observed magnitude of bow, no arguments were found to justify a division of the logs into more than two grades. How to divide depends on which resawing method is to be used. If the studs were to be resawn green, log grades 2- and 3- could be united into a grade less suitable for stud production while the differences between 1, 2+ and 3+ were small. Among studs resawn dry, a rejection of grade 3- logs was definitely needed in the production of wall studs and 3+ was less suitable while the differences between grade 1, 2+ and 2- were small.
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Table B.5: Magnitude of Bow in wall studs grouped by resawing method, Dry and Green, and by the logs' outer features in five grades. The results are shown as number of observations, n, group mean values, Mean, standard deviations and if significant difference were found to other classes.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Mean (mm)</th>
<th>Standard Deviation</th>
<th>Significantly Different from</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Dry 1</td>
<td>32</td>
<td>3.4</td>
<td>3.98</td>
<td>E</td>
</tr>
<tr>
<td>B: Dry 2+</td>
<td>44</td>
<td>3.1</td>
<td>2.31</td>
<td>E</td>
</tr>
<tr>
<td>C: Dry 2-</td>
<td>27</td>
<td>3.8</td>
<td>2.64</td>
<td>E</td>
</tr>
<tr>
<td>D: Dry 3+</td>
<td>28</td>
<td>4.6</td>
<td>2.70</td>
<td>E</td>
</tr>
<tr>
<td>E: Dry 3-</td>
<td>48</td>
<td>7.5</td>
<td>6.66</td>
<td>All</td>
</tr>
<tr>
<td>F: Green 1</td>
<td>36</td>
<td>2.0</td>
<td>1.93</td>
<td>E</td>
</tr>
<tr>
<td>G: Green 2+</td>
<td>36</td>
<td>3.1</td>
<td>3.06</td>
<td>E</td>
</tr>
<tr>
<td>H: Green 2-</td>
<td>32</td>
<td>3.9</td>
<td>3.91</td>
<td>E</td>
</tr>
<tr>
<td>I: Green 3+</td>
<td>36</td>
<td>2.4</td>
<td>2.44</td>
<td>E</td>
</tr>
<tr>
<td>J: Green 3-</td>
<td>40</td>
<td>4.6</td>
<td>4.58</td>
<td>E</td>
</tr>
</tbody>
</table>

In table B.6 the results for magnitude of spring of each log grade are shown. The same trend can be seen for spring that was shown for bow. Notable was that the mean magnitudes of spring were at the same levels as observed for bow in comparable log grades.

The observed differences in magnitude of mean spring between the five studied grades do not justify more than two grades of logs. If the mean value and the standard deviation are regarded for each log grade, it is only log grade 3- that shows a strikingly larger spring than the other log grades, regardless of resawing method.

In table B.7 the magnitude of twist is shown for each log grade. Notable was that no apparent relation could be seen between magnitude of twist and the quality of the log. Studs that were resawn green showed a slightly larger twist than studs resawn dry did. Regarding the magnitude of twist, the observed differences were too small to justify pregrading of the logs.
### Table B.6: Magnitude of Spring in mm of wall studs grouped by resawing method, Dry and Green, and the logs' outer features in five classes. The results are shown as number of observations, \( n \), group mean values, \( Mean \), standard deviations and whether significant difference were found to other classes.

<table>
<thead>
<tr>
<th></th>
<th>( n )</th>
<th>( Mean ) (mm)</th>
<th>Standard Deviation</th>
<th>Significantly Different from</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Dry 1</td>
<td>32</td>
<td>4.0</td>
<td>4.34</td>
<td>E</td>
</tr>
<tr>
<td>B: Dry 2+</td>
<td>44</td>
<td>3.1</td>
<td>2.32</td>
<td>E, J</td>
</tr>
<tr>
<td>C: Dry 2-</td>
<td>27</td>
<td>3.9</td>
<td>3.61</td>
<td>E</td>
</tr>
<tr>
<td>D: Dry 3+</td>
<td>28</td>
<td>4.3</td>
<td>3.15</td>
<td>E</td>
</tr>
<tr>
<td>E: Dry 3-</td>
<td>48</td>
<td>7.8</td>
<td>6.66</td>
<td>A, B, C, D, F, G, H, I</td>
</tr>
<tr>
<td>F: Green 1</td>
<td>36</td>
<td>3.3</td>
<td>1.88</td>
<td>E, J</td>
</tr>
<tr>
<td>G: Green 2+</td>
<td>36</td>
<td>3.6</td>
<td>3.10</td>
<td>E</td>
</tr>
<tr>
<td>H: Green 2-</td>
<td>32</td>
<td>3.9</td>
<td>2.63</td>
<td>E</td>
</tr>
<tr>
<td>I: Green 3+</td>
<td>36</td>
<td>3.1</td>
<td>2.35</td>
<td>E, J</td>
</tr>
<tr>
<td>J: Green 3-</td>
<td>40</td>
<td>6.2</td>
<td>5.46</td>
<td>B, F, I</td>
</tr>
</tbody>
</table>

### Table B.7: Magnitude of Twist in mm of wall studs grouped by resawing method, Dry and Green, and the logs' outer features in five grades. The results are shown as number of observations, \( n \), group mean values, \( Mean \), standard deviations and whether significant differences were found to other classes.

<table>
<thead>
<tr>
<th></th>
<th>( n )</th>
<th>( Mean ) (mm)</th>
<th>Standard Deviation</th>
<th>Significantly Different from</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Dry 1</td>
<td>32</td>
<td>0.5</td>
<td>0.81</td>
<td>G</td>
</tr>
<tr>
<td>B: Dry 2+</td>
<td>44</td>
<td>0.8</td>
<td>1.14</td>
<td>G</td>
</tr>
<tr>
<td>C: Dry 2-</td>
<td>27</td>
<td>1.0</td>
<td>1.30</td>
<td>G</td>
</tr>
<tr>
<td>D: Dry 3+</td>
<td>28</td>
<td>1.4</td>
<td>1.39</td>
<td>G</td>
</tr>
<tr>
<td>E: Dry 3-</td>
<td>48</td>
<td>1.2</td>
<td>2.04</td>
<td>G</td>
</tr>
<tr>
<td>F: Green 1</td>
<td>36</td>
<td>1.5</td>
<td>1.81</td>
<td>G</td>
</tr>
<tr>
<td>G: Green 2+</td>
<td>36</td>
<td>1.7</td>
<td>1.56</td>
<td>G</td>
</tr>
<tr>
<td>H: Green 2-</td>
<td>32</td>
<td>4.1</td>
<td>2.50</td>
<td>All</td>
</tr>
<tr>
<td>I: Green 3+</td>
<td>36</td>
<td>1.5</td>
<td>1.57</td>
<td>G</td>
</tr>
<tr>
<td>J: Green 3-</td>
<td>40</td>
<td>1.7</td>
<td>2.16</td>
<td>G</td>
</tr>
</tbody>
</table>
When the results of the five-grade and the VMR classifications of the studs were compared, it could be seen that among studs resawn dry, the differences were small for logs of the better quality (low amounts of compression wood and no observed log sweep). Among studs originating from logs of a poorer quality, the five-grade method showed a better ability to identify logs that gave high magnitudes of bow and spring. The observed differences in twist were, however, small.

If corresponding comparisons were made between studs resawn green, the five-grade classification showed a better ability to find logs that resulted in studs with low bow and twist than the VMR method. For spring the differences between the methods were negligible. Regarding studs originating from logs of a poorer quality, the five-grade method proved better there, as well; for bow and spring group 3 had higher mean values than log grade IV did and equal magnitudes of twist.

The conclusion was that the VMR method was competitive in identifying logs giving low magnitudes of warp. The resolution of the five-grade method, however, was better at identifying logs giving high magnitudes of bow and spring.

B.4.2 Yield of accepted studs

In this part the studs were graded with respect to straightness according to the regulations recommended by Johansson et al. (1993) for the purpose of studying the impact of resawing methods and log features on the level of accepted studs.

The wall studs were grouped in three different ways: by the quality grade of the logs according to the method of VMR, by the five-grade method and by grouping based on the yield of accepted studs from each log.

In this chapter the studs were graded with respect to the magnitude of warp into two classes: those that met the tolerances for straightness and those that did not. In the tables only the amount of studs meeting the demands for straightness were shown, expressed in % of the total number of studs per group.

In those cases where only two groups were compared, a Fischer's Exact Chi² test with one degree of freedom was applied, and when more than two groups were compared a Pearson's Chi² test was used, both methods at an alpha-level of 0.05.

Logs grouped by VMR quality:

In table B.8 the acceptance levels are shown for wall studs grouped by the logs' quality grades (VMR). If the total acceptance is compared, it can be seen that the two resawing methods gave approximately the same yield of accepted studs.

Among studs originating from logs of grade IV there was a tendency for resawn green to give the higher yield. Large differences between the resawing methods can only be shown in twist for logs of grade III and in bow for logs of grade IV, both differences statistically significant.
Table B.8: Percentage of wall studs meeting the tolerances for bow, spring and twist when all three features were regarded, Total, and for each single type of warp. The studs were grouped by resawing method, Green and Dry and by the quality grade of the log, III and IV. Sign. Diff. indicates whether the observed difference between the resawing methods was significant. In brackets the probability of a randomly chosen distribution giving an equal or larger difference than the observed is shown.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow</td>
<td>89</td>
<td>94</td>
<td>No (0.32)</td>
<td>57</td>
<td>82</td>
<td>Yes (0.00)</td>
</tr>
<tr>
<td>Spring</td>
<td>73</td>
<td>73</td>
<td>No (1.00)</td>
<td>44</td>
<td>57</td>
<td>No (0.15)</td>
</tr>
<tr>
<td>Twist</td>
<td>98</td>
<td>84</td>
<td>Yes (0.00)</td>
<td>96</td>
<td>92</td>
<td>No (0.34)</td>
</tr>
<tr>
<td>Total</td>
<td>67</td>
<td>61</td>
<td>No (0.60)</td>
<td>31</td>
<td>45</td>
<td>No (0.07)</td>
</tr>
<tr>
<td>n</td>
<td>107</td>
<td>96</td>
<td>204</td>
<td>72</td>
<td>84</td>
<td>156</td>
</tr>
</tbody>
</table>

The differences due to log grade were considerably larger than the observed differences between resawing methods (tables B.8 and B.9). In table B.9 the differences between the log grades shown in table B.8 are compared for each resawing method. Both resawing methods showed a significantly higher total yield of accepted studs from logs of quality grade III than the total yield from logs of grade IV. In both cases, the higher yields were due to fewer studs being rejected due to bow and spring. Only minor differences in rejection rates due to twist were found.

Table B.9: Tests for significant differences in observed mean values of warp between studs grouped by log grades and resawing method. In brackets the probability of a randomly chosen distribution giving an equal or larger difference than the observed is shown.

<table>
<thead>
<tr>
<th>Significant Differences in the Amount of Accepted Wall Studs Grouped by Log Grade</th>
<th>Sign. Diff.</th>
<th>Sign. Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIII/DIV</td>
<td>Yes (0.00)</td>
<td>Yes (0.02)</td>
</tr>
<tr>
<td>Bow</td>
<td>Yes (0.00)</td>
<td>Yes (0.03)</td>
</tr>
<tr>
<td>Spring</td>
<td>Yes (0.00)</td>
<td>No (0.17)</td>
</tr>
<tr>
<td>Twist</td>
<td>No (0.39)</td>
<td>Yes (0.04)</td>
</tr>
<tr>
<td>Total</td>
<td>Yes (0.00)</td>
<td>Yes (0.04)</td>
</tr>
<tr>
<td>n</td>
<td>179</td>
<td>180</td>
</tr>
</tbody>
</table>

The general conclusions are: logs corresponding to quality grade III could be resawn by any of the methods, while the tendency was that logs corresponding to log grade IV should be resawn to wall studs when green.
Logs grouped by five-grade:

In chapter B.4.1 no significant differences were found between the logs of grade 1, 2+ and 3+. In this chapter these grades were united into one grade, denoted as 123+, in order to improve the resolution of the tests by an increased number of observations. The remaining two classes were, however, unchanged.

A comparison of the results from all three types of deformations revealed that the difference between the resawing methods was small (see Total in table B.10). Two thirds of all studs originating from high quality logs, 123+, were accepted. Divided into the original grades, the corresponding yield was 66% for log grade 1, 69% for grade 2+ and 59% for log grade 3+ when bow, spring and twist were taken into account.

The largest cause of degradation of the wall studs for all log groups was excessive spring. The yields for bow and spring showed approximately the same trends.

The differences in acceptance between the log grades 123+, 2- and 3- were proven to be significant in all cases except twist. Significance was tested by a Pearson Chi² test with 3 degrees of freedom and at an alpha level of 0.05.

Table B.10: Amount of accepted wall studs due to each specific type of warp and in total when all warps were taken into account, expressed in % of the total amount of studs in each group. The studs were grouped by method of resawing, Green and Dry, and by the quality of the logs in three classes, based on the five-grade log grading method. S.D denotes whether a statistical difference between the resawing methods exists. In brackets the probability of randomly chosen distributions causing a difference equal to or larger than the observed is given.

<table>
<thead>
<tr>
<th></th>
<th>123+</th>
<th></th>
<th></th>
<th>2-</th>
<th></th>
<th></th>
<th>3-</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Green</td>
<td>S.D</td>
<td>Dry</td>
<td>Green</td>
<td>S.D</td>
<td>Dry</td>
<td>Green</td>
</tr>
<tr>
<td>Bow</td>
<td>86</td>
<td>95</td>
<td>Yes</td>
<td>85</td>
<td>81</td>
<td></td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.02)</td>
<td></td>
<td></td>
<td>(0.74)</td>
<td></td>
<td></td>
<td>(0.03)</td>
</tr>
<tr>
<td>Spring</td>
<td>69</td>
<td>74</td>
<td>No</td>
<td>68</td>
<td>62</td>
<td></td>
<td>42</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.43)</td>
<td></td>
<td></td>
<td>(0.79)</td>
<td></td>
<td></td>
<td>(0.83)</td>
</tr>
<tr>
<td>Twist</td>
<td>94</td>
<td>95</td>
<td>No</td>
<td>96</td>
<td>62</td>
<td>Yes</td>
<td>94</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.21)</td>
<td></td>
<td></td>
<td></td>
<td>(0.00)</td>
<td></td>
<td>(0.46)</td>
</tr>
<tr>
<td>Total</td>
<td>63</td>
<td>67</td>
<td>No</td>
<td>57</td>
<td>41</td>
<td>No</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.77)</td>
<td></td>
<td></td>
<td>(0.30)</td>
<td></td>
<td></td>
<td>(0.64)</td>
</tr>
<tr>
<td>n</td>
<td>104</td>
<td>108</td>
<td>212</td>
<td>27</td>
<td>32</td>
<td>59</td>
<td>48</td>
<td>40</td>
</tr>
</tbody>
</table>
Yield per log:
The comparisons made above were all focused on how many studs were accepted from a group of logs of a specific quality. In this part the focus is on describing the yield of accepted wall studs for each log. The combination of yield and cost of sawlogs determines whether or not a log is profitable to saw. This was one reason why the acceptances were expressed per log for the purpose of evaluating the possibility of grading each individual log by its potential to yield a high amount of accepted wall studs. A study based on 89 logs in total.

Yield per log/ VMR:
In table B.11 the amounts of accepted studs are shown for the log grades III and IV, divided into three yield classes: 0-1, 2-3 and 4 accepted studs per log. In columns denoted III and IV the amount of accepted studs is shown without regard for the resawing methods used. In columns denoted D-III, G-III, D-IV and G-IV the logs are grouped by resawing method used, as well, Dry and Green. The results below columns III and IV show if differences in distribution could be found between the two log grades. The other two show if differences could be found between the resawing methods for each log grade.

As can be seen, the difference in the distribution between the log grades was large enough to be significant in this study. The grade III logs gave a higher yield than logs of grade IV. More interesting, however, was the distribution of logs over the three yield classes. One half of the logs of grade III were found in yield class 2-3, and one fifth in yield class 0-1.

A comparison of yield distribution between the resawing methods used shows no significant differences on this material. The tendencies found were that logs of grade III were more advantageously resawn dry, while the method of resawing green was more beneficial in producing wall studs from grade IV logs (table B.11 column D-III to G-IV).
Table B.11: Distribution of logs in yield classes defined as the number of accepted studs out of 4 possible per log, that is, the number of studs that met demands on straightness. The logs were grouped by VMR's log grades, III and IV, and by resawing method, Dry and Green. For each yield class the numbers of logs expressed in % of all logs of each grade is shown. N is the number of logs included in the Chi² tests and n is the number of logs of each grade. Sign. diff. denotes if significant differences in the distributions could be shown at an alpha level of 0.05. D.F. is the tests’ degrees of freedom. Chi² is the calculated Chi² values of each test. Cell Chi² is each cell’s value. Prob > Chi² is the probability of a randomly chosen distribution showing a difference as equal to or larger than the observed.

<table>
<thead>
<tr>
<th></th>
<th>III</th>
<th>IV</th>
<th>D-III</th>
<th>G-III</th>
<th>D-IV</th>
<th>G-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>19.6</td>
<td>52.6</td>
<td>18.5</td>
<td>20.8</td>
<td>6.1</td>
<td>45.0</td>
</tr>
<tr>
<td></td>
<td>Cell Chi²</td>
<td>3.0</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.25</td>
</tr>
<tr>
<td>2-3</td>
<td>51.0</td>
<td>36.8</td>
<td>44.4</td>
<td>58.3</td>
<td>33.3</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td>Cell Chi²</td>
<td>0.4</td>
<td>0.6</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>29.4</td>
<td>10.5</td>
<td>37.0</td>
<td>20.8</td>
<td>5.6</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Cell Chi²</td>
<td>1.5</td>
<td>2.1</td>
<td>0.5</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>N</td>
<td>51</td>
<td>39</td>
<td>27</td>
<td>24</td>
<td>18</td>
<td>21</td>
</tr>
</tbody>
</table>

Yield per log/five-grade:
The logs were originally grouped into 5 grades based on degree of log sweep and amount of visible compression wood in the logs’ butt ends. As shown in previous chapters, the number of grades could be reduced as a consequence of small differences in magnitudes of warp and grading results. In this part the distribution of logs per yield class is shown for all 5 grades (table B.12). As could be expected, grade 1 had the largest amount of logs where all 4 studs were accepted, and grade 3- the lowest. A statistical test for significance in the observed differences between all 5 log groups in table B.12 showed a 0.00 probability that a randomly chosen distribution could give the same differences, or larger, than the observed. The test used was Pearson Chi² test with 8 degrees of freedom and 90 observations. From the cell-chi²-values it could be concluded that it was primarily logs of grade 3- that caused the significant difference in the test by giving a considerably poorer yield of accepted studs.

By chi² tests it could be shown that no statistically significant differences could be proven to exist between logs of grade 1, 2+ and 3+.
Table B.12: The frequency distribution, in %, of logs in three yield classes, 0-1, 2-3 and 4 studs out of 4 possible studs accepted per log. The logs were grouped by the five-grade method into the classes 1, 2+, 2-, 3+ and 3-. The calculated Chi² value of each group is also shown.

<table>
<thead>
<tr>
<th>Yield of Accepted Studs/Log</th>
<th>1</th>
<th>2+</th>
<th>2-</th>
<th>3+</th>
<th>3-</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1 %</td>
<td>18</td>
<td>10</td>
<td>47</td>
<td>31</td>
<td>64</td>
<td>31</td>
</tr>
<tr>
<td>Chi²</td>
<td>1.4</td>
<td>3.5</td>
<td>0.6</td>
<td>0.0</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>2-3 %</td>
<td>47</td>
<td>65</td>
<td>27</td>
<td>44</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Chi²</td>
<td>0.0</td>
<td>1.9</td>
<td>1.1</td>
<td>0.0</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>4 %</td>
<td>35</td>
<td>25</td>
<td>27</td>
<td>25</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>Chi²</td>
<td>1.6</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>17</td>
<td>20</td>
<td>15</td>
<td>16</td>
<td>22</td>
<td>90</td>
</tr>
</tbody>
</table>

The relation between the yield of accepted studs and the quality of the logs was not totally linear; a stepwise decrease of the yield could be seen, exemplified by the fact that more than 80% of the logs of grade 1 and 2+ yielded 2 or more accepted studs, while 75% of the logs of grade 2- and 100% of the grade 3- logs yielded 3 or fewer accepted studs per log. These findings were indications of log sweep being a better indicator than the amount of compression wood in predicting the yield of accepted studs. This assumption is based on the fact that the major shift occurs when the log sweep changes, while a change in the amount of compression wood has only a minor impact on the distribution (see log grade 1, 2+ and 3+).
B.5 Yield of accepted studs, logs’ magnitude of sweep and amount of compression wood

It has been shown in earlier chapters that the two compression-wood-related log features studied, sweep and butt-end compression wood, can be used to increase the yield of accepted wall studs. In these comparisons a tendency was noticed for the magnitude of log sweep to be the better indicator in predicting the yield of accepted studs.

In table B.14 the correlation coefficients between the three types of deformations bow, spring and twist and each one of the two log features are shown. Twist shows almost no correlation to the two log features, and the correlation is also rather low for Bow and Spring.

Table B.14: Observed correlation \([r]\) between the two studied log features respectively and each type of deformation, split between the two resawing methods, Dry and Green.

<table>
<thead>
<tr>
<th></th>
<th>Bow</th>
<th>Spring</th>
<th>Twist</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW-log Green</td>
<td>0.25</td>
<td>0.33</td>
<td>-0.11</td>
</tr>
<tr>
<td>CW-log Dry</td>
<td>0.39</td>
<td>0.32</td>
<td>0.14</td>
</tr>
<tr>
<td>Sweep Green</td>
<td>0.32</td>
<td>0.40</td>
<td>0.04</td>
</tr>
<tr>
<td>Sweep Dry</td>
<td>0.24</td>
<td>0.33</td>
<td>0.13</td>
</tr>
</tbody>
</table>

In figure B.3 the distribution of the yield of studs meeting the tolerances for straightness is shown for an increasing magnitude of log sweep. The yield of accepted studs decreases with increasing magnitude of log sweep. Among logs with no sweep, 67% of the studs met the demands on straightness, while less than 17% of the studs from logs with a sweep of 4 cm or more were accepted. Log sweep was expressed in cm and measured over a length of 3 m. Group 0 was based on 188 studs, 52 studs were included in group 1, 60 studs in group 2, 24 studs in group 3 and 36 studs in group 4.

Based on these findings it can be concluded that a minor amount of compression wood can be accepted on logs suitable for wall studs production, but not more than 35 to 40 cm². Logs with a large amount, 100 cm² or more, are not suitable at all due to the poor yield of accepted wall studs. In comparison, log sweep seems to have the larger impact on the yield of accepted wall studs and can therefore be regarded as the more efficient indicator of the two features. The differences were however small. In practice the log sweep is a considerably more reliable feature than the amount of compression wood, in terms of measurability. If this latter argument is regarded, only log sweep should be measured in a pre-grading to avoid compression wood in the sawn products.
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Figure B.3:  The yield of accepted studs, in %, from logs grouped by the magnitude of sweep, in cm, measured over a length of 3 m.

Figure B.4:  Yield of accepted studs, in %, from logs grouped by the amount of visible butt-end compression wood.
APPENDIX C

Relationship between the amount of compression wood in sawn products and the magnitude of warp
C.1 Purpose
The purpose of the comparisons made in this appendix was to study the relationships between the amount of compression wood visible on the faces of the piece of wood; the resawing method, green or dry; and the amount of accepted studs when graded with respect to straightness, all this in order to evaluate the possibility of separating planks suitable for resawing from those that are not.

C.2 Major findings
The major findings shown in this appendix are as follows:

- Only planks showing low amounts of compression wood, up to 10%, are suitable for wall stud production and should be resawn when dried to achieve highest possible yield of accepted wall studs.

- Planks showing high amounts of compression wood (>50%) are not suitable for wall stud production no matter what resawing method is used. However, considerably fewer of the resawn dry studs were accepted, 18%, compared to studs resawn green, 35%.

C.3 Material and methods
This study was based on 168 wall studs of the nominal dimensions 50 x 75 mm resawn out of 84 planks of the nominal dimensions 50 x 150 mm. The studs were grouped by the amount of observed compression wood into three groups and by resawing method, green or dry, into 6 groups. 21 planks with small amounts of compression wood, less than 105 CW-units or < 12%, are denoted as CW-Low. A group of 42 planks with an amount of compression wood between 105 and 453 CW-units, 12% to 50%, are denoted as CW-Medium. The remaining 21 planks, denoted as CW-High show more than 453 CW-units, or > 50%, of compression wood. The theoretically maximum amount of compression wood seen on the surface of a plank, when the surface is totally covered by compression wood, was 900 CW-units.
C.4 Results

The observed linear correlations between the amount of compression wood and each of the types of warp bow, spring or twist were all too poor to make a reliable prediction of each stud’s magnitude of bow, spring or twist. The correlations \( r \) shown between the amount of compression wood and bow was 0.32, spring 0.46, and twist 0.005 based on 168 studs of the dimensions 50 x 75 mm in this study. No differences could be found between the two resawing methods. The observed correlations were statistically significant at an alpha level of 0.05 for bow and spring, but not for twist.

The mean amount of compression wood in planks classified as \( CW-Low \) was 35.5 CW-units or 3.9%. Planks classified as \( CW-Medium \) had a mean value of 281 CW-units or 31%. And finally, planks classified as \( CW-High \) had a mean value of 625 CW-units or 69%.

C.4.1 Magnitude of warp

In this chapter the studs were grouped by the amount of compression wood visible on the surface of the plank into three groups. The purpose was to determine if planks with high amounts of compression wood show larger magnitudes of warp than planks free from compression wood do.

In table C.1 it is shown how the mean magnitude of bow increases with increasing amounts of compression wood, a tendency more pronounced among the wall studs resawn dried. The impact of the resaw green method on the magnitude of bow was greater than that of the resawn dry method. Significant differences in group mean values could, however, only be shown between studs from planks resawn dry, medium to high in compression wood, and studs from planks resawn green, medium to low in compression wood.

Table C.1: Observed height of bow, in mm over a length of 3 m, measured on wall studs grouped by resawing method and amount of compression wood visible on the original planks. \( CW-Low \) were planks with less than 12% compression wood, \( CW-Medium \) 12% to 50% and \( CW-High > 50\% \). Dry denotes planks resawn when dried and Green denotes planks resawn when green. Sign. Diff. shows if the group mean value is significantly different from any other group.

<table>
<thead>
<tr>
<th>Observed Bow of Wall Studs</th>
<th>n</th>
<th>Mean (mm)</th>
<th>Std. Dev. (mm)</th>
<th>Sign. Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: CW-High Dry</td>
<td>22</td>
<td>5.6</td>
<td>3.52</td>
<td>D, F</td>
</tr>
<tr>
<td>B: CW-High Green</td>
<td>20</td>
<td>3.4</td>
<td>2.91</td>
<td>---</td>
</tr>
<tr>
<td>C: CW-Medium Dry</td>
<td>48</td>
<td>4.2</td>
<td>3.50</td>
<td>F</td>
</tr>
<tr>
<td>D: CW-Medium Green</td>
<td>36</td>
<td>3.2</td>
<td>2.72</td>
<td>A</td>
</tr>
<tr>
<td>E: CW-Low Dry</td>
<td>12</td>
<td>2.9</td>
<td>1.62</td>
<td>---</td>
</tr>
<tr>
<td>F: CW-Low Green</td>
<td>30</td>
<td>1.8</td>
<td>1.88</td>
<td>A, C</td>
</tr>
</tbody>
</table>
In table C.2 the corresponding values are shown for spring. A tendency toward a correlation between amount of compression wood and magnitude of spring could be seen; the larger amount of compression wood on the plank, the larger the magnitude of spring that can be expected. This tendency was more pronounced among the resawn dry planks. As can be seen in table C.2, only plank group CW-High Dry had an amount of spring that was significantly larger than the other groups.

Table C.2: Observed height of spring, in mm over a length of 3 m, measured on wall studs grouped by resawing strategy and amount of compression wood in the original planks. CW-Low were planks with less than 12% compression wood, CW-Medium 12% to 50% and CW-High > 50%. Dry denotes planks resawn when dried and Green denotes planks resawn when green. Sign. Diff. shows if the group mean value is significantly different from any other group.

<table>
<thead>
<tr>
<th>Observed Spring of Wall Studs</th>
<th>n</th>
<th>Mean (mm)</th>
<th>Std. Dev. (mm)</th>
<th>Sign. Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: CW-High Dry</td>
<td>22</td>
<td>7.5</td>
<td>6.19</td>
<td>C, D, E, F</td>
</tr>
<tr>
<td>B: CW-High Green</td>
<td>20</td>
<td>5.1</td>
<td>4.39</td>
<td>---</td>
</tr>
<tr>
<td>C: CW-Medium Dry</td>
<td>48</td>
<td>3.8</td>
<td>3.44</td>
<td>A</td>
</tr>
<tr>
<td>D: CW-Medium Green</td>
<td>36</td>
<td>3.1</td>
<td>2.29</td>
<td>A</td>
</tr>
<tr>
<td>E: CW-Low Dry</td>
<td>12</td>
<td>1.5</td>
<td>1.57</td>
<td>A</td>
</tr>
<tr>
<td>F: CW-Low Green</td>
<td>30</td>
<td>3.2</td>
<td>1.86</td>
<td>A</td>
</tr>
</tbody>
</table>

In table C.3 the magnitudes of twist are shown. In general, there was no tendency toward a relationship between the magnitude of twist and the amount of compression wood. However, studs resawn dry had a lower mean magnitude of twist than studs resawn green did. But only CW-High Dry and CW-High Green had a difference large enough to be statistically significant in this study; the latter showed the higher magnitude of twist.

C.4.2 Yield of accepted studs

Notable findings when the yield of accepted wall studs resawn by the methods dry and green shown in table C.4 are compared are: No significant differences could be seen between the two resawing methods when all three types of warp are considered together (Total). There was, however, a tendency for the resawn dry method to be more advantageous when only small amounts of compression wood were present, while the resawn green method became more and more advantageous when the amount of compression wood increased.

Throughout all three warp types, the resaw dry method gave higher yields than the resaw green method when only a minor amount of compression wood was present. The
more compression wood there is, the more beneficial the resaw green method becomes in
respect of bow. The difference between the methods that is due to spring disappears, and
as regards degradation due to excessive twist, the proportions were unchanged.

Table C.5 shows if the observed differences between the three CW-groupings were
large enough to be statistically significant. Twist was the only warp type where no
differences could be proven for either resawing method. As expected, studs resawn from
green planks showed no difference either. In all other comparisons, the differences were
large enough to be statistically significant at an alpha level of 0.05.

Conclusions that can be drawn based on the results shown in tables C.4 and C.5:
For planks with no or small amounts of compression wood, the tendency is that resawing
when dried gives a higher yield of accepted wall studs. When a large amount of
compression wood is present, approximately 50%, the resawn green method is the more
advantageous of the two methods compared. These trends are caused primarily by the
magnitude of spring, which caused the largest degradation of the studs, while degradation
due to excessive twist was very low.

If the best possible yield of accepted wall studs is to be achieved, it seems advisable to
resaw only planks free from compression wood and to use the resaw dry method. Planks
with large amounts of compression wood should not be resawn into wall studs at all.

Table C.3: Observed height of twist, measured on wall studs in mm over a length of
3 m. grouped by resawing method and amount of compression wood in the original
planks. CW-Low were planks with less than 12% compression wood, CW-Medium
12% to 50% and CW-High > 50%. Dry denotes planks resawn when dried and
Green denotes planks resawn when green. Sign. Diff. shows if the group mean value
is significantly different from any other group.

<table>
<thead>
<tr>
<th>Observed Twist of Wall Studs</th>
<th>n</th>
<th>Mean (mm)</th>
<th>Std. Dev. (mm)</th>
<th>Sign. Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: CW-High Dry</td>
<td>22</td>
<td>0.6</td>
<td>1.05</td>
<td>B</td>
</tr>
<tr>
<td>B: CW-High Green</td>
<td>20</td>
<td>2.5</td>
<td>3.22</td>
<td>A</td>
</tr>
<tr>
<td>C: CW-Medium Dry</td>
<td>48</td>
<td>1.1</td>
<td>1.73</td>
<td>---</td>
</tr>
<tr>
<td>D: CW-Medium Green</td>
<td>36</td>
<td>2.1</td>
<td>2.40</td>
<td>---</td>
</tr>
<tr>
<td>E: CW-Low Dry</td>
<td>12</td>
<td>0.7</td>
<td>1.23</td>
<td>---</td>
</tr>
<tr>
<td>F: CW-Low Green</td>
<td>30</td>
<td>1.7</td>
<td>2.05</td>
<td>---</td>
</tr>
</tbody>
</table>
Table C.4: Yield of accepted wall studs in %, divided into 6 groups by the amount of compression wood in planks and resawing method. CW-Low were planks with less than 12% compression wood, CW-Medium 12% to 50% and CW-High > 50%. Tests for significant difference between the resawing groups were made by Fisher's Exact test at an alpha level of 0.05. The value between brackets is the probability of a randomly chosen distribution showing equal or larger differences between the groups than observed.

<table>
<thead>
<tr>
<th></th>
<th>CW-Low</th>
<th></th>
<th></th>
<th>CW-Medium</th>
<th></th>
<th></th>
<th>CW-High</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow</td>
<td>100</td>
<td>93</td>
<td>No (1.00)</td>
<td>75</td>
<td>92</td>
<td>No (0.08)</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Spring</td>
<td>92</td>
<td>83</td>
<td>No (0.66)</td>
<td>69</td>
<td>69</td>
<td>No (1.00)</td>
<td>41</td>
<td>40</td>
</tr>
<tr>
<td>Twist</td>
<td>100</td>
<td>90</td>
<td>No (0.55)</td>
<td>98</td>
<td>92</td>
<td>No (0.31)</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Total</td>
<td>92</td>
<td>70</td>
<td>No (0.23)</td>
<td>58</td>
<td>61</td>
<td>No (0.83)</td>
<td>18</td>
<td>35</td>
</tr>
<tr>
<td>n</td>
<td>12</td>
<td>30</td>
<td>42</td>
<td>48</td>
<td>36</td>
<td>84</td>
<td>22</td>
<td>20</td>
</tr>
</tbody>
</table>

Table C.5: Tests for significant differences between the three CW groups of wall studs shown in table C.4. The results are shown for each resawing method, Dry or Green. The total \( \chi^2 \) value (Pearson) of the test and whether significant differences could be proven are indicated for each comparison, and in brackets the probability of a randomly chosen distribution showing an equal or larger difference than the observed is shown. N is the number of observations and D.F is the degrees of freedom of the test.

<table>
<thead>
<tr>
<th></th>
<th>Bow</th>
<th>Spring</th>
<th>Twist</th>
<th>Total</th>
<th>N</th>
<th>D.F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry ( \chi^2 )</td>
<td>8.4</td>
<td>6.8</td>
<td>0.8</td>
<td>14.8</td>
<td>82</td>
<td>2</td>
</tr>
<tr>
<td>Sign. Diff</td>
<td>Yes (0.02)</td>
<td>Yes (0.03)</td>
<td>No (0.68)</td>
<td>Yes (0.00)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green ( \chi^2 )</td>
<td>0.18</td>
<td>10.4</td>
<td>1.8</td>
<td>6.2</td>
<td>86</td>
<td>2</td>
</tr>
<tr>
<td>Sign. Diff</td>
<td>No (0.91)</td>
<td>Yes (0.01)</td>
<td>No (0.40)</td>
<td>Yes (0.04)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX D

Comparison of differences in the yield of accepted studs for different resawing patterns
D.1 Purpose
The purpose of the study described in this appendix was to compare the impact of different resawing patterns, symmetrical and asymmetrical, on the magnitude of warp and levels of acceptance. The background of the comparisons made was a question from a sawmill as to whether it was true that narrower studs in an asymmetrical resawing of the planks had the larger magnitudes of warp.

D.2 Major findings
The major findings in this appendix are as follows:

- The quality of the sawlog had a greater impact on the magnitude of warp than did the symmetry of the resawing pattern. No differences in the yield of accepted studs were found between studs asymmetrically and studs symmetrically resawn out of planks originating from the same log quality.

- In a pairwise comparison of the warp of the two studs from asymmetrically resawn planks showed: No differences in magnitude of bow, the narrower dimension showed on average a significantly larger magnitude of spring, while the wider studs tended to have a larger magnitude of twist.

D.3 Material and methods
The degree of warp of three different dimensions, of the nominal dimensions 50 x 50 mm, 50 x 75 mm and 50 x 100 mm, were compared. Studs of the dimensions 50 x 75 mm were symmetrically resawn out of the plank, and the other two dimensions were asymmetrically resawn (figure D.1). In all, 88 planks were symmetrically resawn and 91 asymmetrically resawn.

In order to investigate whether there was a difference due to the symmetry of the resawing pattern, the planks were sorted according to VMR log quality (Anon 1997). The purpose was to create a difference between the groups of wall studs according to the amount of compression wood. Studs originating from logs of quality grade III showed on average a smaller amount of compression wood than studs from log quality IV.

Comparisons were done from two perspectives.
The plank perspective: the studs were grouped based on the symmetry of the resawing pattern of the plank and were graded with respect to the straightness of the stud according to the tolerances and methods recommended by Johansson et al. (1993).

The asymmetrical perspective: a comparison done to discover if a difference exists in warp between the two asymmetrically resawn studs from the same plank.

Comparisons of differences in group mean value were analysed with the aid of Tukey-Kramers HSD test. Comparisons of differences in acceptance levels when graded
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with respect to straightness were analysed with the aid of Fisher's Exact Chi² Test. In the asymmetrical perspective, paired comparisons were done with the aid of a Student's t-test or a Signed-Rank test, depending on how valid an assumption of the observations being normally distributed was. All comparisons were done at a significance level (alpha level) of 0.05.

Figure D.1 A symmetrical resawing of a plank with the nominal dimensions 50 x 150 mm to two studs with the nominal dimensions 50 x 75 mm and an asymmetrical resawing to 50 x 50 mm and 50 x 100 mm.
D.4 Results

D.4.1 The magnitude of warp

In following three tables D.1, D.2 and D.3 the observed warp of studs grouped according to symmetry of the resawing pattern and log quality is compared.

Table D.1: Observed Bow on wall studs grouped according to symmetry of the resawing pattern and log grade shown as the number of observations, \( n_{\text{studs}} \), group mean values. Mean, and standard deviations, \( \text{Std Dev} \), of the observed bow. The wall studs were grouped according to symmetry of the resawing pattern into Asym for the asymmetrically resawn planks and Sym for the symmetrically resawn planks and by VMR-defined log quality into grades III and IV. Significant differences between the group mean values are shown, as well.

<table>
<thead>
<tr>
<th></th>
<th>( n_{\text{studs}} )</th>
<th>Mean (mm)</th>
<th>Std Dev (mm)</th>
<th>Sign.Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Asym-III</td>
<td>100</td>
<td>3.0</td>
<td>2.21</td>
<td>B</td>
</tr>
<tr>
<td>B: Asym-IV</td>
<td>84</td>
<td>5.7</td>
<td>5.76</td>
<td>A, C</td>
</tr>
<tr>
<td>C: Sym-III</td>
<td>103</td>
<td>3.1</td>
<td>3.10</td>
<td>B</td>
</tr>
<tr>
<td>D: Sym-IV</td>
<td>72</td>
<td>4.3</td>
<td>2.95</td>
<td>---</td>
</tr>
</tbody>
</table>

As can be seen in table D.1, no differences were observed in the magnitude of bow between studs resawn by different patterns and originating from the same log quality. Studs originating from logs of grade IV showed a tendency towards larger mean bow, but only the asymmetrically resawn studs had a significantly larger bow than the others.
The same tendencies were observed for spring as for bow, only more pronounced (table D.2). Larger magnitudes of spring were observed for studs originated from quality IV logs. The significant differences between the Asym-IV studs and the other groups were due primarily to the 50 x 50 mm studs (table D.6).

Table D.2: Observed Spring on wall studs grouped according to symmetry of the resawing pattern and log grade shown as the number of observations, n<sub>studs</sub>, group mean values, Mean, and standard deviations, Std Dev, of the observed bow. The wall studs were grouped according to symmetry of the resawing pattern into Asym for the asymmetrically resawn planks and Sym for the symmetrically resawn planks and by VMR-defined log quality into grades III and IV. Significant differences between the group mean values are shown, as well.

<table>
<thead>
<tr>
<th>Observed Spring of Wall Studs</th>
<th>n&lt;sub&gt;studs&lt;/sub&gt;</th>
<th>Mean (mm)</th>
<th>Std Dev (mm)</th>
<th>Sign.Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Asym-III</td>
<td>100</td>
<td>3.3</td>
<td>2.54</td>
<td>B</td>
</tr>
<tr>
<td>B: Asym-IV</td>
<td>84</td>
<td>6.8</td>
<td>5.65</td>
<td>A, C, D</td>
</tr>
<tr>
<td>C: Sym-III</td>
<td>103</td>
<td>3.6</td>
<td>3.28</td>
<td>B</td>
</tr>
<tr>
<td>D: Sym-IV</td>
<td>72</td>
<td>4.5</td>
<td>4.44</td>
<td>B</td>
</tr>
</tbody>
</table>

In table D.3 the observed magnitudes of twist of the studs are shown. No differences were found between the different groups of studs.

Table D.3: Observed Twist on wall studs grouped according to symmetry of the resawing pattern and log grade shown as the number of observations, n<sub>studs</sub>, group mean values, Mean, and standard deviations, Std Dev, of the observed bow. The wall studs were grouped according to symmetry of the resawing pattern into Asym for the asymmetrically resawn planks and Sym for the symmetrically resawn planks and by VMR-defined log quality into grades III and IV. Significant differences between the group mean values are shown, as well.

<table>
<thead>
<tr>
<th>Observed Twist of Wall Studs</th>
<th>n&lt;sub&gt;studs&lt;/sub&gt;</th>
<th>Mean (mm)</th>
<th>Std Dev (mm)</th>
<th>Sign.Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Asym-III</td>
<td>100</td>
<td>1.7</td>
<td>1.92</td>
<td>---</td>
</tr>
<tr>
<td>B: Asym-IV</td>
<td>84</td>
<td>1.8</td>
<td>2.14</td>
<td>---</td>
</tr>
<tr>
<td>C: Sym-III</td>
<td>103</td>
<td>1.5</td>
<td>2.08</td>
<td>---</td>
</tr>
<tr>
<td>D: Sym-IV</td>
<td>72</td>
<td>1.1</td>
<td>1.60</td>
<td>---</td>
</tr>
</tbody>
</table>
D.4.2 Grading with respect to the degree of warp

The magnitude of warp alone does not give a complete picture of how the yield of accepted studs is affected by the symmetry of the resawing pattern. Therefore, in this chapter the asymmetrically resawn studs, 50 x 50 mm and 50 x 100 mm, were compared to the results for the symmetrically resawn studs, 50 x 75 mm. The studs were grouped, as before, by the quality grade of the log according to the rules of VMR. The purpose was to determine if the log features affect the yield of accepted studs, especially the differences in the amount of compression wood.

In table D.4 the amounts of accepted wall studs are shown grouped according to symmetry of the resawing pattern and the quality grade of the log.

Table D.4: Studs grouped according to the VMR-defined log quality into III and IV, and according to symmetry of the resawing pattern, asymmetrical and symmetrical. The amount of accepted studs, in percent, is shown for each type of warp, Bow, Spring and Twist, separately and taken all together; n_{studs} is the total number of studs per group.

<table>
<thead>
<tr>
<th></th>
<th>Symmetrical 50x75mm/50x75 mm</th>
<th>Asymmetrical 50x50mm/50x100 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>Bow</td>
<td>88.5</td>
<td>73.6</td>
</tr>
<tr>
<td>Spring</td>
<td>70.2</td>
<td>58.3</td>
</tr>
<tr>
<td>Twist</td>
<td>91.3</td>
<td>97.2</td>
</tr>
<tr>
<td>Total</td>
<td>63.5</td>
<td>43.1</td>
</tr>
<tr>
<td>n_{studs}</td>
<td>103</td>
<td>72</td>
</tr>
</tbody>
</table>

As expected, in general the studs from logs of quality grade III gave a larger total yield of accepted studs than the logs of quality grade IV. If the three warp types were studied separately, the same tendencies were found for bow and spring. However, no large differences were observed between the log grades in the level of acceptance in terms of twist. As can be seen, larger differences between the log grades were found for studs resawn in an asymmetrical pattern than were observed among the symmetrically resawn studs. When the total yields were compared (Total in table D.4) a Fisher's Exact Chi² test showed that the observed differences between the log grades were statistically significant.

Only minor differences could be seen when asymmetrically resawn studs were compared to symmetrically resawn studs originating from the same log grade, III or IV. Among logs of grade III, the asymmetrically resawn studs gave the higher yield, while the opposite was found for logs of grade IV. The observed differences where, however, in no case proven to be statistically significant.
D.4.3 Difference in the magnitude of warp between asymmetrically resawn studs

In this section the warp of the two asymmetrically resawn studs from the same plank is compared. The comparison was based on the difference between the wider 50 x 100 mm stud and the narrower 50 x 50 mm stud. If no difference could be found between the pair of studs, the mean value for the entire test would be zero. Consequently, the null hypothesis, \( H_0 \), that no difference was found between the two studs was tested against the alternative hypothesis, \( H_a \), that a difference was present.

\[ H_0: |Warp_{100}| - |Warp_{50}| = 0.0 \]
\[ H_a: |Warp_{100}| - |Warp_{50}| \neq 0.0 \]

No differences in the magnitude of bow of the two stud dimensions could be statistically proven. In both log grades, however, the wider 50 x 100 mm stud had a slightly larger mean bow (tables D.5 and D.6). But larger differences were observed in the magnitude of spring. On average, the narrower 50 x 50 mm stud had the larger magnitude of spring (tables D.5 and D.6). Regarding magnitude of twist, the wider studs, 50 x 100 mm, had a significantly larger magnitude than the narrower studs for studs originating from log grade III logs, if the twist was expressed in mm only, (tables D.5 and D.6). Expressed as a twist-angle the opposite was true, the narrower stud showed the larger twist, significant at an alpha-level of 0.10, (results not shown).
## Methods for Avoiding the Negative Effects of Compression Wood

Table D.5: The difference in the magnitude of warp, in mm, between asymmetrically resawn studs from logs of quality grade III. The nominal dimensions of the wall studs were 50 x 50 mm and 50 x 100 mm. A paired comparison was done to test whether the observed 95% confidence interval of mean difference differs from the value 0.0 mm, based on 50 planks. Testing was done on the hypothesis of (H₀: |Warp₁₀₀| - |Warp₅₀| = 0.0) and (Hₐ: |Warp₁₀₀| - |Warp₅₀| ≠ 0.0). The value within brackets states the probability of generating larger differences than the observed values by chance alone.

<table>
<thead>
<tr>
<th>Differences in Warp between Studs from Logs of Grade III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow (mm)</td>
</tr>
<tr>
<td>Mean 95% Conf. int</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Signif. Diff</td>
</tr>
</tbody>
</table>

Table D.6: The difference in the magnitude of warp, in mm, between asymmetrically resawn studs from logs of quality grade IV. The dimensions of the wall studs were 50 x 50 mm and 50 x 100 mm. A paired comparison was done to test whether the observed 95% confidence interval of mean difference differs from the value 0.0 mm, based on 42 planks. Testing was done on the hypothesis of (H₀: |Warp₁₀₀| - |Warp₅₀| = 0.0 and Hₐ: |Warp₁₀₀| - |Warp₅₀| ≠ 0.0). The value within brackets states the probability of generating larger differences than the observed values by chance alone.

<table>
<thead>
<tr>
<th>Differences in Warp between Studs from Logs of Grade IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow (mm)</td>
</tr>
<tr>
<td>Mean 95% Conf. int</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Signif. Diff</td>
</tr>
</tbody>
</table>
Modelling Compression Wood in Sawn Timber of Scot's pine and Norway spruce

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SUMMARY
Compression wood in both Scots pine (Pinus silvestris L.) and Norway spruce (Picea abies L.) is regarded as a serious defect, which affects the warp and machinability of the sawn timber. It implies lower quality grade and a reduction of value. To be able to predict the amount of compression wood within the sawn timber is therefore of interest in the sawing process, and the sooner the better.

The objective of this study was to investigate the possibility of predicting the amount of compression wood within the sawn timber by the use of some traditional log features such as log-sweep, oval shape, amount of juvenile wood, fraction of visible compression wood in the butt end of the sawlog (CW-log), as well as the growth-stress related bow of the green sawn timber (Green-Bow).

The results show that it is possible to separate logs with severe amounts of compression wood from those with small amounts. The R² values of the best prediction models found were 0.66 for Scots pine and 0.64 for Norway spruce. The most important features for both species in explaining the variation of the amount of compression wood within the sawn timber are the Green-Bow and its square and cubic terms, while some minor contribution can be achieved by the CW-log. No other features contribute to the explained variation.

INTRODUCTION
Compression wood (CW) in Gymnosperms is in many situations a problem and thereby regarded as a severe defect. During processing growth stresses related to the presence of compression wood might be released to such an extent that production is disturbed. More accentuated, though, is the impact of compression wood on the warp of the sawn and dried products, which results in a lower grade and thereby a reduction of value.

The earlier a reliable prediction of the amount of compression wood within the sawn timber can be made, the better. The possibility to take action against the unwanted effects of compression wood on the final products increases.

In Sweden today, one method is in use which deals to some extent with the CW problem. It is a grading method based on a visual inspection of the sawlogs, where the amount of CW in the butt end cut of the log (CW-log) is only one of many defects that indicate the grade of the log (Anon, 1997a). Unfortunately, the estimation of CW-log, is
not a reliable indicator of the amount of CW within the sawn timber (CW-board), the correlation between the two factors is far to poor \([r<0.57]\). The correlation between CW-log and the degree of warp of the dried sawn timber is even poorer \([r<0.3]\) (Beard et al., 1993; Warensjö et al., 1998; Öhman, 1998).

The objective of this study was to evaluate the possibility of improving the predictability of the amount of CW within the sawn timber by using some CW-related properties of the sawlog and the growth-stress related bow of the green sawn timber.

**MATERIAL AND METHODS**

The study was based on 64 Norway spruce (*Picea abies* (L.) Karst.) and 51 Scots pine (*Pinus silvestris* L.) butt logs from the northern half of Sweden. Top diameters of the logs were for the Norway spruce logs in the range of 17 cm to 24 cm, 19.7 cm on average. The corresponding range of the Scots pine logs was 15 cm to 21 cm, 17.7 cm on average.

All logs were cant sawn, 2 ex-log. Only the two centre boards, with the dimensions 50 by 125 mm, were included in the study.

The log and sawn timber features measured were; CW-log, log-sweep, oval shape, fraction of juvenile wood, green bow and CW-board.

CW-log is in use today as an indicator of quality in the grading of sawlogs and is taken into account only if the fraction of dense CW exceeds half the width of the annual ring. The amount of CW in the butt end of the log was expressed as the visually estimated fraction of the CW in an imaginary area defined as the top diameter of the log minus 10 mm (Figure 1) (Anon, 1997a).

Log-sweep is another indicator of quality used in the grading of sawlogs (Anon, 1997a). It was included in the study due to the assumption that increased log-sweep indicates increased amounts of CW. Since trees strive to keep an upright position, they will try to correct any deviation from this upright position by, for example, forming CW. Log-sweep is measured and expressed as the greatest distance between a straight line joining the centres of the ends of the log and a line drawn through the middle of the log.

Oval shape was measured in both ends of the sawlog and was expressed as the difference between the largest and smallest diameters of the oval. In areas of CW, the annual ring tends to be broader than the ring is elsewhere. The greater the amount and density of CW present, the greater the oval shape that can be expected. But, as Timell says in his book, "it is not an infallible method to predict the presence of CW since it could occur in perfectly concentric stems as well as being entirely absent in eccentric stems" (Timell, 1986).
Modelling Compression Wood in Sawn Timber of Scot's pine and Norway spruce

Figure 1  A, is the area of dense compression wood under consideration (CW-log), measured as the fraction of the circular area C. A plus B is the total amount of dense compression wood in the butt-end cut of the sawlog. The diameter of C is the top diameter of the sawlog minus 10 mm.

Green-Bow is the growth-stress related deformation of the green sawn timber. In this study it is measured as the largest distance between the two green centre boards of the same log (Figure 2). Green-Bow was included in the because the presence of CW affects the normal longitudinal stress and strain distribution across the diameter of the log. A change of stress and strain distribution will affect the deformation of the green sawn timber, as well. Since longitudinal growth stresses correlate well to the intensity of CW, is it likely that the amplitude and direction of Green-Bow also correlate to the amount of CW within the sawn timber (Jacobs, M. R. 1965; Watanabe, H. 1965; Hallock, H. 1966; Okuyama et al., 1986;).

Figure 2  Growth-stress related deformation of the green sawn timber, Green-Bow, expressed as the largest span between two centre boards. The span shown here indicates a large amount of compression wood.
Juvenile wood was expressed as the diameter of the first 5, 10 and 15 annual rings in the top end of the sawlog. Since juvenile wood has a large microfibrillar angle in the cells’ S₂ layer and shows a high shrinking behaviour along the grain compared to normal wood, it might well affect the deformation of the green sawn timber (Koehler, 1938; Paul, 1930, 1957).

CW-board is the estimation of the amount of CW within the sawn timber based on the amount of visible CW on the four faces of the boards. CW was defined in accordance with the definition found in the grading rules of Nordic timber (Anon, 1997b). CW-board was expressed as the amount of CW in both centre boards of the log.

Partial Least Square Regression (PLS) was used to identify the relations between CW-board and the other variables. PLS is a statistical method where the x-variables can be correlated to each other and that there can be noise in the data as well as structures in the residuals (Lindgren, 1994). Because of these assumptions, PLS is a well-suited tool for studies on wood in general and for the variables of this study in particular, especially in consideration of possible bias in the visual estimations and presence of possible correlated variables. The PLS analysis was done with the aid of the software program SIMCA (Anon, 1998).

In a PLS model the covariance between the features (x-variables) is maximised to the linear combination of one, or many, y-variables (Marten & Naes, 1989a). CW-board was the y-variable in this study.

The features of importance for explaining the variance in the data set were identified with regard to four parameters: $R_y^2$, $R_x^2$, $Q^2$ and VIP. The coefficient of determination, $R_y^2$, represents the proportion of the variation in the present set of y-values that is explained by the model (Mendenhall & Sincich, 1992). $R_x^2$ is the corresponding proportion of the variation in the present set of x-values explained by the model. However, $R_y^2$ does not warn whether the model explains random relations, model overfitting or the true relations between x- and y-variables.

An alternative is to use cross validation (Marten & Naes, 1989b). When cross validating, N models are built, each time excluding an Nth part of the observations and thereby creating a training set. Each model is then tested on the excluded observations, the test set. SIMCA expresses the result of the cross validation as $Q^2$, which is a measure of the model’s ability to predict future observations, i.e. observations which were not included in the model. $Q^2$ represents the proportion of variation of y-values in the test sets that is explained by the model. A model which explains random variations in the training set will fail when tested with new observations and hence $Q^2$ will be low for such a model (Marten & Naes, 1989b). Consequently, a model showing significantly higher $R_y^2$ value than $Q^2$ indicates modelling of random variation in the data, i.e. noise, while equal values describe true relations between the x- and y-variables.

VIP, variable importance, is another term used by SIMCA and expresses the sum over all model dimensions of the variable influence (VIN) contributions. For a given PLS dimension $a$, $(VIN)_{ab}^2$ is equal to the squared PLS weight $(w_{ab})^2$ of that term, multiplied by the percent of residual sum of squares (SS) explained by that PLS dimension. If A is
the number of PLS dimensions and \( p \) is the number of features (x-variables), then the accumulated test quantity (overall PLS-dimension) is divided by the total percent of SS explained by the PLS model and multiplied by the number of terms in the model.

\[
[k = 1, 2, \ldots, p, a = 1, 2, \ldots, A]
\]

The squared sum of all VIPs is equal to the number of x-terms in the model due to the centring and scaling effect. The larger the VIP-value, the better the x-variable contributes to the explanation of the variation of the y-variables (Anon, 1998).

By using back propagation in finding the best PLS model, features showing low VIP-values were eliminated one by one until the \( Q^2 \) value was as high as possible and showed an acceptably small difference from the \( R_y^2 \) value. The remaining variables in the PLS model are then regarded as important indicators.

**RESULTS**

In Figure 3 both VIP values and the pairwise correlation between the CW-board and the different variables are shown. For Norway spruce was the largest correlation, 0.78, found between CW-board and Green-Bow. No significant correlation could be found between CW-board and the two oval-shaped variables, while the correlation between CW-board and the remaining variables, CW-log, all three juvenile wood variables and log-sweep were poor. A similar situation can be shown for Scots pine, CW-board showed a correlation of 0.71 to Green-Bow, while no significant correlation can be found for top oval-shape, and all the remaining variables show poor correlation. Green-Bow and its square and cubic terms were the most important variables among the eight studied variables both for Scots pine and for Norway spruce. Some minor contribution from CW-log can be found for both. None of the other variables contributed to the explanation by the PLS-models of the variation of the amount of CW within the sawn timber. The \( R_y^2 \)-value between observed amount of CW and the best possible prediction models were 0.64 for Norway spruce and 0.66 for Scots pine. Corresponding values for \( Q^2 \) were 0.61 for Norway spruce and 0.63 for Scots pine (Table 1). Both PLS-models were based on one principal component including the variables CW-log, Green-Bow and the square and cubic terms of Green-Bow. If the PLS-models were based only on Green-Bow and its square and cubic terms, the corresponding \( R_y^2 \)-values decreased to 0.57 for Norway spruce and to 0.55 for Scots pine, while the \( Q^2 \)-values decreased to 0.55 and 0.53 respectively.
**Paper 5**  
*Modelling Compression Wood in Sawn Timber of Scot's pine and Norway spruce*

### Norway spruce

![Graph showing pairwise correlation and VIP values for Norway spruce](image)

**Figure 3**
The grey bar shows the Pairwise Correlation (r) between CW-board and the 8 different variables. The black bar shows the VIP values of the 8 different variables generated by the partial least square regression.

### Scots pine

![Graph showing pairwise correlation and VIP values for Scots pine](image)

### Table 1

<table>
<thead>
<tr>
<th>Prediction Model</th>
<th>$R^2_{y \text{adj}}$</th>
<th>$Q^2$</th>
<th>Standard Deviation</th>
<th>RSD</th>
<th>Number of Observations</th>
<th>Degree of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scots pine</td>
<td>0.66</td>
<td>0.63</td>
<td>19</td>
<td>11</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>Norway spruce</td>
<td>0.64</td>
<td>0.61</td>
<td>23</td>
<td>13</td>
<td>64</td>
<td>62</td>
</tr>
</tbody>
</table>
CONCLUSIONS AND DISCUSSION

The two PLS-models based mainly on the bow of the boards directly after the sawing process (Green-Bow) give a fairly accurate prediction of the compression wood in the sawn timber both for Scots pine and for Norway spruce (Figure 4). A comparison between Figure 4 and Figure 5 shows that the PLS-models have a better predictability than the CW-log variable that is in use today.

**Norway spruce**

![Graph showing predicted versus observed amount of compression wood for Norway spruce](image)

$R^2 = 0.64$ (0.57)

**Scots pine**

![Graph showing predicted versus observed amount of compression wood for Scots pine](image)

$R^2 = 0.66$ (0.55)

Figure 4 Predicted versus observed amount of compression wood in the sawn timber (CW-board) for Scots pine and Norway spruce.
Figure 5 Observed amount of visible compression wood in the butt end of the sawlog, CW-log, compared to the amount of compression wood within the sawn timber, CW-board.

The PLS-models are not good enough for an individual ranking of boards. It is, however, possible to separate the sawn timber into one better and one worse group, low vs. high amount of CW within the boards.

The results of this study show that Green-Bow is the dominating variable and the rest of the variables contribute only to a minor extent, or not at all, to the explanation of the amount of CW in sawn timber. This fact does not necessarily mean that the variables do not at all indicate the amount of CW. It might be an effect of inappropriately expressed variables. All variables are measurements describing the situation in only one position of the entire, log e.g. the greatest log-sweep, the diameter of 5 annual rings in one position, the largest top diameter etc. It means that no measurement expresses the change of the variable over the whole length of the log, which might tell more about the amount of CW than one local measured quantity does.

However, the results of this study clearly show that the outer features of a sawlog measured by the traditional local approach, such as the largest log-sweep and the oval-shapes found in the ends of the log, do not contribute to the explanation of the variation of the amount of CW in the sawn timber. For that the correlation is far too poor.

The poor contribution of juvenile wood may be a result of the local measurement approach. If juvenile wood affects Green-Bow, it is very likely that the position of the juvenile wood within each crosscut of the sawn timber is of great importance both for the magnitude and for the direction of the deformation of the sawn timber as well as for the correlation between Green-Bow and the amount of CW.
REFERENCES

Watanabe H. 1965: A study of the origin of longitudinal growth stresses in tree stems, IUFRO section 41, forest proceedings, Vol. 3.
Paper VI
Measurement of green plank shape for prediction and elimination of compression wood

Micael Öhman, Jan Nyström
(Luleå university of technology, department of wood technology, Skeria 3, S-931 87 Skellefteå Sweden) Received June 7, 2001. Accepted 011210. Scand. J. For. Res. 00:000-000,200x.

The objective of this study was to predict the amount and the distribution of compression wood (CW) within a Norway spruce (Picea abies (L.) Karst.) plank based on green plank curvature. The findings indicated a possibility of predicting the longitudinal distribution of CW from the green plank curvature. Areas free from CW showed a typical concave shape in relation to the centre of the log, while CW was present when a convex shape was shown. The larger the magnitude of convex curvature was, the higher were the concentrations of CW that could be found, as well as a larger fraction of dried planks rejected due to excessive warp. This study determines, as well, what information can be used to eliminate areas of high concentrations of CW by cutting and how cutting affects the grading results with respect to warp. Over 50% of the plank length showing a high concentration of CW, > 30% of the crosscut volume, was successfully cut off. Cutting strategies based on predicted CW concentrations resulted in a 10% to 40% increase of accepted plank length.

Key words: board, cutting, deformation, grade, Norway spruce, Picea abies, predict, quality, warp
INTRODUCTION

Compression wood (CW) in Norway spruce (*Picea abies* (L.) Karst.) is considered to be a problem in many situations and is thus regarded as a severe defect in sawn timber. The origin of the problem is the difference in shrinking/swelling properties compared to normal wood when the moisture content of the wood changes. The longitudinal swelling of CW can be up to 10 times larger than the swelling of normal wood in Norway spruce (Schultz et al. 1984) and is an effect of several factors. One major cause is the increased microfibril angle in the S2 layer of the tracheid in compression wood. Other factors are the increased thickness of the tracheid wall and the differences in proportion between the S1 and S2 layers in CW compared to normal wood (Cave 1972, Wloch 1975, Boyd 1977, Harris 1977).

The difference in shrinkage will result in an unfavourable stress level within the material, and when asymmetrically distributed it can result in warp of the sawn product. High stress levels can also result in significant machining problems during secondary processing when the established stress equilibrium within the plank is disturbed. Consequently, the presence of CW is regarded as a potential risk of extreme deformations, decreased yield of acceptable quality products as well as a potential risk of machining and processing problems, in short, increased risk of costs for poor quality.

It would be advantageous if the amount and distribution of CW within the sawlog could be accurately predicted early in the process. Unfortunately, this is not possible to achieve by detection methods in use today. To deal with the CW problem, several inspection methods have been developed for sawlogs as well as for the dried sawn products. These methods define tolerances for acceptable amounts of CW within logs and planks. An example of such a grading standard is *Nordic Timber* (Anon. 1997a) which today is in use in the Nordic countries. This visual grading operation is performed late in the process on dried planks, and can be efficient at separating planks showing high amounts of CW from those free from CW. But when the inspection is made late in the production process, the same amount of value-added activities has been expended on planks that will ultimately be rejected due to excessive CW as has been spent on high quality products.

CW in the sawlog is detected in Sweden using the regulations of the *Swedish Timber Measurement Council* (VMR), a log grading method based on a manual visual inspection of the sawlogs (Anon. 1997b). The amount of visible CW in the butt end of the sawlog (CW-log) is only one of many quality-related features taken into account during such visual grading. This manual technique for estimation of CW is not a reliable indicator of the amount of CW within the sawn timber. Correlation between the CW-log and CW in the planks is far too poor \([r < 0.57]\), and correlation between CW-log and the degree of warp of the dried sawn timber is even poorer \([r < 0.3]\) (Beard et al. 1993, Warensjö et al. 1998, Öhman 1998).

As mentioned before, CW together with normal wood will result in considerable stresses within the sawn products, both in the green and the dried state. Watanabe (1965)
has shown that the presence of CW will disturb the normal longitudinal stress and strain pattern within the trunk of a tree. In normal wood, the lowest values are observed at the pith and increase gradually to become neutral at two thirds of the radius of the trunk and reach the highest positive value at the periphery of the log. When this log of normal wood is then sawn, these stresses are set free and will cause a concave warp of the green plank (F-shape Fig. 1). In sections where CW is present, an increase of strain values can be observed and, as such, the normal stress and strain pattern will be disturbed, and the plank will show a convex deformation in relation to the inner face of the plank (C1-shape Fig. 1 and Fig. 4).

Öhman (1999) has shown that the shape and magnitude of the green deformation of both Scots pine and Norway spruce are important determinants of CW in the centre parts of the log \( R^2 = 0.55 \). In this previous work the visible amount of CW on the surfaces of the 2 planks was related to the largest measured magnitude of deformation between two centre planks (e.g. deviation from parallel). Consequently, the amount and distribution of CW within a single plank cannot be predicted by this previous method. The more detailed the prediction of amount and distribution of CW is, the more useful it is for the lumber manufacturing process in minimising, by grading, the severe effects of CW.

The objective of this study was to predict the amount and distribution of CW within each single Norway spruce plank based on its green plank curvature.
MATERIALS AND METHODS

This study was based on 21 butt logs showing a lower quality than the average Norway spruce log. Reduced log quality was mainly due to a considerable amount of CW present in the butt end cuts and large log sweeps present in approximately 2/3 of the logs. The logs were square sawn into 2 planks each of the dimension 50 x 125 mm and a length of 298 cm.

The 42 planks were scanned green a few hours after sawing and again when dried. When green, the edge sides were scanned by a line scan camera to measure the shape of the green plank. One scan was recorded every 10 mm perpendicular to the lengthwise direction and with a resolution of 0.6 mm/pixel.

All planks were dried and conditioned without restraints or loading to allow free development of warp. The planks were steam heated to a wet-bulb temperature of 60°C, then dried down to fibre saturation point over a period of 64 h, initially with a 6°C wet-bulb depression (WBD) and increased to 18°C at the end. A dry-bulb temperature of 75°C was then held constant for 24 h by a WBD of 15°C. Finally, the planks were conditioned for 48 h in a dry temperature of 75°C and a WBD of 1.5°C. Mean moisture content was 17.7% (S.D=0.95%) measured on 10 planks by a wood moisture meter of resistance type calibrated at 60 °C.

When dried, a CT scanner (Siemens SOMATOM AR.T) was used for measurement of the deformation of the planks and for measurement of the density distribution within the planks. One CT scan was taken every 10th mm and provided a depiction of the mean density of small volume elements in a 5 mm-thick slice of the object, represented as a grey-scale image of the cross-section of the plank. The spatial resolution of the CT image slice was 0.68 x 0.68 mm and 5 mm in depth. The density resolution was based on a 256-level gray scale, 4.8 kg/m³/gray-scale unit, showing the density range in the interval from 0 kg/m³ to 1240 kg/m³.
Measurement of green plank shape for prediction and elimination of compression wood

Figure 1. Four examples of different green plank shapes. The F-shape is a concave shape of curvature typical for planks free from CW. The other three green plank shapes show three different examples of a convex CW-related plank curvature. The magnitude of the green bow was related to the elongation of the plank and expressed as the largest distance between the thin dotted line through the ends of the plank. The broad dashed line represents the location of the pith of the log.

In both the scanning for green bow as well as for the magnitude of bow and spring when dried, the deformations were related to the longitudinal elongation of the plank. The purpose was to relate the shape of each plank, measured before and after drying, to the amount and distribution of CW within the plank.

Dependent on the amount and distribution of the CW within the green plank, various numbers of deformations are possible. The planks of this study were, however, divided into 4 deformation types (Fig. 1). The normal deformation of a green plank free of CW was defined as a concave bow relative to the face closer to the pith of the plank (see the F-shape in Figure 1). In sections where CW was present, the plank will instead show a convex curvature (see the C1-, C2- and S-shapes in Figure 1). The C1-shape shows a completely convex shape indicating CW distributed along the whole length of the plank. The C2-shape and S-shape are two intermediate forms between the F-shape and C1-shape.

The density of CW can be up to twice as high as normal wood (Timell 1981, 1986). The density was used in this study to separate the two types of wood. Pixels showing a measured density \( \geq 630 \text{ kg/m}^3 \) in the CT scans were classified as CW. The value of \( 630 \text{ kg/m}^3 \) was found to be an acceptable compromise in minimising the amount of normal latewood being classified as CW and mild CW being classified as
Measurement of green plank shape for prediction and elimination of compression wood

normal wood. This compromise was based on an assumption of an approximated skewed Normal-distribution, or Weibull-distribution, of the normal wood density in a cross-section (Fig. 2). In parts containing CW, the assumed distribution would be disturbed (Fig. 2). High-density knots were removed by longitudinal median filtering before CW separation to avoid them being classified as CW.

Figure 2. Density histogram of typical cross-section containing compression wood. Estimated distributions of normal and compression wood are marked in the figure. The threshold level of 630 kg/m$^3$ was chosen to minimise false classification.

Each CT scan was classified into 3 different groups by the amount of CW (CW-grades). The amount of predicted CW in each CT scan depicting the density variation within each 5 mm thick cross-section of the plank was expressed as the percentage of the largest amount of CW found in all CT scans included in this study, 7000 pixels (Fig. 3). In the CW grade showing the lowest fraction of CW, denoted by none, $< 5\%$ of the pixels/area were classified as CW. The cross-section was classified as
moderate if the CW fraction detected was between 5% and 30% and classified as severe if the CW fraction was ≥ 30%. In Figure 3, four scans of different CW grades are shown to illustrate the different classifications.

![CT scans](image)

Figure 3. Examples of CT scans showing the density distribution within four cross-sections, 50 x 125 mm. The white areas are high density wood, ≥ 630 kg/m³, regarded in this study as CW. Severe concentration, ≥ 30%, Moderate, ≥ 5 to < 30% and None, 0 to < 5% CW. The values 7000 px, 3200 px, 360 px and 23 px in the figure were the number of pixels classified as CW.

Five different plank cutting strategies were studied for the ability to remove CW concentrations ≥ 30%. Three of these strategies were based on the green shape of the plank, while two were based on fixed lengths. The first strategy, Inflexion Point, was a cutting of the plank at the Inflexion point when the curvature of the plank changes from the largest observed convex bow to a concave bow (Fig. 4). The 2nd and 3rd cutting strategies were both based on the position of the maximum convex bow magnitude (XBM). The reason why these strategies were tested was that the concentration of CW
often had decreased to a minimum at the position of XBM. One strategy was to cut the green plank exactly at this point, denoted as XBM, and one to cut at 75% of the distance between the butt end and the position of XBM, denoted as 75%XBM (Fig. 4). The 75% distance was arbitrarily chosen for evaluation in this study and is not in any way optimised. The remaining 4th and 5th strategies were both fixed-length-cuttings, e.g. if the plank indicated CW, 3 dm or 6 dm was cut off from the butt-end of the plank.

![Figure 4](image)

Figure 4. Three cutting strategies based on the convex part of the green plank shape.

In the comparison of the impact of the cutting strategies on the total length of dried planks accepted in terms of magnitude of bow and spring, several threshold levels for the magnitude of convex green bow were tested. The tested threshold levels were in a range from 0 mm, a cutting of all planks, to 20 mm, no cutting.

The impact of the cutting strategies on grading with respect to warp was evaluated by applying the grading rules for wall studs developed by Johansson et al. (1993) on the observed warp of the dried planks. According to this regulation, a bow magnitude \( \leq 6 \) mm and a spring magnitude \( \leq 4 \) mm is accepted for wall studs no matter the length of the plank. Twist and cupping were not regarded in this study since CW does not contribute to these two deformations (Beard et al. 1993, Öhman 1998).

The original length of the planks was greater than the studied length of 298 cm in this study. The reason why a length of only 298 cm was studied was a matter of keeping scanning costs down. When cut according to strategies based on the green shape, some of the planks would consequently be shorter than the shortest commercially allowed length, 237 cm, based on the applied grading rules (Johansson et al. 1993). In those cases where a plank became shorter than 237 cm when cut, the plank was extrapolated to the minimum length of 237 cm by the chord theorem. The uncut length, the magnitude of green bow and the observed warp when dried, of the planks were also extrapolated by the chord theorem and considered in the comparisons.

The statistical analyses in this study were done with the aid of the software JMP from the SAS Institute Inc (Anon. 1994). Linear correlations were calculated. When the observations were grouped, the Tukey-Kramer Honestly Significant Difference test or a likelihood-ratio-chi\(^2\)-statistics test was used to test if the observed differences in group mean values were significantly different.
RESULTS

The magnitude of the convex green bow of planks was positively correlated with the amount of CW within the plank (r = 0.63, n = 42). The precise level of CW could not be predicted based on the convex green bow alone. The correlation was too low to allow an accurate separation of planks on an individual level. Instead, the planks were divided into 3 groups based on the magnitude of the green convex bow, among which comparisons were made. Group A included 9 planks with a green convex bow < 1 mm. The mean CW content among these planks was 0.4% (SD = 0.6%). Group B contained 23 planks with convex green bows of > 1 mm to ≤ 9 mm, and a mean CW content of 2% (SD = 2.5%). The third group, C, consisting of 10 planks with a green bow > 9 mm, had a mean CW content of 7% (SD = 4.5%). The CW content of group C was significantly higher than A and B (p < 0.05) while the difference between group A and B was not statistically significant.

The uncut dried planks were graded with respect to both bow and spring according to the tolerances suggested by Johansson et al. (1993) for wall studs. The number of planks rejected due to excessive bow and spring increased with increasing magnitude of convex bow (Table 1). All three groups were significantly different using a likelihood-ratio-chi$^2$-statistics test (p = 0.01). The proportion of rejected planks was almost 9 times higher in group C than in group A and 4 times higher in group B than in A.

Table 1. Number of accepted dry planks, $n_{\text{planks}}$, grouped by magnitude of initial green convex bow A, B and C. S.D, are significant differences to other groups in number of accepted planks.

<table>
<thead>
<tr>
<th>Grouped planks</th>
<th>$n_{\text{planks}}$</th>
<th>Accepted$^1$</th>
<th>S.D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A$^2$</td>
<td>9</td>
<td>8</td>
<td>B, C</td>
</tr>
<tr>
<td>B$^2$</td>
<td>23</td>
<td>14</td>
<td>A, C</td>
</tr>
<tr>
<td>C$^2$</td>
<td>10</td>
<td>1</td>
<td>A, B</td>
</tr>
</tbody>
</table>

The only significant difference found (p < 0.05) in the amount of CW was between C2-shaped and S-shaped planks. The F-shaped planks had a mean CW amount of 0.6% (SD = 0.8%, n = 5), the S-shaped had 1.7% (SD = 2.4%, n = 18), the C2-shaped had 5.0% (SD = 4.8%, n = 15), and finally, the C1-shaped had 2.9% (SD = 2.8%, n = 4). In table 2

1 Graded with respect to magnitude of bow and spring tolerances for wall studs according to Johansson et al. (1993). The plank was accepted if observed bow was ≤ 6 mm and observed spring was ≤ 4 mm.
2 Planks grouped by the magnitude of observed convex-shaped green bow, A ≤ 1 mm, B > 1 mm to ≤ 9 mm and C > 9 mm.
the distribution of CW is shown for 4 categories of green plank shapes. Severe concentrations of CW were found only in S-shaped and C2-shaped planks. In half (1.8%) of the crosscuts from C2-shaped planks showing severe CW, ≥30%, the concentration of CW exceeded 50%, while only 0.2% of the crosscuts from the S-shaped planks exceeded 50%. As expected, the fraction of CW was lowest among the F-shaped planks, with < 4% of the board length showing a moderate CW concentration. In spite of high convex green bows, no severe concentration of CW was found among the C1-shaped planks.

Table 2. The percent of CW-grade found on cross-sections for each plank shape (F, S, C1 and C2) based on the fraction of CW in each 1.0 cm thick cross-section of the plank. n_planks is the number of planks of the group, n_cross-sections are the number of cross-sections studied in the group.

<table>
<thead>
<tr>
<th>Plank shape</th>
<th>Compression Wood Distribution</th>
<th>n_planks</th>
<th>n_cross-sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>None 4%</td>
<td>96</td>
<td>1490</td>
</tr>
<tr>
<td>S</td>
<td>Moderate 7.5%</td>
<td>91.8</td>
<td>5364</td>
</tr>
<tr>
<td>C1</td>
<td>Severe 0.7%</td>
<td>87.4</td>
<td>1192</td>
</tr>
<tr>
<td>C2</td>
<td>None 13.9%</td>
<td>82.8</td>
<td>4172</td>
</tr>
</tbody>
</table>

In table 3 it is shown how much wood showing severe CW and how much of the CW free wood were eliminated by each one of the five cutting strategies. Only planks showing S-shapes and C2-shapes were studied since no severe CW was found in the other two plank shapes. Two different scenarios were compared in order to study the potential of regarding the magnitude of the observed convex green bow in the decision if a plank shall be cut or not. In scenario denoted by all, all planks showing an S-shape or C2-shape were cut. In the scenario denoted by 4.0 or 4.8 only planks showing larger magnitudes than these values were cut. The threshold magnitudes of 4.0 mm and 4.8 mm were the optimal levels for identification of all planks containing severe CW and for minimising excessive cutting of CW-free wood in this material. In table 3 it is shown how efficient each cutting strategy was in eliminating severe CW and how much of the CW-free wood were cut off as well. Notable is how the latter could be decreased by regarding the magnitude of the convex green bow. An example is the cutting of S-shaped planks by the XBM strategy where the length of eliminated CW-free wood decreased from 787 cm to 24 cm only.

3 Plank shape curvatures according to Fig. 1.
4 Concentration of CW within each crosscut: None < 5%, Moderate 5% to < 30% and Severe ≥ 30%.
Measurement of green plank shape for prediction and elimination of compression wood

Table 3: Eliminated length of wood free from CW, ≤5%, and of wood with Severe amount of CW, ≥30%, by cutting strategy and with respect to observed magnitude of convex bow. Expressed in % of the total amount of each specific type of wood and plank shape. The plank shapes F and C1 are not shown because they did not include any severe CW. Values of the CW-free wood to the left and severe CW to the right of the slash sign.

<table>
<thead>
<tr>
<th>Plank-shape</th>
<th>Length(^5)</th>
<th>Length(^6)</th>
<th>3 dm(^7)</th>
<th>6 dm(^7)</th>
<th>75%XBM(^7)</th>
<th>XBM(^7)</th>
<th>Inflexion Point(^7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S all</td>
<td>5346 cm</td>
<td>4923/149 cm</td>
<td>7/46</td>
<td>16/46</td>
<td>11/46</td>
<td>16/65</td>
<td>26/100</td>
</tr>
<tr>
<td>C2 all</td>
<td>4455 cm</td>
<td>3698/37 cm</td>
<td>5/70</td>
<td>10/95</td>
<td>13/100</td>
<td>19/100</td>
<td>35/100</td>
</tr>
<tr>
<td>S 4.0</td>
<td>1485 cm</td>
<td>1200/149 cm</td>
<td>0.5/46</td>
<td>2/46</td>
<td>1/46</td>
<td>2/65</td>
<td>9/100</td>
</tr>
<tr>
<td>C2 4.8</td>
<td>3564 cm</td>
<td>2806/37 cm</td>
<td>2/70</td>
<td>6/95</td>
<td>6/100</td>
<td>10/100</td>
<td>26/100</td>
</tr>
</tbody>
</table>

In table 4 the average cut-off lengths are shown for the cutting strategies based on convex bow. As expected, the mean cut-off length increased the more centred the position of the largest magnitude of convex bow was. The use of tolerances on the convex bow height resulted in only a minor change in the mean cut-off lengths.

Figure 5 shows how the total length of accepted dried planks changes by a cutting of green planks with respect to the magnitude of convex bow. The planks were graded when dried with respect to magnitude of bow and spring according to the regulations for wall studs suggested by Johansson et al. (1993). The yield of accepted plank length changed with altered tolerance for the magnitudes of convex bow, e.g. only planks with a convex bow larger than the tolerance value were cut. No plank in this study had a convex bow larger than 20 mm, which means that the results shown at this level represent the percentage of acceptable planks when no cutting was done.

\(^5\) Total plank length in each Plank-shape group, in cm.

\(^6\) Total length, in cm, of each type of wood, Free, ≤ 5% CW and Severe, ≥ 30 CW %, before cutting.

\(^7\) Cutting strategies tested: 3 dm and 6 dm were fixed cut lengths. XBM was a cut at the position of the largest magnitude of convex bow, 75%XBM a cut at a point three quarters of the distance between the butt end of the plank and the position of XBM. Inflexion Point was a cut at the position where the largest convex bow changed to concave (fig. 3).
Table 4. Mean cut-off lengths and standard deviations, in cm, for each plank shape and cutting strategy based on the convex green bow.

<table>
<thead>
<tr>
<th>Plank shape</th>
<th>n</th>
<th>Cut Length, in cm</th>
<th>75%XBM</th>
<th>XBM</th>
<th>Inflexion Point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>S.D</td>
<td>Mean</td>
<td>S.D</td>
</tr>
<tr>
<td>S_all</td>
<td>18</td>
<td>44</td>
<td>42</td>
<td>59</td>
<td>56</td>
</tr>
<tr>
<td>C1_all</td>
<td>4</td>
<td>108</td>
<td>11</td>
<td>143</td>
<td>15</td>
</tr>
<tr>
<td>C2_all</td>
<td>15</td>
<td>66</td>
<td>20</td>
<td>87</td>
<td>26</td>
</tr>
<tr>
<td>S_4.0</td>
<td>5</td>
<td>46</td>
<td>17</td>
<td>61</td>
<td>23</td>
</tr>
<tr>
<td>C2_4.8</td>
<td>12</td>
<td>61</td>
<td>16</td>
<td>81</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 5. Percentage of accepted dried length of S-shaped and C2-shaped planks from each cutting strategy. The threshold level in mm denotes at which magnitude of the convex bow a cut was considered. At 0 mm all planks with a convex bow magnitude more than 0 mm were cut, etc., until the largest threshold level where none of the planks were cut. (Maximum magnitude found in this study was < 20 mm).

The results shown in figure 5 were based on a limited number of observations, 15 C2-shaped and 18 S-shaped planks. The result of the C1-shaped planks is not shown due to too few observations. For S-shaped planks, a fix 3 dm cut showed the best result with the highest increase in accepted plank length. Using a fixed 3 dm strategy increased the yield from an uncut level of acceptance of 72% to more than 82%. Yield improvements using the 75%XBM and XBM strategies were slightly less than the fixed strategy. The sensitivity of the magnitude of chosen tolerance was low for the fixed 3 dm strategy, while the 75%XBM and XBM strategies did not perform well for cutting planks with very small convex bow magnitudes. An increase from the uncut level of acceptance of 33% to approximately 75% was possible for the C2-shaped planks with a fixed 6 dm cutting in this study. Optimum results can be seen at a threshold level of 6 mm, whereas in the range from 0 mm to 6 mm only a minor change could be noticed.
If no difference was made between the S- and C2-shapes, a strategy based on the location of maximum convex bow magnitude was the best choice. In this study the 75%XBM strategy was found to perform best in cutting of S- and C2-shaped green planks and was less than 5 percentage units lower than the best strategy of each plank shape. Using the 75%XBM strategy, an improvement in acceptance of 10 percentage units was shown for the S-shaped planks and for the C2-shaped planks the level was improved by 33 percentage units compared to acceptance of the uncut length.

**DISCUSSION**

Traditionally, the grading of sawn products is performed late in the sawing process. The drawback to this strategy is that the alternatives for products not conforming to tolerances are limited, and the costs for poor quality will be high.

The earlier grading can be done, the more the opportunity to find raw material better adapted to the requirement of each end product increases. The end product becomes more homogeneous in quality while the rate of rejected products and the costs for poor quality decrease.

The objective of this study was to investigate the possibility of predicting the amount in terms of volume and the location of compression wood, CW, within green planks, based on curvature. This is a method well suited to decreasing the costs for poor quality, since the amount of CW is a good estimate of the occurrence of large magnitudes of bow and spring in wood when dried.

None of the commercial automated systems of today are designed to deal with CW. However, methods for predicting compression wood in single green planks have been studied and evaluated. The majority of the published studies are based on different camera techniques, which suggests the possibility of non-destructively predicting the amount of compression wood on the surface of the plank with acceptable accuracy (Hagman 1997, Nyström & Hagman 1999a, Nyström & Hagman 1999b, Nyström 1999). Regarding the detection of compression wood within green planks, Nyström & Kline (2000) showed that X-ray-based scanning was not useful due to inconsistent moisture content masking the density variations caused by compression wood.

The benefit of measuring the curvature of planks is that standard commercial measurement equipment can be used on-line after sawing in the sawmill. However, the same drawbacks can be found as for the other methods; the prediction of the volume and distribution of CW within the plank was based on secondary features. In this study, prediction was based on the shape of the green plank that were caused by internal forces resulting from the presence of compression wood, a secondary feature. The other methods are based on the appearance of CW on the surfaces only, which as well is a secondary feature in a prediction of the total CW-volume within the plank.

The results reported in this study were, however, too few to allow any general conclusions about the accuracy of the method. Still, the results are too promising not to be reported, and they are worthy of further study.
The most interesting findings were:

- A strong indication of the possibility of detecting the presence of compression wood from the green curvature of the piece of wood. In parts with a concave green bow curvature, little or no CW can be expected, while the opposite can be expected when a convex bow curvature is present.

- The shape and proportion of the green convex bow can be used to predict the longitudinal distribution and local concentration of compression wood. The longitudinal extension of compression wood is predictable from the length of the convex bow, while the proportion of the amplitude of convex bow to its longitudinal extension can be used to predict the local concentration of compression wood.

- The amplitude of the green convex bow can indicate the risk of rejection of the dried planks when graded with respect to straightness. The larger the amplitude of the green convex bow, the larger the risk of degradation due to excessive bow and spring.

- The simulations done in this study indicate the possibility of increasing the total amount of dried planks that meet tolerances for straightness by implementing a strategy for cutting the green planks that is based on the shape of the convex green bow.

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