LICENTIATE THESIS

How Planing Affects Warp

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LULEÅ UNIVERSITY OF TECHNOLOGY

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From such crooked wood
as that wich man is made of,
nothing straight can be fashioned.
Immanuel Kant

PREFACE

Some of the keys to successful research are funding, the right people and the right equipment. I am thankful that the European Regional Development Fund, Objective 2, Northern part of Sweden via Tillväxtverket (the Swedish Agency for Economic and Regional Growth) and Vinnova (the Swedish Agency for Innovation Systems) funded my work.

The people were, besides me; my supervisors Professor Anders Grönlund and Associate Professor Mats Ekevad, at the Division of Wood Science and Engineering at Luleå University of Technology in Skellefteå, where the work behind this licentiate thesis has been carried out. Göran Forsberg and Fredrik Persson at SP Wood Technology carried out some of the measurements. I would like to thank you all warmly.

As machines generally do not read licentiate theses it is hard to give thanks to the equipment in this preface but I can and will thank the men behind the machines. Thanks to Birger Marklund who taught me to handle the CT-scanner and the personnel at the planing mill at Martinsons Sawmill in Kroksjön who planed my pine planks.

A general thanks also goes out to my colleagues and co-workers here at LTU Skellefteå, you know who you are, for both the serious and the not so serious conversations around the coffee table and in the corridors.

Of course, I would also like to thank my family and friends for their support.

Ann Axelsson
Skellefteå, June 2012

ABSTRACT

Although planers and wood machining researchers have been around a long time, the interactions between planks and planers have been neglected in basic research. With a solid understanding of the movements of planks during planing, planers and planing strategies can be developed to reduce waste and improve the value yield.

Cutting depths, changes in the amount of warp and cross-sectional shape were used to analyse the movements of the planks during planing, the alignment between the planks cross-sections and planers cutters and the improvement potential. The feeding roller in the planer intake had most control over the plank motion. Apart from cup reduction, the parts mostly affected by planing were the top and the butt end, where twist-induced misalignment between the cross-sections and the planers cutters resulted in skewed cross-sections and reduced rectangularity. By adjusting the cutting depths and in some cases the sawing over-size, planer misses could have been avoided but improvements in rectangularity would have required changes in the planer setting or planer design.

This thesis increases the knowledge on how a 4-side planer works together with warp to affect 50 × 150 mm planks. For the 20 planks used in this study, the planer removed cup, it decreased the amount of twist and crook but had no effect on bow. The major factor reducing the rectangularity of the planed planks was twist.

In the future, knowledge derived from this thesis can be used to create a simulation tool to model the behaviour of warped planks in a planer.

LIST OF PAPERS

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Axelsson, A. (2012). Effect of planing on warp in Scots Pine (Pinus sylvestris). *Wood Material Science and Engineering*, 7:3, 154-161

II. Axelsson, A. (2012). Rectangularity of planed Scots Pine (Pinus sylvestris) planks. *Wood Material Science and Engineering*. Submitted paper

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1 Introduction

Nowadays, green timber can be sawn with small sawing variations in modern sawmills. However, because wood is an orthotropic material with varying fibre directions, and varying shrinkage characteristics due to drying, planks and boards end up with distortions, such as cup, twist, bow and crook and with varying dimensions after drying. A simple method to even out the dimensional variations and obtain a smooth surface after drying is by planing. Additionally, the distortions, or warp are to some extent affected by the planing process.

To be able to reduce waste without sacrificing quality, a model or simulation tool that can satisfactorily predict the outcome of planing would be beneficial. To be able to create this kind of model, information is required about how a plank is affected by pressure elements and how it moves in relation to the cutters.

When searching earlier work about planers and wood, it is most common to find studies about the surface quality and gluing properties. Those studies, no matter how good they are, are not very useful when evaluating the behaviour of a plank during planing. If research has been done on the interaction between planers, planks and drying deformations, it is certainly hard to find… until now.

In this study, 20 Scots pine (*Pinus sylvestris*) planks with a rough dry target dimension of 50 × 150 mm and with a wide spread of properties were used. Half of the planks were selected due to their high amount of warp. This made it possible to draw some conclusions about how the different warp types were affected by planing but also on how planing in combination with warp introduced cross-sectional skewness and planer misses. The planks were planed in an industrial planer with standard settings, at a sawmill in northern Sweden. The different types of warp were recorded for the rough and planed planks and the changes of warp and cross-sectional shape, as well as cutting depths were analysed.

In summary, I have:

- Shown that it is possible to predict whether or not a plank would be approved after planing according to the requirements given by "Nordic Timber" and by the "Rules for Purchase of Structural Timber" with the aid of simple models (Paper I).
- Shown that the single most important factor reducing the rectangularity of planed planks is twist (Paper II).

2 Problem description

In 1990, 1.2 million cubic metres of planed goods were exported from Sweden. This corresponded to 10% of the total sawmill production (Skogsindustrierna, 2011). In 2010, the amount of planed goods that were exported had risen to 4.7 million cubic metres, or 28% of the total sawmill production. As the produced volume of planed goods increases, so does the volume of material waste and rejected goods unless the production process improves. Thus, it has become increasingly important to improve the quality of planed goods and reduce waste during planing.

In the wood industry, there are numerous types of waste. When it comes to planing, there is the potential for both waste of material, as well as waste of production capacity. Material can be wasted either by unnecessarily large allowances in planing, or by poor end results resulting in the rejection of planed planks. In the latter scenario, a plank will have been sawn, dried and planed in vain.

The amount of allowed warp is regulated by the requirements given in "Nordic Timber" (Anon, 1994) and there are stricter requirements in the "Rules for Purchase of Structural Timber" (Johansson *et al.*, 1993) developed for the construction industry. When cross-sectional shape is concerned, it has a large influence on the gluing performance. Skewed cross-sections and planer misses cause problems with gluing and thickness variations can accumulate if they do not occur randomly. The maximum deviation from the average thickness in a lamination should not exceed 0.2 mm when components for windows and exterior doors are manufactured (Hägglund & Marklund, 1992) and the maximum thickness variation in a lamination allowed by the American standard (AITC, 2004) is also 0.2 mm across the width (i.e., in a specific cross section).

Imagine being able to determine and control the dimensions and the amount of drying deformations of planed goods during the log sorting. If there was a simulation tool that could predict for a log, prior to being cut into individual planks and boards:

1. the shrinkage due to drying,
2. the amount of warp,
3. the necessary planing allowance, and
4. the optimal planer settings

it would be possible to determine the best green target dimensions for the sought outcome after planing. It would also be possible to sort the logs so that they could be used for production of the appropriate end products. The earlier links of the chain in the process have been studied, for example, here at Luleå University of Technology (Chapter 5). This licentiate thesis is focused on the last link, planing.

In order to create a model that can predict the outcome of planing, knowledge about the movement of sawn timber during planing is required. Important considerations are how and to what extent the pressure elements straighten the planks during planing and how the planks are aligned in relation to the cutters. The aim in this study was to shed light on those issues.

As this study includes only 20 planks of which half were selected because of their high amount of warp and as they were all planed in the same planer, the absolute numbers cannot be translated into every thinkable planing case but the general ideas about how the planks move during planing should be valid.

3 Result and discussion

A summary of the measured properties of the planks is given in Table 1. Rectangularity, which is defined in Chapter 4.2, is a measure of how rectangular a shape is in relation to a rectangle. A rectangle has the rectangularity 1, while other shapes have a lower value. Due to the selection of 10 severely warped planks, the mean values are not representative for a normal planing situation where the average values for twist, bow and cup would be lower.

Table 1: Properties for the 20 studied pine planks. Standard deviations are given in parentheses.

Property		Minimum	Maximum	Mean
MOE (MPa)		6,500	12,000	9,400 (1,600)
Length (m)		2.9	5.5	4.2 (0.65)
Width (mm)	Rough	150	153	152 (0.96)
	Planed	142	145	144 (0.54)
Thickness (mm)	Rough	49	52	50 (0.66)
	Planed	44	45	45 (0.16)
Rectangularity	Rough	0.91	0.97	0.94 (0.013)
	Planed	0.92	0.99	0.98 (0.012)
Cup (mm)	Rough	1.5	3.8	2.5 (0.5)
	Planed	0.0	0.6	0.2 (0.1)
Twist (mm/2m)	Rough	0.4	24.5	11.7 (7.0)
	Planed	0.8	20.1	8.7 (5.4)
Bow (mm/2m)	Rough	1.0	8.6	4.6 (2.2)
	Planed	1.7	8.9	4.9 (2.3)
Crook (mm/2m)	Rough	0.9	8.5	2.7 (2.1)
	Planed	0.7	6.2	2.2 (1.4)

Of course, the width and thickness of the planks were reduced by planing and the spread in those dimensions was reduced, especially for thickness. The average bow was subject to a slight increase, whilst to a large extent, cup was removed. On average twist and crook were reduced (Paper I).

3.1 Flattening of planks during planing

If the planer (Figure 1) had completely flattened the planks during planing, all warp types would have remained the same after planing. The only warp type that this was valid for was bow, which is a two-dimensional warp type in the weakest direction of the planks. Even though it was subject to a small amount of enlargement, it could be considered as unaltered in practical applications.

Cup was largely eliminated, which means that the planer had not flattened the cross-sections at all. This validates the assumption that the face or edge of a plank was cupped until contact with the designated cutter.

Crook, like bow, is a two dimensional warp type. However, interpreting how the planer has manipulated crook is a more complicated matter than for bow, because the lateral movement of the planks during planing was less controlled than the vertical movement. It seems that small amounts of crook (below 5 mm/2 m) were flattened during planing, whilst large amounts of crook (above 7 mm/2 m) were not. However, crook appears in the planks stiffest plane and therefore, is the hardest deformation to flatten during planing. Due to the stiffness and the inconsistent behaviour between small and large amounts of crook, it is assumed that there was no flattening effect during planing.

In all cases, except for one plank, the amount of twist decreased and the one exception was so small that it is likely to have been a measurement error. In general, the twist decreased by 25% irrespective of the amount of rough twist. Thus, the conclusion can be drawn that there was some degree of flattening

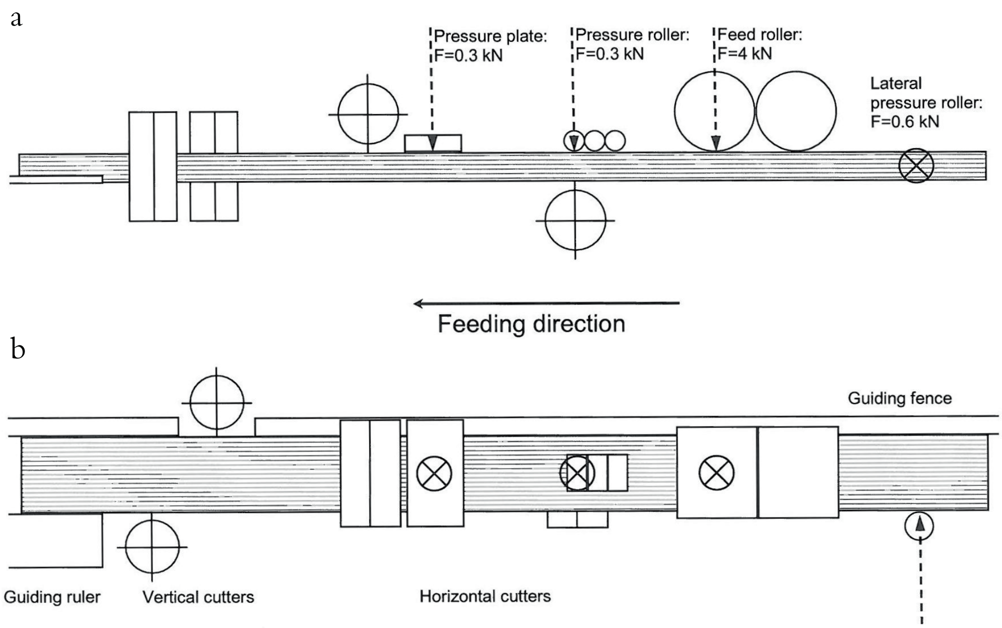

Figure 1: Schematic planer with measured pressure forces, a) side view and b) top view.

during planing, as the twist for the planed planks was reduced by planing and the experimental result was located between the two extreme scenarios of zero pressure acting on the planks from the planer resulting in no flattening of the planks during planing and high pressure acting on the planks from the planer resulting in total flattening of the planks during planing (Paper I).

As stated earlier, bow and crook both have a two-dimensional nature, so they should affect evenly the cutting depths on opposite faces (bow) or edges (crook). If no other drying deformations had been present, oblique cutting would not have been performed. However, if the amount of twist was reduced, which it was, some oblique cutting had to have taken place, i.e., the cross-sections had to have been rotated with respect to the cutters. This rotation is given by the angle of cut, which is zero if the face or edge of a cross-section is aligned to the corresponding cutter, i.e., no oblique cutting takes place (Chapter 4.2). The angle of cut for five evenly distributed cross-sections, CS1 to CS5 (Chapter 4.1 and Figure 5) is shown in Table 2. The angle of cut was largest in CS1 (top end) and CS5 (butt end) for both faces and both edges while the intermediate faces and edges where more or less aligned to the corresponding cutter. This tells us that the twist that was removed by planing was removed from the top and butt ends (Paper II).

Table 2: Angle of cut for the sapwood and pith faces and also for the right and left edges, as well as average rectangularity after planing (Chapter 4.2) for five evenly distributed cross-sections (Figure 5). Standard deviations are given in parentheses.

	Sapwood face (°)	**Pith face (°)**	**Right edge (°)**	**Left edge (°)**	**Rectangularity**
CS1	- 0.4 (0.6)	- 1.0 (1.0)	- 0.4 (1.7)	- 1.5 (1.6)	0.97 (0.017)
CS2	0.1 (0.2)	- 0.1 (0.4)	0.1 (1.0)	- 0.5 (1.4)	0.98 (0.0064)
CS3	0.1 (0.2)	0.0 (0.3)	0.2 (1.3)	- 0.1 (1.1)	0.98 (0.0050)
CS4	0.0 (0.2)	0.0 (0.4)	0.4 (1.0)	0.5 (1.5)	0.98 (0.0050)
CS5	1.1 (0.8)	0.9 (0.9)	0.8 (1.3)	1.5 (1.6)	0.97 (0.014)

3.2 Vertical movement

The movements of the planks were controlled by feeding rollers and pressure elements (Figure 1). The feeding rollers in the planers intake exert the highest amount of downward force; the force from subsequent pressure rollers and pressure plates is about one-tenth of the force from the feeding rollers. When evaluating how the planks have moved vertically during planing, the cutting depths adjusted for planer misses, cup and thickness variations on the sapwood and pith face have been used (Table 3), as well as the angles of cut for the faces and rectangularity (Table 2). Adjusted cutting depth, angle of cut and rectangularity is defined in Chapter 4.2.

Table 3: Average real and average cutting depths adjusted for thickness variation, planer misses and cup (Chapter 4.2) for the sapwood and pith face divided into five evenly distributed cross-sections (Figure 5). Standard deviations are given in parentheses.

	Sapwood face		**Pith face**	
	Real (mm)	Adjusted (mm)	Real (mm)	Adjusted (mm)
CS1	1.4 (1.1)	1.9 (1.1)	5.0 (2.1)	3.3 (1.7)
CS2	2.0 (0.8)	2.6 (0.5)	3.9 (1.3)	2.1 (0.7)
CS3	2.2 (0.8)	2.7 (0.4)	3.6 (1.3)	1.8 (0.6)
CS4	2.1 (0.7)	2.7 (0.4)	3.8 (1.2)	2.0 (0.6)
CS5	1.3 (1.2)	1.4 (1.6)	5.0 (1.9)	3.4 (1.5)

In general, the intermediate cross-sections CS2, CS3 and CS4 had similar adjusted cutting depths and angles of cut on the sapwood face, which shows that the movement of the middle sections of the planks was straight and controlled past the bottom cutter, which was the first cutter after the feeding rollers (Figure 2b). The adjusted cutting depths of CS1 and CS5 were smaller than for the rest of the cross-sections, which means that the top and butt end of the planks were not pushed down as much as the rest of the planks (Figure 2a and c). In addition, the angle of cut deviated from zero more than for the other cross-sections. The combined information from the adjusted cutting depths and the angle of cut on the sapwood face shows that bow and twist had sprung back in the top and butt end of the planks when the sapwood face was planed.

The differences between the adjusted cutting depths of the sapwood face and the pith face showed a larger variation over the length of the planks on the pith face. This shows that a higher amount of warp was present during planing by the top cutter located further away from the feeding roller, than during planing by the bottom cutter. Further differences between the two faces can be determined from the combined effects of the bottom and top cutters. The rectangularity was lower for CS1 and CS5 than for the intermediate cross-sections. This was additional evidence that the motion for CS2, CS3 and CS4 was more controlled than for CS1 and CS5. As the average rectangularity was the same for the two end cross-sections, the difference in angles of cut should be the similar for CS1 and CS5 but on average, the difference in angles of cut is much smaller for CS5. When the difference in the angles of cut was viewed on an individual basis (Paper II), it became apparent that the spread in the difference in the angles of

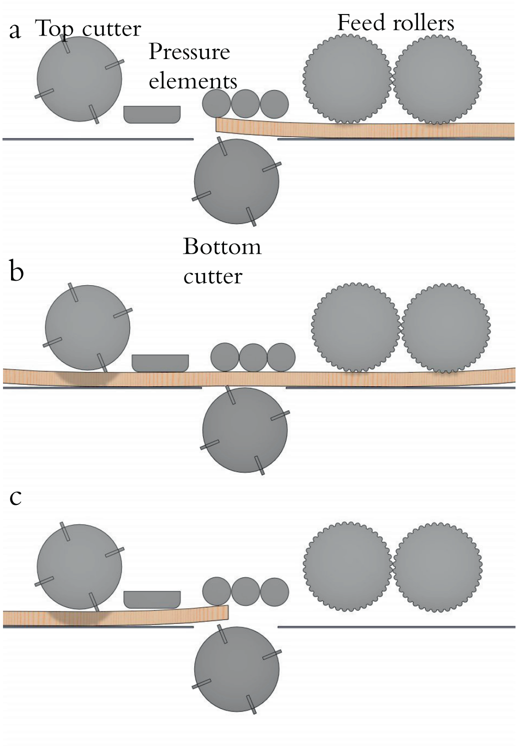

Figure 2: Vertical movements of a plank in the proximity of the bottom and top cutter.

cut for CS5 is larger than that for CS1. This could explain the low average in difference in angles of cut for CS5. The cause for the disparity in spread is that when the top end was planed, the plank was still firmly held by the feeding roller but when the butt end reached the cutters, the plank had passed the feeding rollers and was only controlled by the succeeding pressure elements.

3.3 Lateral movement

In a planer, crook is a lateral deformation, which in combination with adjusted cutting depths of the right and left edge, (Table 4) and angles of cut for the edges, (Table 2) can be used as a key to determine the lateral movements of a plank in a planer. Unlike bow, crook is located in the stiffest direction of a plank and therefore, should be very hard for a planer to straighten out, due to the small forces controlling sideways motion (Figure 1).

As the feeding roller is the major contributor to the control of plank motion, the nature of the movement should be more wobbly the further away from the feeding roller a particular cross-section gets. The side cutters were the last machining elements in the planer and as the angles of cuts on the edges displayed a more irregular pattern than for the faces, it was clear that the motion of the planks was less controlled when the edges were planed compared with when the faces were planed.

Table 4: Average real and average cutting depths adjusted for thickness variation, planer misses and cup (Chapter 4.2) for the right and left edge divided into five evenly distributed cross-sections (Figure 5). Standard deviations are given in parentheses.

	Right edge		**Left edge**	
	Real (mm)	Adjusted (mm)	Real (mm)	Adjusted (mm)
CS1	2.1 (1.0)	2.2 (1.8)	3.8 (1.8)	2.0 (1.7)
CS2	2.5 (0.5)	2.9 (0.6)	4.1 (1.2)	1.4 (0.7)
CS3	2.5 (0.7)	2.9 (0.6)	3.6 (1.3)	1.1 (0.9)
CS4	2.4 (0.7)	2.7 (0.7)	3.9 (1.3)	1.6 (1.0)
CS5	2.4 (1.0)	2.3 (2.5)	3.5 (2.4)	1.4 (2.6)

The adjusted cutting depths on the right edge were smallest in CS1 and increased for the following cross-section. After the middle cross-section, the cutting depths decreased slightly. On the left edge, the adjusted cutting depth was largest in CS1 and decreased towards CS3 located in the middle of the planks.

The changes in the adjusted cutting depths along the planks lengths and by extension, the lateral movement, were affected by the curvature of the crook. According to the data for these planks, the outer side of the crooks curvature was directed towards the guiding fence and the lateral pressure roller guided the planks towards the guiding fence in the in-feed of the planer (Figure 3a). In the beginning of the planing operation, the top end cross-section was aligned perpendicular to the guiding fence. As the top end left the pressure roller, the cross-section that at that moment was in line with the lateral pressure roller aligned itself perpendicular to the guiding fence, which forced the top end to move towards the left (Figure 3b). After passing the left cutter, a guiding ruler steered the top end towards the right again, increasing the cutting depths on the right edge and decreasing the cutting depths on the left side (Figure 3c).

When the butt end of the planks had left the lateral pressure roller, the guiding fence and the guiding ruler after the side cutters controlled the lateral movement of the planks in a straighter path. As the butt end, due to the curvature of the crook, was directed towards the left, the cutting depths decreased slightly on the right edge and increased slightly on the left edge.

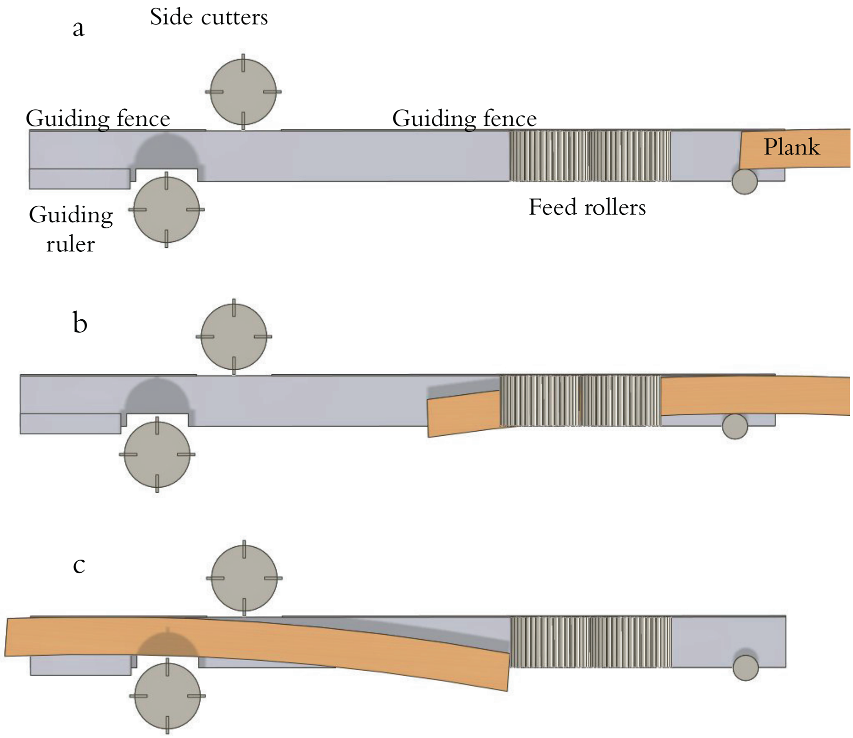

Figure 3: Excessive lateral movements of a plank due to crook.

3.4 Reducing plank rejection

Two main sources for plank rejection were considered in this study: one was excessive warp (Paper I) and the second was faulty cross-sectional shapes (Paper II).

3.4.1 Warp

The amount of warp before and after planing, as well as theoretical models for planers with a high amount of pressure acting on the planks and zero pressure acting on the planks (Paper I) were compared with both the requirements given by "Nordic Timber" (1994), which is a commercial sorting rule without concerns for the final use and the "Rules for Purchase of Structural Timber" (Johansson *et al.*, 1993), which was adapted to meet the demands of the construction industry. The only level of acceptable deformation agreed on by the two requirements is cup, while the "Rules for Purchase of Structural Timber" have higher demands for straightness.

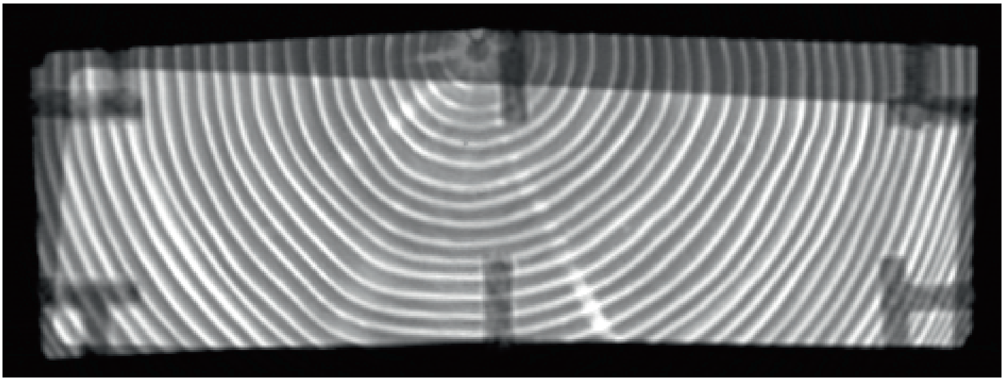

Figure 4: An example of a cross-section that has been rotated with respect to the cutters. The shaded areas are material removed by the planer. On the right side of the sapwood face (down) there is an unplaned surface, i.e., a planer miss.

By planing, the number of planks approved according to "Nordic Timber" increased from 8 to 10, whereas the number approved according to the "Rules for Purchase of Structural Timber" increased from 1 to 3. The theoretical models for high pressure acting on the planks from the planer completely flattening the planks during planing corresponded to no change of warp after planing and therefore, planing did not change the number of planks with approved warp irrespective of requirements.

The difference in planks approved after planing between the theoretical models for zero pressure acting on the planks from the planer and the experimental result was one plank for the "Nordic Timber" requirements and three planks for the "Rules for Purchase of Structural Timber".

The theoretical models for zero pressure were also used to evaluate the maximum deformation reduction with the cutting depths used in the planer, because a planer with zero pressure acting on the planks would have the largest deformation reduction possible. If the cutting depths were unchanged but the pressure acting on the planks by the planer was reduced, the maximum number of approved planks according to "Nordic Timber" would have been 11. By increasing the cutting depth on the sapwood face to 3.5 mm, a total of 16 planks had the potential for being approved.

As the requirements in the "Rules for Purchase of Structural Timber" are stricter, the number of approved planks was lower than for "Nordic Timber". By reducing the straightening effect by the planer, a total of six planks could have been approved. When manipulating the cutting depth on the sapwood face, further reductions in twist could have been achieved but the amount of bow would in most cases have been too high. Irrespective of whether bow was assumed to have been flattened during planing or not, the maximum number of approved planks reached six.

3.4.2 Cross-sectional shape

A majority of the planks had planer misses (Figure 4), and most of them were located on the top and butt end of the sapwood face (Figure 5).

A total of 14 planks had planer misses on the sapwood face and the average depth of the planer misses at the measuring points was 0.9 ± 1.0 mm. If the cutting depth on the sapwood face had been 1 mm greater a total of 21 planer misses on eight of the planks would have been avoided. When the cutting depth on both the sapwood face and pith face were added, the average total allowance for planing in the thickness direction was 6.0 ± 1.2 mm and the average minimum allowance for planing was 4.5 ± 0.7 mm and thus, there were sufficient margins to adjust the cutting depth. When planer misses were included in the calculations, the average total allowance for planing decreased to 5.9 ± 1.2 mm, whilst the average minimum allowance for planing became 4.2 ± 1.2 mm.

Sapwood face

	CS 1	CS 2	CS 3	CS 4	CS 5
Right	4				
Middle	8		1		7
Left	1				11

Pith face

	CS 1	CS 2	CS 3	CS 4	CS 5
Right					
Middle					
Left					

Right edge

	CS 1	CS 2	CS 3	CS 4	CS 5
Upper	1				1
Lower	3				1

Left edge

	CS 1	CS 2	CS 3	CS 4	CS 5
Upper	1		1		1
Lower			1		

Figure 5: Locations and total number of planer misses. Right, middle, left, upper and lower are defined as positions during planing.

With regard to edges, 5 of the planks had planer misses. On the right edge, the average depth of the planer misses was 4.8 ± 3.4 mm and the corresponding number for the left edge was 0.2 ± 0.24 mm. A cutting depth adjustment by 1 mm could have decreased the number of planks with planer misses on the edges by three planks. However, most of the planer misses on the edges were located on a single plank and the depth of those misses were so large that they could not have been avoided by adjusting cutting depths while achieving the target thickness. For this, the most crooked plank, a planed plank without planer misses would have required either a larger rough target size or a smaller target size after planing. If the planer misses on this extremely crooked plank were excluded, the average depth of planer misses on the right edge decreased to 1.4 ± 1.0 mm. The average total allowance for planing on the remaining planks was 6.2 ± 1.5 mm with an average minimum allowance for planing of 4.0 ± 1.4 mm.

Overall, when the most crooked plank was excluded, there was enough over-size to completely avoid planer misses and there was still room for reducing the green cross-sectional dimensions by approximately 4 mm in both directions.

For rectangularity, increasing the allowance for planing or adjusting the cutting depths would not have been sufficient to reduce completely skewed cross-sections, as the angles of cut for opposing faces and edges were not parallel in the cross-sections in question. This would require changes in the planer setting or the design of the planer.

A more even distribution of pressure forces that could keep the outer shape constant throughout the planing process would ensure that the cross-sections had the same alignment towards the opposite cutters. Another option is to reduce the distance between opposing cutters so that there is no room for changes in the outer shape of the planks between the cutters. In both cases, the opposite faces and edges would be more parallel and any deviations from rectangularity would be caused by planer misses due to too small an allowance for planing or inaccurately set cutters.

4 Material and method

4.1 Experimental set-up

Twenty Scots Pine (*Pinus sylvestris*) planks with a dry target size of 50 mm × 150 mm and moisture contents between 6% and 10% were chosen for this study. They had varying lengths and modulus of elasticity, half of the planks were selected due to their high degree of drying deformation, whereas the rest had more moderate amounts of deformation (Table 1).

For every plank, five cross-sections were selected. Cross-section one, CS1 was positioned 10 cm from the top end of the planks and cross-section five, CS5 was located 10 cm from the butt end of the planks. The intermediate cross-sections were evenly distributed between CS1 and CS5 (Figure 5). For every cross-section, 10 holes were drilled marking measuring locations (Figure 4 and 7). Three holes were drilled on both the sapwood face and the pith face, while two holes were drilled on both the right edge and the left edge. The right and left edges were defined as viewed in the direction of feed. The cross-sections were scanned in an X-ray CT-scanner the day before and the day after planing. The image processing software ImageJ (freeware from the National Institute of Health, NIH) was used to make the necessary measurements in the CT-images.

The planks were machined in an automatic 4-side planer to dimensions of 45 × 145 mm at a sawmill located in northern Sweden. The planks were fed with the top end first and the sapwood face down, resulting in planing with a fixed cutting depth on the right edge and sapwood face (down) and dimension planing on the left edge and pith face (up). The planks were all sawn through the pith. The settings on the planer and the responding forces from the pressure rollers and pressure plate were registered (Figure 1). The positions of the cutters in relation to the feed rollers and the pressure elements, together with the degree of pressure, govern the effect of the planer on the planks.

4.2 Measurements

On the same day as the planing took place, the drying deformations (twist, crook, bow and cup) were measured in a measuring device that uses laser triangulation (Grönlund *et al.*, 2009b).

The angle of cut, i.e., the angle between a cross-section and a cutter at the moment of cut was defined as positive if a cross-section was rotated in a clockwise direction relative to the matching cutter. The angle of cut was measured by comparing the cutting depths of the outer holes on a face or an edge (Paper II).

Rectangularity R, was measured using the minimum bounding method (Rosin, 1999), where rectangularity is defined as the ratio between the area of the cross-sections A_{cs} and the area of its minimum bounding rectangle A_{MBR} (Figure 6 and Paper II).

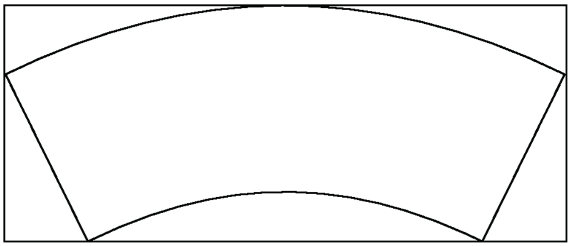

Figure 6: An excessively cupped cross-section and its bounding rectangle.

The cutting depths were calculated by measuring the depths of the drilled holes before and after planing. To be able to compare planks with different rough cross-sectional dimensions and different amounts of cup but also to include planer misses, adjusted cutting depths were used (Paper II).

Idealised cross-sections shaped like perfect rectangles with the dimension 50 × 150 mm were fitted to the real rough cross-sections. The idealised cross-sections shared their bases with the two lowest points on the real and deformed cross-sections and the right edge of the idealised cross-sections were located onto the points furthest to the right in the real cross-sections (Figure 7). When the adjusted cutting depth was calculated, the depths of the holes for the rough planks were measured from the idealised cross-sections instead of from the surface. The cutting depth at planer misses is by definition zero but as the location of the cutter in relation to the plank was of interest, the distance between a hole and an extension of the cutting plane was measured in the planed cross-section, resulting in a negative adjusted cutting depth. The extension of the cutting plane was given by extending a line aligned with the planed part of the face or edge on the cross-section in question.

The amount of warp after planing was compared with theoretical models of two extreme scenarios (Paper I). One scenario is for fully flattened planks during planing. In that scenario, the drying deformations would have been unaltered. The other scenario was zero flattening of the planks during planing. The result in this scenario would be the largest possible reduction of deformations. For developing the zero pressure model, it was assumed that the middle cross-sections, CS3 was straight and parallel to the top and bottom cutter. Also, the assumptions that twist was evenly distributed over a quarter of the lengths of the planks, whilst bow and crook were evenly distributed over the entire length were made after a visual inspection of the planks at hand.

In order to judge the size of the drying deformations in both the experiment and for the theoretical models, the deformations were compared with the requirements given in "Nordic Timber" (Anon. 1994) and the "Rules for Purchase of Structural Timber" (Johansson *et al.*, 1993).

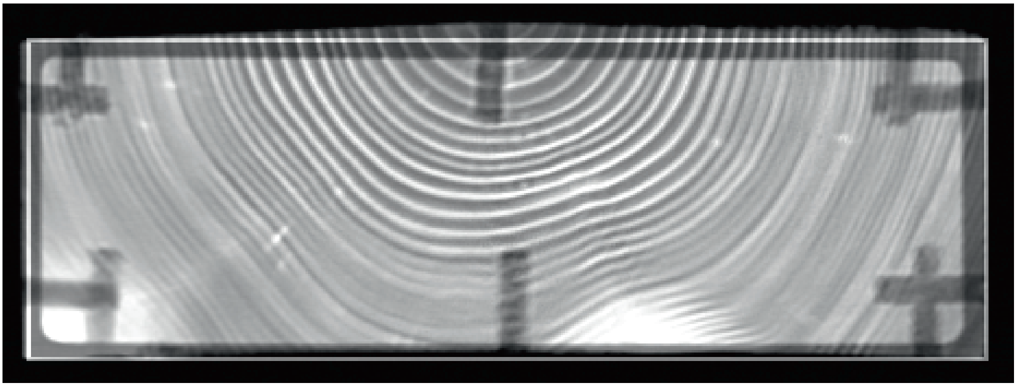

Figure 7: Example of a cross-section where the white rectangle is the idealised cross-section. The shaded area is material removed by the planer.

5 Related work

Most of the available research work in wood technology has taken place outside the scope of this thesis. Concerning interactions between planks and planers; the people with the knowledge are seemingly not part of the scientific article publishing community but I would gladly be proven wrong. However, Wang (1984) made a model determining cutting depths during planing based on the rough dry sawing variation complete with a model determining the rough dry sawing variation based on the rough green sawing variation.

To put my work into context and to be able to create a unifying theory so that the outcome of planing can be predicted and controlled by the properties of a log, the scope has to be expanded to include the steps from a log to its dry rough planks. Some of the things that need to be considered to judge the necessary green target size and allowance for planing are drying shrinkage and warp, especially twist.

Grönlund *et al.* (2009a) found that the drying shrinkage for spruce planks was mainly influenced by the distance to the pith and that density and annual ring width was of less importance. When the distance to the pith increased, the shrinkage of the width also increased while the shrinkage of the thickness decreased. Faced with the same experimental data and with the aid of finite element modelling, Ekevad *et al.* (2011), apart from the correlation between distance from pith and drying shrinkage, also showed that cup deformations decreased with increasing distance from the pith.

Both bow and crook are usually tied to uneven longitudinal shrinkage. According to Perstorper *et al.* (2001), longitudinal shrinkage decreases slightly with increasing distance from the pith but it also increases with increasing annual ring width and it increases considerably with the presence of compression wood. Öhman (1999) and Warensjö & Rune (2004) have all shown that compression wood influences bow and crook. Other studies have shown that release of growth stresses is also a source for bow and crook (Johansson & Ormarsson, 2009) and that the amount of those warp types decreases with increasing modulus of elasticity.

The variation in longitudinal shrinkage can be predicted by analysing images of the timber surface (Johansson *et al.*, 2003) both by using colour and by tracheid scanning.

Most researchers have reached the conclusion that the key to twist lies in the spiral grain. Some examples are Warensjö & Rune (2004) who found that the spiral grain angle and the grain angle affected twist. Ekevad (2005) showed that the amount of twist depended on the spiral grain gradient and Johansson &

Ormarsson (2009) found that the spiral grain angle and location of a board within a log influenced the amount of twist.

Sepúlveda (2001) was able to measure the spiral grain angle before sawing using computed tomography. Sepulveda *et al*. (2003) concluded that although an X-ray LogScanner may not detect the actual spiral grain, it could be used to identify the most affected logs. Furthermore, Nyström (2003) showed that the spiral grain angle can also be measured using the tracheid effect.

Some amount of warp can be avoided by drying with restraints or drying with a pre-twist in the case of expected warp (Ekevad *et al*., 2006). Früwald (2007) showed that the improved effect of restrained drying on warp is permanent even after moisture changes for Norway spruce. Warp that occurs during storage, i.e., delayed warp, depends on stress relaxation due to moisture changes and not on the moisture content (Rice, 2000).

6 Conclusions

During planing, the planks were controlled mainly by the feeding rollers positioned before the bottom cutter. The motion of the planks became more unstable as they moved further away from the feeding rollers.

The middle parts of the planks (CS2, CS3 and CS4) behaved similarly and were controlled during planing. The divergent parts of the planks were located in the top and butt ends (CS1 and CS5), where it was primarily twist that caused misalignment between the cross-sections and the cutters, with reduced twist and skewed cross-sections as a result. To be able to avoid reduced rectangularity due to twist, changes in the planer setting or planer design would have been needed, or it could have been resolved by cutting off the top and butt ends.

The sawing over-size could have been reduced and even most planer misses could have been avoided through cutting depth adjustments.

7 Future work

The insight into the behaviour of planks during planing given in this study, together with further industrial experiments in other planers with other species and dimensions will be used to create a model predicting the outcome from planing.

8 References

American Institute of Timber Construction (2004). Standard specifications for structural glued laminated timber of softwood species: AITC 117-2004.

Ekevad, M. (2005). Twist of wood studs: Dependence on spiral grain gradient. *Journal of Wood Science, 51*(5), 455-461. doi:10.1007/s10086-004-0679-2

Ekevad, M., Lundgren, N. & Flodin, J. (2011). Drying shrinkage of sawn timber of Norway spruce (picea abies): Industrial measurements and finite element simulations. *Wood Material Science Engineering, 6*(1-2), 41-48. doi:10.1080/17480272.2010.523121

Ekevad, M., Salin, J., Grundberg, S., Nyström, J., & Grönlund, A. (2006). Modelling of adequate pretwist for obtaining straight timber. *Wood Material Science & Engineering, 1*(2), 76-84. doi:10.1080/17480270600977872

Frühwald, E. (2007). Effect of high-temperature drying and restraint on twist of Norway spruce. *Drying Technology, 25*(3), 489-496. doi:10.1080/07373930601184056

Grönlund, A., Flodin, J. & Wamming, T. (2009a) Adaptive control of green target sizes. *Proceedings of the 19th Wood Machining Seminar*, Nanjing, China, October 2009.

Grönlund, A., Flodin, J., Vikberg, T., Nyström, J & Lundgren, N. (2009b). Monitoring of lumber size, shape and mismatch in double-arbour saws – development and validation of scanning equipment. In: *Proceedings of the 19th International Wood Machining Seminar.* Nanjing, China, October 2009.

Hägglund, A. & Marklund P. O. (1992). *Limmade ämnen till fönster och ytterdörrar – Nordiska bestämmelser för tillverkning och kontroll. (Glued material for windows and exterior doors – Nordic requirements for construction and control, in Swedish)* (Rapport: P 9208051) Skellefteå: Trätek

Johansson, G., Kliger, R. & Perstorper, M. (1993). *Inköpsregler för byggnadsvirke: Byggbranschens kvalitetskrav (Rules for purchase of structural timber, in Swedish).* Stockholm: Statens råd för byggforskning,

Johansson, M., Nyström, J., & Öhman, M. (2003). Prediction of longitudinal shrinkage and bow in Norway spruce studs using scanning techniques. *Journal of wood science* 49(4), 291-297. doi:10.1007/s10086-002-0480-z

Johansson, M. & Ormarsson, S. (2009). Influence of growth stresses and material properties on distortion of sawn timber - numerical investigation. *Annals of Forest Science, 66*(6), 604-604p10. doi:10.1051/forest/2009045

Nordiskt trä. sorteringsregler för sågat virke av furu och gran (Nordic Timber – Grading rules for Pine and Spruce timber, in Swedish) (1994). Stockholm: Arbor Publishing

Nyström, J. (2003). Automatic measurement of fiber orientation in softwoods by using the tracheid effect. *Computers and Electronics in Agriculture, 41*(1-3), 91-99. doi:10.1016/S0168-1699(03)00045-0

Öhman, M. (1999). Correspondence between manually estimated compression wood in Norway spruce and the warp of the sawn timber. *Holz Roh- Werkstoff 57*(5), 391-396

Perstorper, M., Johansson, M., Kliger, R. & Johansson, G. (2001). Distortion of Norway spruce timber. Part 1. Variation of relevant wood properties. *Holz Roh-Werkstoff 59*(1-2)*,* 94-103

Rice, R. W. (2000). Measurements of delayed warp in eastern spruce studs. *Drying Technology, 18*(8), 1833-1847. doi:10.1080/07373930008917813

Rosin, P. L. (1999). Measuring rectangularity. *Machine Vision and Application*, 11(4), 191-196.

Sepúlveda, P. (2001). Measurement of spiral grain with computed tomography. *Journal of Wood Science, 47*(4), 289-293. doi:10.1007/BF00766715

Sepúlveda, P., Kline, D.E. & Oja, J. (2003). Prediction of fiber orientation in Norway spruce logs using an X-ray log scanner: A preliminary study. *Wood and Fiber Science, 35*(3), 421-428.

Skogsindustrierna (2011). Skogsindustrin – En faktasamling 2010 års branschstatistik (Sawn timber industry – A collection of facts, in Swedish).

Wang, S. J. (1984). A new approach to calculating target sizes. *Forest Products Journal, 34*(9), 53-60.

Warensjö, M. & Rune, G. (2004). Effect of compression wood and grain angle on deformations of studs from 22-year-old Scots Pine trees. *Scandinavian Journal of Forest Research, 19*(5), 48-54

Paper I

Effect of planing on warp in Scots Pine (Pinus sylvestris).

Ann Axelsson

Wood Material Science and Engineering, 7:3, 154-161

Wood Material Science and Engineering, 2012; 7: 154–161

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ORIGINAL ARTICLE

Effect of planing on warp in Scots Pine (*Pinus sylvestris*)

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Abstract

If a sawn board or plank that is warped after drying is being planed, the feed rollers and the pressure elements will more or less straighten the wood during planing. However, when the pressure is released, some degree of warp will recur since the wood will spring back. With a large amount of straightening, only the cross-sectional dimensions of the wood should be affected by the planing operation, leaving warp unchanged, while a small amount of straightening should have a larger impact on warp. The objective of this study was to evaluate how warp is affected by planing in an industrial planer with standard configuration. A total of 20 pine planks with the dry target dimension 50 mm × 150 mm were selected, of which half were severely warped. The worst twist, crook and bow per two metres and maximum cup were measured both before and after planing.

The planer in the experiment had different impacts on the different warp types. For the individual planks, twist was reduced by 25% and crook was reduced by about 20% on average. Although bow decreased for half of the planks, the total average change for individual planks was a slight increase. Cupping practically vanished.

Keywords: *Bow, crook, cup,* Pinus sylvestris*, planing, Scots Pine, skip, twist, warp.*

Introduction

In modern sawmills, green timber can be sawed with small tolerances. However, drying and moisture equilibration during storing and shipping generally distorts the shapes of planks and boards, with warp like cup, twist, bow and crook as a consequence. Clear rules about allowable warp in different quality grades are stated by 'Nordic Timber' (Anon 1994), and recommendations for acceptable warp in the construction industry are stated by 'Rules for Purchase of Structural Timber' (Johansson *et al.* 1993).

During planing, planks are straightened to some extent due to feed rollers and pressure elements, but how much a planer can straighten a plank depends on the amount of pressure applied from rollers and other pressure elements, and also on how flexible the material is. When the pressure is released, the wood springs back and some degree of warp reoccurs. How much planing influences warp depends on the amount of warp, the planer, its settings, forces from pressure and feeding elements and the plank's modulus of elasticity.

To be able to adjust the green target sizes to give the required dimensions and shape after drying and planing, the correlations between properties of the raw material, the sawing process, drying process and planing need to be considered. The early parts of this chain of processes have been investigated by researchers here at Luleå University of Technology (Ekevad 2006, Grönlund *et al.* 2009b, Ekevad *et al.* 2010, 2011, Lundgren *et al.* 2011). Now the time has come to examine the role of the planer. While most of the research concerning the quality of planed wood in general is focused on the finished surface and its roughness – or lack thereof (Franz 1958, Hernandéz and Fernando de Moura 2001, Kilic *et al.* 2006, Coelho *et al.* 2007, Malkoçoglu 2007), and surface properties (Naderi and Hernández 1999), or occurrence of skip areas based on surface roughness (Wang 1984), this study concentrates on how the planing operation affects the warp of planed wood.

In this study, test samples with a wide spread of properties were used. This made it possible to draw general conclusions about which properties were the

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key to determining the effect a planer had on plank shape. A number of planks with varying degrees of warp, lengths and modulus of elasticity were planed in an industrial planer at Martinson Sawmill in Kroksjön with standard settings. The different types of warp were recorded for the rough and planed planks, and the changes of warp were analysed.

Materials and methods

In this study, 20 Scots Pine (*Pinus sylvestris*) planks with a dry target size of 50 mm × 150 mm, a moisture content of about 7% and varying degrees of deformations were used. All of the planks were sawn through the pith.

For all the planks, five evenly distributed cross-sections were selected, numbered from CS1, located 10 cm from the top end, to CS5, located 10 cm from the butt end. On every cross-section, 10 positions were marked with drilled holes; three on each face and two on each edge (Figure 1). The right and left edges were defined viewed in the feeding direction. The cross-sections were scanned in an X-ray CT scanner the day before and the day after planing. The image processing software ImageJ was used to measure both the depths of the drilled holes and the width and thickness of the cross-sections at hand.

On the same day as the planing, the rough and the planed planks were scanned from top end to butt end, standing on their edge in a measuring rig using laser triangulation (Grönlund *et al.* 2009a) and a Matlab program calculating maximum cup, and maximum crook, twist and bow per two metres (Table I). Also, the global modulus of elasticity, MOE, was measured according to standard EN408 (2003) on the day of the experiment.

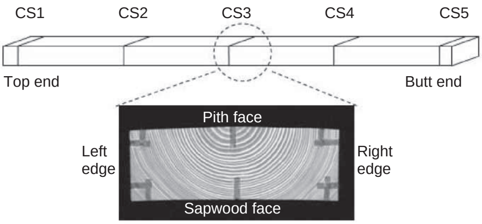

Figure 1. Locations of the selected cross-sections and an example of a CT image of a cross-section with holes.

To calculate cutting depths, the depths of the drilled holes were measured on the rough planks as well as on the planed planks. On the sapwood face, the holes to the right and to the left were used, and on the right edge, the upper hole was used, since those positions require less considerations of cupping.

The planks were machined in an automatic four-side planer (combined jointer and thickness planer) at Martinsons Sawmill in Kroksjön to the dimensions 45 mm × 145 mm. The planks were fed with the top end first and the sapwood side face down, resulting in jointing on the right edge and sapwood face and dimension planing on the left edge and pith face. The settings on the planer and the responding forces from the pressure rollers and pressure plate were registered (Figure 2).

The experimental values were compared to one theoretical model for each type of warp (cup, twist, bow and crook) developed from simplified planks. An assumption was used that no straightening at all occurred in the planer, that is zero pressure from rollers and plates. The middle cross-section, CS3, was assumed to be straight and parallel to the top and bottom cutters. A visual inspection of the planks at hand led to the assumptions that twist was evenly distributed over a quarter of the length of the planks, while bow and crook were evenly distributed over the entire length. Figure 3 shows the variables for the different warp types.

The models became:

$$\mathrm{Cup_P} = \begin{cases} 0, & \text{if} \quad \mathrm{Cup_R} \le d_{sf} \\ \mathrm{Cup_R} - d_{sf} & \text{if} \quad \mathrm{Cup_R} > d_{sf} \end{cases}, \tag{1}$$

where $\mathrm{Cup_P}$ = Cup for the planed plank (mm), $\mathrm{Cup_R}$ = Cup for the rough plank (mm) and d_{sf} = depth of cut on the sapwood face (mm),

$$\mathrm{Twist_P} = \begin{cases} 0, & \text{if} \quad \mathrm{Twist_R} \le d_{sf}\frac{8}{l} \\ \mathrm{Twist_R} - d_{sf}\frac{8}{l} & \text{if} \quad \mathrm{Twist_R} > d_{sf}\frac{8}{l} \end{cases}, \tag{2}$$

Table I. Plank properties and rough warp of the 20 planks.

Property	Minimum	Maximum	Average	Standard deviation
Length (m)	2.9	5.5	4.2	0.65
MOE (MPa)	6500	12,000	9400	1600
Cup (mm)	1.5	3.8	2.5	0.5
Twist (mm/2m)	0.4	24.5	11.7	7.0
Bow (mm/2m)	1.0	8.6	4.6	2.2
Crook (mm/2m)	0.9	8.5	2.7	2.1

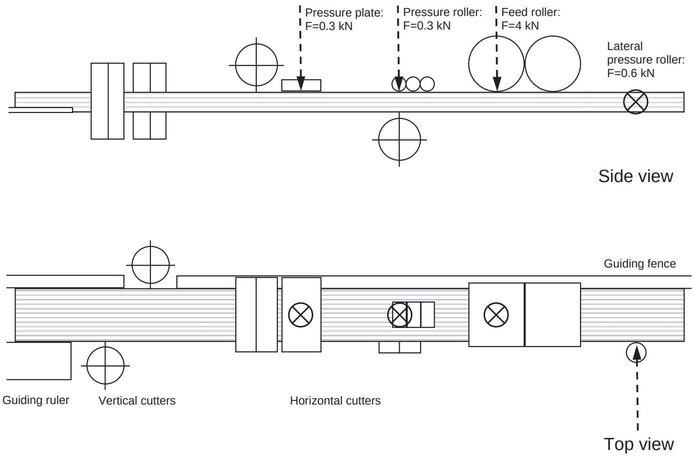

Figure 2. Schematic side and top view of the planer with measured pressure positions.

where Twist_P = Twist for the planed plank (mm/2m), Twist_R = Twist for the rough plank (mm/2m) and l = length of the plank (m),

$$\text{Bow}_\text{P} = \begin{cases} 0, & \text{if} \quad \text{Bow}_\text{R} \leq (t_\text{R} - d_\text{sf} - t_\text{T})\frac{2}{l} \\ \text{Bow}_\text{R} - (t_\text{R} - d_\text{sf} - t_\text{T})\frac{2}{l} & \text{if} \quad \text{Bow}_\text{R} > (t_\text{R} - d_\text{sf} - t_\text{T})\frac{2}{l}, \end{cases} \tag{3}$$

where Bow_P = Bow for the planed plank (mm/2m), Bowt_R = Bow for the rough plank (mm/2m), t_R = rough thickness (mm) and t_T = target thickness (mm),

$$\text{Crook}_\text{P} = \begin{cases} 0, & \text{if} \quad \text{Crook}_\text{R} \leq (w_\text{R} - d_\text{re} - w_\text{T})\frac{2}{l} \\ \text{Crook}_\text{R} - (w_\text{R} - d_\text{re} - w_\text{T})\frac{2}{l} & \text{if} \quad \text{Crook}_\text{R} > (w_\text{R} - d_\text{re} - w_\text{T})\frac{2}{l}, \end{cases} \tag{4}$$

where Crook_P = Crook for the planed plank (mm/2m), Crook_R = Crook for the rough plank (mm/2m), d_re = depth of cut on the right edge (mm), w_R = rough width (mm) and w_T = target width (mm).

As the theoretical models only consider one type of warp at a time without any considerations to linked effects between the different warp types, deviations between the experimental result and the theoretical models were expected. To judge the size of warp in both the experiment and in the theoretical models, the warp was compared to the requirements given in 'Nordic Timber' (Anon 1994) and 'Rules for Purchase of Structural Timber' (Johansson *et al.* 1993).

In order to examine the importance of length, l, modulus of elasticity, MOE, and initial deformation, linear regression analyses using the least squares method were used to develop adapted models for the deformations after planing. To single out the most important factors, initial models with the scaled and centred variables were used. The key variables were kept in final adjusted models with real values.

Results and discussion

Dimensions

For the rough planks, the average width was 151.7 mm with a standard deviation of 1.3 mm, while the average thickness was 50.4 mm with a standard deviation of 0.8 mm. After planing, the average dimensions were reduced to 144.3 mm with a standard deviation of 1.0 and 44.7 mm with a standard deviation of 0.4 mm.

The average cutting depths on the sapwood face and the right edge for the different cross-sections are listed in Table II. In the theoretical models, the total average cutting depths on the sapwood face and right edge were needed. As the standard deviations in CS1 and CS5 were large in comparison with the others,

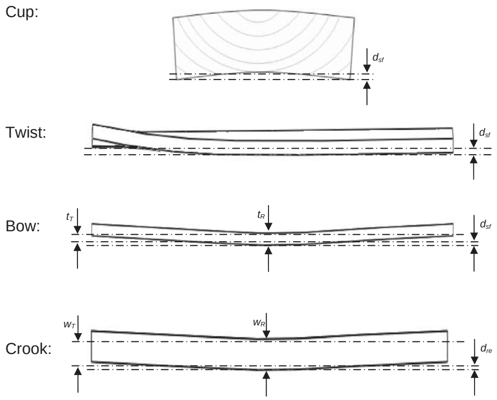

Figure 3. Warp and variables for the theoretical models.

CS1 and CS5 were omitted in calculation of total average cutting depths which were 2.3 mm for the sapwood face and 2.8 mm for the right edge.

Common for the sapwood face and the right edge was that the planer had removed most material in the middle of the planks with decreasing depths of cut towards the butt and top end, although the difference between CS2, CS3 and CS4 was minor. There was a larger difference between CS1 and CS2 as well as between CS4 and CS5 for the sapwood face than for the right edge.

Cup

Very nearly all cupping was removed during planing and the average cup reduction was 2.3 mm for the experimental values while it was 2.4 mm in the theoretical model. The largest difference for an individual plank between the two cases was only 0.6 mm (Figure 4). All in all, the experimentally planed planks' cup follows the theoretical model well, so the pressure roller above the bottom spindle did not flatten the cross-section during planing.

Twist

After planing, twist for the individual planks was reduced by 25% on average in the experiment, and in general a larger rough twist was subjected to a larger reduction of twist (Figure 5). According to the theoretical model, the average twist reduction would have been 36%. For planks with a smaller twist (below approximately 10 mm/2 m) the twist remained more or less unaltered. For planks with a larger twist (above approximately 13 mm/2 m) the experimental values agreed well with the theoretical model.

A linear regression analysis with scaled and centred variables gave the relationship:

$$\mathrm{Twist}_P^* = 8.9 \times 10^{-17} - 0.17 \times l^* + 2.6 \times 10^{-3}\mathrm{MOE}^* + 1.0 \times \mathrm{Twist}_R^*$$

where the star index represents scaled and centred variables. The coefficient of determination for the initial model was 0.98. The formula shows that the dominant factor for twist after planing is the initial twist, while the influence of MOE was peripheral. A suitable twist formula from the experiments was:

$$\mathrm{Twist}_P = 0.75 \times \mathrm{Twist}_R,$$

with an R^2 value of 0.98. Since the adjusted formula based on the experiment is independent of MOE, there could be other mechanisms than flattening at work. One possibility is that the distance between the downward forces is large enough and that the pressures are weak enough to enable the planks to wobble in the planer, and thus it only appears like the planks with a smaller twist have been flattened in the planer.

Bow

Bow appears in the weakest direction of the planks and should be the easiest warp to flatten. In the experiment, bow only decreased for half of the planks, while it increased for the rest and the average change was a slight increase (Figure 6). When looking at the cutting depths for the sapwood side, it looks like some bow was present during planing as there was a difference in cutting depth between the ends and the middle cross-section. According to the theoretical model, bow should be reduced by 29% on average. For the experiment, bow after planing is spread out around the case of no alterations of bow

Table II. Average cutting depths on the sapwood face and right edge for the different cross-sections.

	Sapwood face Cutting depth (mm)	Standard deviation (mm)	Right edge Cutting depth (mm)	Standard deviation (mm)
CS1	1.9	1.0	2.3	0.9
CS2	2.5	0.4	2.8	0.4
CS3	2.7	0.4	2.9	0.7
CS4	2.5	0.5	2.8	0.5
CS5	1.6	1.2	2.8	1.0

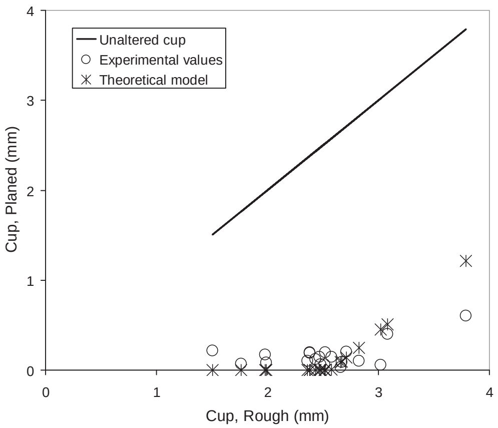

Figure 4. Comparison of cup after planing for the experimental values and the theoretical model.

after planing. Generally, the planks with the smallest difference between the experimental and the theoretical bow after planing were the planks with a high MOE, showing that planks with a larger stiffness where less flattened during planing.

The theoretical model is based on the assumption that no forces act on the planks, but there is also another way of looking at the model. One can consider the theoretical model as planing of a very stiff material since the wood does not change its outer shape except for removal of material, which explains the poor correlation between the theoretical model and the experiment. As stated earlier, planks are weak in the bow direction and gravity introduces some amount of flattening without outer pressure forces. In the theoretical model, it is assumed that bow only appears in one direction, which also could

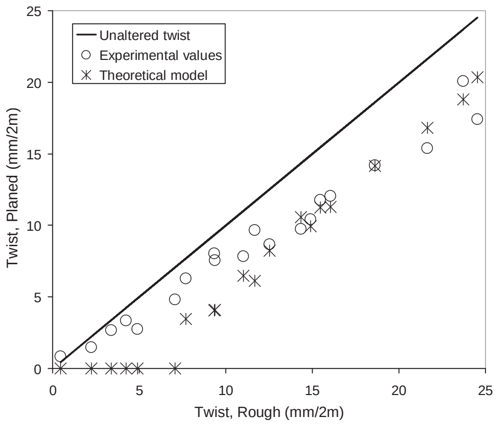

Figure 5. Comparison of twist after planing for the experimental values and the theoretical model.

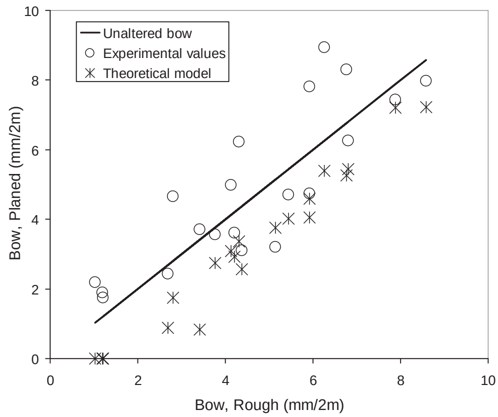

Figure 6. Comparison of bow after planing for the experimental values and the theoretical model.

be a source of error; however since bow is practically unaffected by planing, the bow direction does not matter; instead an alternative theoretical model irrespective of bow direction could be used:

$$\mathrm{Bow_P} = \mathrm{Bow_R}, \qquad (5)$$

which corresponds to the solid line in Figure 6.

Linear regression for scaled centred variables gave:

$$\mathrm{Bow_P^*} = 2.5 \times 10^{-16} + 0.86 \times l^* - 0.71 \times \mathrm{MOE}^* + 0.78 \times \mathrm{Bow_R^*},$$

which had an R^2 value of 0.85. For bow, all variables had equal importance, so the final model was chosen as:

$$\mathrm{Bow_P} = 1.0 \times l - 3.5 \times 10^{-4} \times \mathrm{MOE} + 0.83 \times \mathrm{Bow_R}$$

where the R^2 value for the model was 0.85. According to the regression model, MOE has a negative influence for bow after planing, which indicates that a stiffer plank is harder to flatten, which results in a decreased bow. The negative influence MOE has on bow was an expected result. Bow was the only warp type that showed any dependency of length according to the final regression models.

Crook

For the majority of the planks, crook decreased during planing, and the average change was an approximate reduction of 20%, while the theoretical model predicted an average reduction of 73% (Figure 7). The model predicted that small crooks would be planed off; but that was not the case. In the

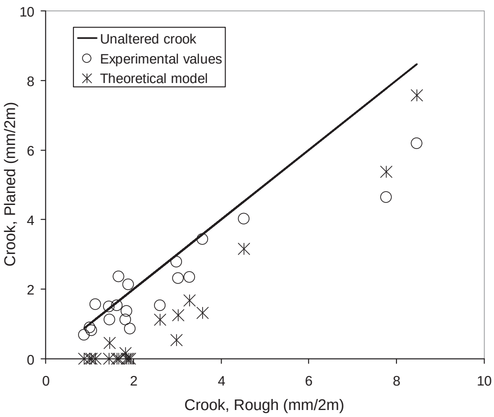

Figure 7. Comparison of crook after planing for the experimental values and the theoretical model.

experiment, a smaller original crook (below approximately 5 mm/2 m) remains unchanged after planing, while planks with a larger original crook (above approximately 7 mm/2 m) have been subjected to a larger shape modification by planing in the experiment than in the theoretical model.

Since crook appears in the stiffest direction of the planks, it should be the hardest deformation to straighten out, and the experimental values should therefore correspond well with the theoretical model. However, there is a large difference between the experiment and the theoretical model, which probably depends on the simple assumption that the middle cross-section is straight and parallel to the top and bottom cutters. The movement of the planks through the planer is a much more complicated matter. There are two principal scenarios; crook can either be directed towards or away from the guiding fence. In one scenario, the plank should move straight through the planer since there are two contact zones between the plank and the guiding fence: one in the top end and one in the butt end. As a result, the cutting depths on the right edge of the plank would be largest in CS1 and CS5 while they would be smallest in CS3 with intermediate cutting depths on CS2 and CS4. In the other scenario, on which the theoretical model is based, there is only one contact zone between the plank and the guiding fence in the beginning of the planing operation. The lateral pressure roller guides the part of the plank located in the planer intake towards the guiding fence. At first, the top end cross-section would be aligned perpendicular to the guiding fence, and as the plank progresses further in the planer, the plank's curvature would make the top end move left until the point where the guiding ruler controls the planks motion and guides the planks towards the right. Then, the plank is steered both in the top end and in the butt end making the plank move straight in the planer until the butt end of the plank leaves the lateral pressure roller. By then, the top part of the plank is wedged between the guiding fence and the guiding ruler making the plank move straight. In this scenario, the cutting depth would be smallest in CS1 and increasing in the following cross-sections due to both a more controlled motion and the planks curvature. After the middle cross-section, the curvature of the crook would make the cutting depth decrease, but since the motion of the plank is controlled, the cutting depth of CS5 would be larger then the cutting depth of CS1. This is the case in the experiment, which shows that the crook direction was correctly assumed in the theoretical model for the planks at hand.

The first model with scaled and centred variables was:

$$\text{Crook}_P^* = -1.5 \times 10^{-17} - 0.11 \times l^* + 0.44 \times \text{MOE}^* + 0.80 \times \text{Crook}_R^*,$$

for which R^2 was 0.90. For crook, the most influential factor was original crook, followed by MOE, while length had a minor influence. The final formula became:

$$\text{Crook}_P = -0.52 + 1.0 \times 10^{-4} \times \text{MOE} + 0.64 \times \text{Crook}_R,$$

for which $R^2 = 0.90$. Since MOE has a positive effect on crook after planing, that is the stiffer the material the larger the defect after planing, some mechanism other than forces flattening the planks is responsible for the seemingly straightened small crooks during planing. The real reason could be the lateral movements of the plank as discussed earlier.

Approved warp

Warp for rough and planed planks was compared with two different requirements with different bases. 'Nordic Timber' (Anon 1994) is a commercial sorting rule without concerns about the final use, while 'Rules for Purchase of Structural Timber' (Johansson *et al.* 1993) is adapted to meet the demands of the building industry; this makes the former more general than the latter.

When planks were rough, eight of them passed the requirements given by 'Nordic Timber'; and after planing, the number of approved planks in the experiment had increased to 10. The theoretical models (Equations 1–5) were able to predict whether or not bow and cup would be approved after planing while they had one miss for twist and crook, respectively. All in all, the difference between the experimental and the theoretical case was one plank, since planks can be discarded due to more than one warp type.

Only one of the rough planks would pass the stricter requirements given by 'Rules for Purchase of Structural Timber', and in the experiment three planks were approved after planing. The theoretical models could predict if the plank's cup would be approved (Equation 1), but had one miss for twist (Equation 2), two misses for crook (Equation 4) and three misses for bow (Equation 3). If the alternative model with unaffected bow after planing was used (Equation 5), the difference between the model and the experiment when it comes to approval would be two planks.

The findings indicate that if the question is whether or not a plank would be approved after planing according to those two guidelines, an easy, theoretical model would be sufficient. They also indicate that there is no major improvement potential when it comes to meeting the requirements in adjusting the forces acting on the planks from the planer in the experiment while keeping the cutting depths.

Conclusion

If the planks were completely straightened during planing, all warps would have remained the same after the planing process. This is not the case, therefore some degree of warp remained present during planing, and since bow increased in half of the planks, the planer actually introduced more deformation. Conclusions that can be made are:

- an increased MOE led to a decreased bow and a increased crook, but had no effect on twist;
- an increased length led to an increased bow, but had no effect on twist or crook;
- the planer did not flatten the planks' cross-sections during planing, which was shown since the experimental results for cup corresponded to the theoretical model;
- the only deformation that the planer did flatten during planing was bow, since bow was nearly unaffected by the operation;
- small amounts of twist and crook were not affected by planing while large amounts of twist and crook were reduced after planing; and
- simple theoretical models can be used to predict if a plank would pass the requirements stated by 'Nordic Timber' or 'Rules for Purchase of Structural Timber'.

More experimental work is planned to validate the study and develop an improved model with, for example, variations in moisture contents and planer settings.

Acknowledgements

The author wishes to thank the European Regional Development Fund, Objective 2, Northern part of Sweden via Tillväxtverket (the Swedish Agency for Economic and Regional Growth) and Vinnova (the Swedish Agency for Innovation Systems) for financial support.

References

Anon. (1994). *Nordic Timber – Grading Rules for Pine and Spruce Timber* (In Swedish: Sorteringsregler för sågat virke av furu och gran) (Stockholm: Arbor Publishing).

Coelho, C. L., Carvalho, L. M. H., Martins, J. M., Costa, C. A. V., Masson, D. & Méausoone, P. (2007). Method for evaluating the influence of wood machining conditions on the objective characterisation and subjective perception of a finished surface. *Wood Science and Technology*, 42 (3), 181–195.

Ekevad, M. (2006). Modelling of dynamic and quasistatic events with special focus on wood-drying distortions. Doctoral thesis, Luleå University of Technology, Division of Wood Science and Technology, Skellefteå, Sweden.

Ekevad, M., Lundgren, N. and Flodin, J. (2010). Choosing green sawing dimensions for best value yield of Norway spruce: Industrial measurements and physical modeling. *Proceedings of the 11th International IUFRO Wood Drying Conference: Recent Advances in the Field of Wood Drying*, 18–22 January, Skellefteå, Sweden.

Ekevad, M., Lundgren, N. & Flodin, J. (2011). Drying shrinkage of sawn timber of Norway spruce (Picea Abies): Industrial measurements and finite element simulations. *Wood Material Science and Engineering*, 6 (1–2), 41–48.

European standard EN408. (2003). Timber structures – structural timber and glued laminated timber – determination of some physical and mechanical properties.

Franz, N. C. (1958). An analysis of the wood-cutting process. Ph.D. thesis, University of Michigan Press, Ann Arbor, MI.

Grönlund, A., Flodin, J., Vikberg, T., Nyström, J. and Lundgren, N. (2009a). Monitoring of lumber size, shape and mismatch in double-arbour saws – development and validation of scanning equipment. *Proceedings of the 19th International Wood Machining Seminar*, 9 October, Nanjing, China.

Grönlund, A., Flodin, J. and Wamming, T. (2009b). Adaptive control of green target sizes. *Proceedings of the 19th International Wood Machining Seminar*, 9 October, Nanjing, China.

Hernandéz, R. E. & Fernando de Moura, L. (2002). Effects of knife jointing and wear on the planed surface quality of Northern Red Oak Wood. *Wood and Fiber Science*, 34 (4), 540–552.

Johansson, G., Kliger, R. and Perstorper, M. (1993). *Rules for Purchase of Structural Timber* (In Swedish: Inköpsregler för byggnadsvirke: byggbranschens kvalitetskrav) Stockholm: Statens råd för byggnadsforskning.

Kilic, M., Hiziroglu, S. & Burdurlu, E. (2006). Effect of machining on surface roughness of wood. *Building and Environment*, 41 (8), 1074–1078.

Lundgren, N., Ekevad, M. & Flodin, J. (2011). Choosing green sawing dimensions for Norway spruce from stochastic simulations. *Journal of Wood Science*, 57 (2), 94–99.

Malkoçoğlu, A. (2007). Machining properties and surface roughness of various wood species planed in different conditions. *Building and Environment*, 42 (7), 2562–2567.

Naderi, N. & Hernández, R. E. (1999). Effect of planing on physical and mechanical properties of sugar maple wood. *Wood and Fiber Science*, 31 (3), 283–292.

Wang, S. J. (1984). A new approach to calculating target sizes. *Forest Products Journal*, 34 (9), 53–60.

Paper II

Rectangularity of planed Scots Pine (Pinus sylvestris) planks

Ann Axelsson

Submitted to:
Wood Material Science and Engineering.

Rectangularity of planed Scots pine (*Pinus sylvestris*) planks

ANN AXELSSON

Abstract

This study deals with how warp affects the cross-sectional shape of planed planks. A total of 20 planks with dry target cross-sectional dimensions of 50 × 150 mm were planed to 45 × 145 mm. The rectangularity of five cross-sections of every plank was measured before and after planing. The cutting depths were measured in 10 positions in the cross-sections and the angles between the planks and the cutters were calculated. Also, the warp, that is, twist, bow, crook, and cup, was measured before and after planing.

All the studied properties pointed in the same direction. In terms of both rectangularity and angles of cut, the problems were larger in the top and butt ends of the investigated planks than in the intermediate parts, and the main reason for deviations from the desired result after planing was twist.

Key Words: *Cross-section, Drying deformations, Warp*

Introduction

Ideally, all sawn timber, including planks, should end up warp-free and with rectangular cross-sections with the target width and thickness after drying; however, in reality this is not the case. The inherent properties of wood as well as the sawing pattern influence the amount of warp after drying (e.g. Perstorper *et al.*, 2001; Warensjö & Rune, 2004; Grönlund *et al.*, 2009a; Ekevad *et al.*, 2011). Each plank has its own individual properties, resulting in varying amounts of warp in various planks. One way to eliminate or partly reduce these drying deformations and to achieve the desired dimensions is to plane the dried planks.

In the last decades, the importance of planing has increased in Sweden. In 1990 about 1.2 million cubic meters of planed goods were exported, which accounted for roughly 10% of the total sawmill production. During the following 20 years the amount of planed goods exported rose to 4.7 million cubic meters, which represented 28% of the total sawmill production in Sweden in 2010 (Skogsindustrierna, 2011). As the volume of planed goods increases, the volume of planed goods rejected due to quality issues also increases unless production development takes place. The quality of planed goods concerns aspects like surface roughness (e.g. Franz, 1958; Jackson *et al.*, 2002; Coelho *et al.*, 2007; Malkoçoğlu, 2007), occurrence of warp (Axelsson, 2012) and planer misses (Wang 1984) as well as the shape of the cross-sections.

The most troublesome type of drying deformation for building contractors is twist (Johansson *et al.*, 1994). There are at least two ways to deal with twist: one is to reduce the twist and the other is to reduce the consequences of twist. Drying with restraints on deformations (by using, e.g., fixed and loaded stickers) or drying with pretwist (Ekevad *et al.*, 2006) are means of reducing twist after drying. Twist after drying can be reduced by planing; however if the dry target cross-sectional sizes is adjusted to cope with planks with a high amount of twist the result is unnecessary material waste for planks with a low amount of twist, as the allowance for planing becomes larger than needed for those planks. An alternative approach is to use a small dry target cross-sectional size and to discard individual planks that have excessive amounts of twist either before or after planing. In order to reduce the amount of waste, the dry target cross-sectional dimensions could be adjusted for the expected amount of warp and the necessary allowance for planing of individual planks.

The consequences of twist can be decreased by gluing pieces of wood together, which results in a higher shape stability (Eriksson *et al.*, 2004). In that case, if thickness variations or planer misses are present, problems with gluing between laminations can arise. Thickness variations in the laminations can also accumulate if they do not occur randomly. The maximum deviation from the average thickness in a lamination should not exceed 0.2 mm when components for windows and exterior doors are manufactured (Hägglund & Marklund, 1992) and the maximum variation in thickness in a lamination allowed by the American standard (AITC, 2004) is also 0.2 mm across the width (i.e., in a specific cross-section). Thickness variation in a cross-section leads to a lower rectangularity of the cross-section in question.

This study was aimed at increasing the knowledge of the effects of planing, with a focus on how warp affects the cross-sectional shape after planing.

Method

Twenty Scots pine (*Pinus sylvestris*) planks with dry target cross-sectional dimensions of 50 mm × 150 mm and moisture content between 6 and 10% were chosen for this study. Half of the planks were selected due to their high amount of warp while the other half had more moderate amounts of warp (Table 1). All planks had been sawn through the pith (Figure 1a). As the study was focused on how planing and warp affected the result after planing the underlying causes of warp were not considered and there were no records of the planks' histories in terms of green properties or drying conditions.

The planks were machined at a sawmill in the northern part of Sweden in an automatic four-side planer (combined jointer and thickness planer) to the dimensions 45 mm ×145 mm. The planks were fed with the top end first and the sapwood face down, resulting in jointing on the right edge and sapwood face (down) and dimension planing on the left edge and pith face (up). The settings on the planer and the corresponding forces from the pressure rollers and pressure plate were registered (Figure 2). The positions of the cutters in relation to the feed rollers and the pressure elements, together with the size of the pressure, govern the effect of the planer on the planks.

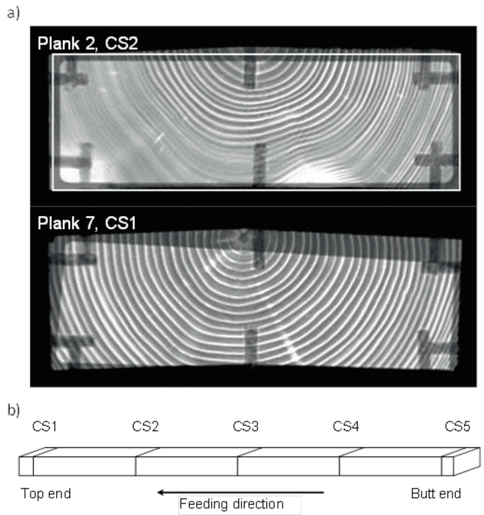

Figure 1: a) CT-images of two cross-sections before and after planing. Plank 2 had a rough twist of 7.1 mm/2 m and the cross-section had a cup of 0.4 mm. Plank 7 had a rough twist of 24.5 mm/2 m with a cup of 1.6 mm in the cross-section. The shaded areas are the material removed during planing; the white rectangle on Plank 2 is the idealized cross-section before planing and the drilled holes where cutting depths have been measured can be seen. b) Locations of the selected cross-sections and the feeding direction in the planer.

Just before and after planing, twist, crook, bow, and cup were measured according to standard SS-EN 1310 (1997) in a measuring device that uses laser triangulation (Grönlund *et al.*, 2009b). Five cross-sections were selected for more detailed analysis. Cross-section one, CS1, was positioned 10 cm from the top end of the planks, and cross-section 5, CS5, was located 10 cm from the butt end (Figure 1b). The intermediate cross-sections were evenly distributed between CS1 and CS5. The cross-sections were scanned in an X-ray CT-scanner the day before and the day after planing. The image processing software ImageJ (freeware from the National Institute of Health, NIH) was used to make the necessary measurements in the CT-images.

Rectangularity was evaluated using the minimum bounding rectangle method (Rosin, 1999), which gives the rectangularity as the ratio between the area of the cross-section, A_{cs} and the area of its minimum bounding rectangle, A_{MBR}:

$$R = \frac{A_{cs}}{A_{MBR}},$$

where $R = 1$ for a perfect rectangle. The fitting of the bounding rectangle was done manually in the images. Regarding the rectangularity measure in relation to the maximum allowed thickness variations according to the American standard mentioned above, the following serves as an example: assuming that both edges and one face of a 45 × 145 mm cross-section are straight and orthogonal while the remaining face is skewed, a maximum deviation from the average thickness of 0.2 mm corresponds to a minimum rectangularity of 0.99. If the deviation of the average thickness is doubled (0.4 mm), the rectangularity decreases to 0.98. A further doubling (0.8 mm) corresponds to a rectangularity of 0.96.

In the selected cross-sections, holes were drilled in 10 places on every cross-section (Figure 1). The cutting depths were calculated by measuring the depths of the holes before and after planing. To be able to compare planks with varying rough dimensions and varying amounts of cup, adjusted cutting depths were used. Idealized cross-sections shaped like perfect rectangles with dimensions of 50 × 150 mm were fitted to the real rough cross-sections. The idealized cross-sections shared their bases with

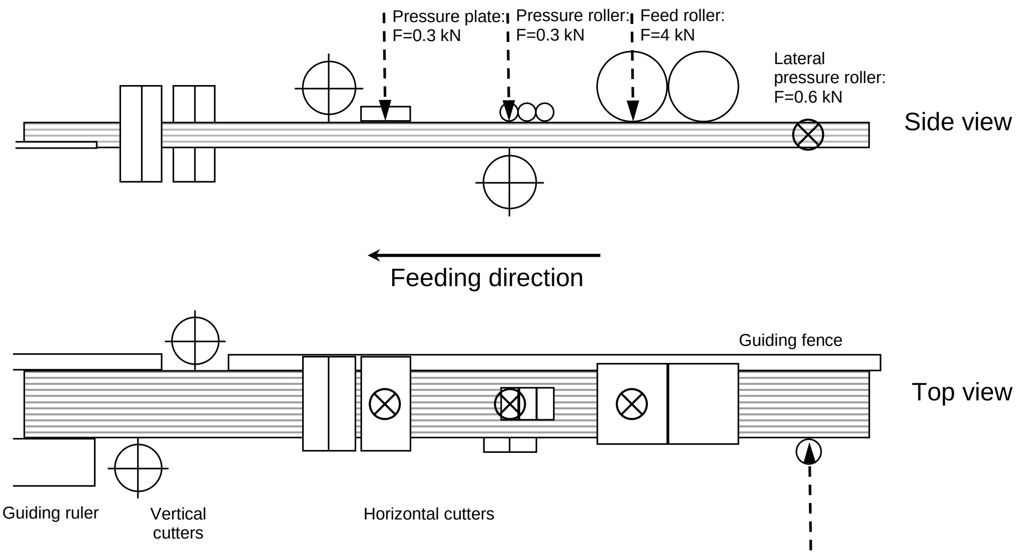

Figure 2: Schematic side and top view of the planer with the positions where the pressure was measured.

the two lowest points on the real cross-sections and the right edges of the idealized cross-sections were located on the points furthest to the right in the real cross-sections (Figure 1a). The depth of the holes in the rough planks was measured from the idealized cross-section instead of from the surface of the real rough cross-section. The depth of the holes after planing was measured from the surface except when planer misses were present. Since the location of the cutter in relation to the plank was of interest, the cutting plane was extended by extending a line aligned with the planed part of the face or edge of the cross-section in question. So when planer misses were present, the depth of the hole after planing was measured from the extended cutting plane, resulting in a negative cutting depth.

To evaluate whether the cuts had been oblique, the angle of cut (AOC, the angle between the planks and cutters) was calculated by comparing cutting depths of the outer holes on a face or edge. If the cross-section was angled in a clockwise direction during the cut, the AOC was defined as positive. Four AOCs were calculated for each cross-section: two for the faces and two for the edges. The AOC could be used as an indicator of how much the planer and its pressure element had straightened the planks during planing. If a plank was loaded with pressure to make it straight (without twist) during planing, the AOC would be zero and the twist would recur after planing. On the other hand, if no straightening at all occurred during planing, the AOC would be equal to the angle of twist for the individual cross-section of the rough plank. In the latter case, the twist of the whole plank would be reduced after planing. In this study, however, the differences between AOCs on opposing faces or edges were the interesting features, since they showed whether or not opposite faces or edges were parallel. For a fictitious cross-section with the two edges parallel, one face orthogonal to the edges, and the other face skewed, a maximum deviation of 0.2 mm from the average thickness of the cross-section corresponds to a difference in AOC between the two opposing faces of 0.2°. A positive difference in AOC between the opposing faces or edges corresponds to a larger AOC on the sapwood face than on the pith face and a larger AOC on the right edge than on the left edge.

Results

A summary of the results of the scanning operation (twist, crook, bow, and cup) and the dimension measurements (length, width, and thickness) is shown in Table 1. Details of how warp was affected by the planing operation have been discussed in a separate paper (Axelsson, 2012). All planks except one had a left-handed twist.

Table 1: Measured dimensions and absolute values of warp of the rough and planed planks. Standard deviation in parentheses.

Property		Minimum	Maximum	Mean
Length (m)		2.9	5.5	4.2 (0.65)
Width (mm)	Rough	150	153	152 (0.96)
	Planed	142	145	144 (0.54)
Thickness (mm)	Rough	49	52	50 (0.66)
	Planed	44	45	45 (0.16)
Cup (mm)	Rough	1.5	3.8	2.5 (0.5)
	Planed	0.0	0.6	0.2 (0.1)
Twist (mm/2m)	Rough	0.4	24.5	11.7 (7.0)
	Planed	0.8	20.1	8.7 (5.4)
Bow (mm/2m)	Rough	1.0	8.6	4.6 (2.2)
	Planed	1.7	8.9	4.9 (2.3)
Crook (mm/2m)	Rough	0.9	8.5	2.7 (2.1)
	Planed	0.7	6.2	2.2 (1.4)

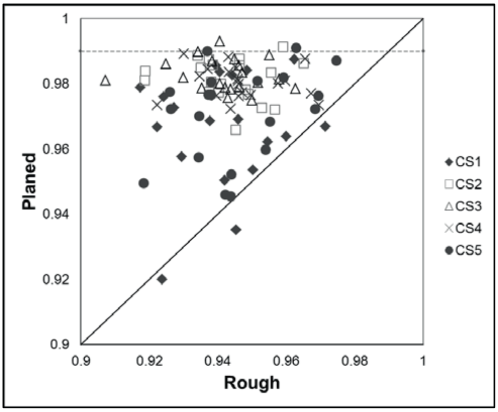

Figure 3: Rectangularity after planing as a function of rectangularity before planing. The dashed line marks the rectangularity corresponding to the maximum thickness variation of 0.2 mm allowed by the American Standard. The solid line marks the same rectangularity after planing as before planing.

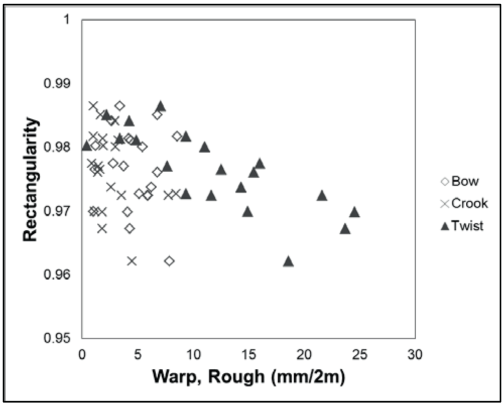

Figure 4: Average rectangularity after planing for all all cross-sections of a plank versus bow, crook, and twist before planing for the planks.

The average rectangularity for all cross-sections of all rough planks put together was 0.94 ± 0.013. After planing, the corresponding numbers were 0.98 ± 0.012. After planing, the rectangularity of the individual cross-sections had increased for all of the planks. On average, the rectangularity was 0.97 ± 0.017 for CS1 and 0.98 ± 0.0064 for CS2. For both CS3 and CS4 the average rectangularity was 0.98 ± 0.0050, while CS5 had an average rectangularity of 0.97 ± 0.014.

Scatter plots of rectangularity for rough and planed planks (Figure 3) showed that rectangularity increased after planing for all the measured cross-sections except three, which were all located in CS1. In general, the cross-sections where the increase of rectangularity was lowest were CS1 and CS5. Only four of the 100 cross-sections had a rectangularity larger than 0.99.

Figure 4 shows the mean rectangularity of all cross-sections of the planks as functions of twist, crook, and bow of the planks. A linear regression gave coefficients of determination R^2 of 0.62, 0.11, and 0.02 for twist, crook, and bow respectively. This means that only twist was correlated to rectangularity, and Figure 4 also shows that the straightest planks had the greatest rectangularity after planing. Cutting depths as well as the adjusted cutting depths are plotted in Figure 5. Common to all four sides of a cross-section was that the highest AOCs were located in CS1 and CS5, that is, the top and the butt end. The difference in AOC between the two opposing faces of a cross-section is shown in Figure 6, which shows that the absolute difference increased with increasing twist, especially for CS1 and CS5. In general, the planks with a left-handed twist (and that was all of the planks but one) had a larger AOC on the pith face than on the sapwood face in CS1 and a larger AOC on the sapwood face than on the pith face in CS5. The AOC for the intermediate cross-sections lay between the values for CS1 and CS5. In total, 41 of the 100 cross-sections had differences in AOC within the range –0.2° to 0.2°.

The differences in AOC on opposing edges in a cross-section (Figure 7) were, with a few exceptions, in the interval between –1° and 1°. The largest absolute difference in AOC appeared in CS5, where the AOC was larger on the left edge than on the right edge.

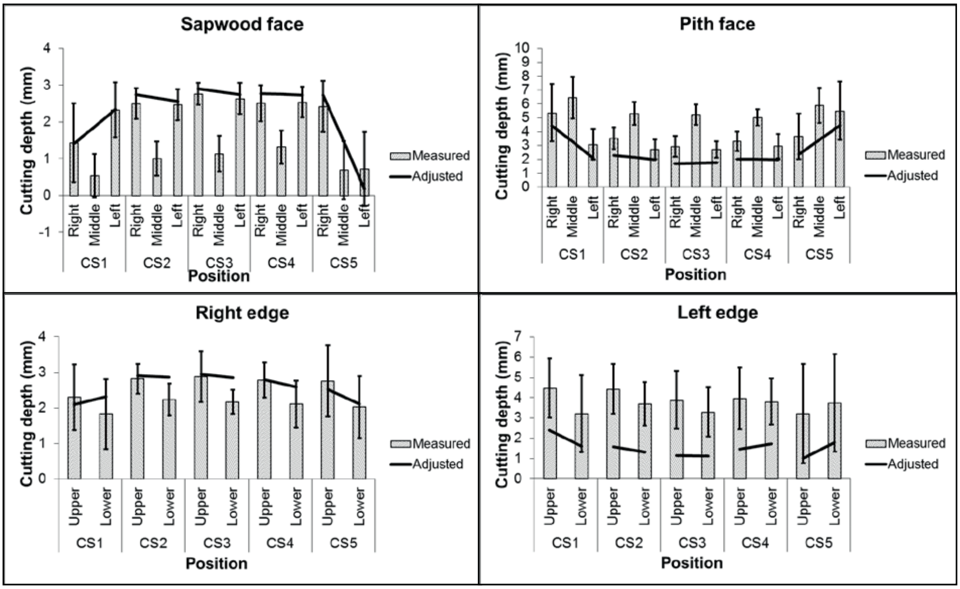

Figure 5: Measured average cutting depths with standard deviations marked and adjusted average cutting depths on the sapwood face, pith face, right edge, and left edge. "Right", "middle", "left", "upper", and "lower" represents the locations of the measurement points during planing.

Discussion

The cross-sectional shape and dimension of a plank is a result of the rough warp, the planer design, the forces of the planer acting on the plank, and the cutting depths. As the rectangularity of the planks before drying is unknown, some skewness of the cross-sections could have been a result of sawing. However, the main reason for low rectangularity of the rough planks seems to have been cupping due to drying shrinkage. Since cupping before planing was equal in the measured positions throughout the planks, the amount of cup was independent of location on the rough planks. After planing, cup was, with a few exceptions, eliminated, which explains the large increase in rectangularity (Figure 3). As the amount of cup on the rough planks was not related to the location, the lower rectangularity in CS1 and CS5 had causes other than cup.

If cupping was excluded, only twist affected rectangularity (Figure 4). Ideally, bow is a drying deformation in one plane, which should affect cutting depths on the sapwood face and pith face evenly and should not result in oblique cutting, that is, a large AOC. In the same manner, crook is also a drying deformation in one plane and should affect the cutting depth on the right edge and left edge evenly. According to the low coefficients of determination, a simplification that neither bow nor crook affected rectangularity after planing is sufficient. Twist, on the other hand, is a three-dimensional drying deformation affecting how the planks' edges and faces are aligned compared to the cutters. There were no indications that the lengths of the planks were of importance; instead the distance from the cross-section to the nearest end influenced the result after planing. The parts of the planks along the length where drying deformations had the most influence were located near the top and the butt end, that is, in CS1 and CS5, because the absolute AOCs were largest in those cross-sections for all faces and edges of the planks. However, a large AOC on a face or edge does not necessarily influence rectangularity if the

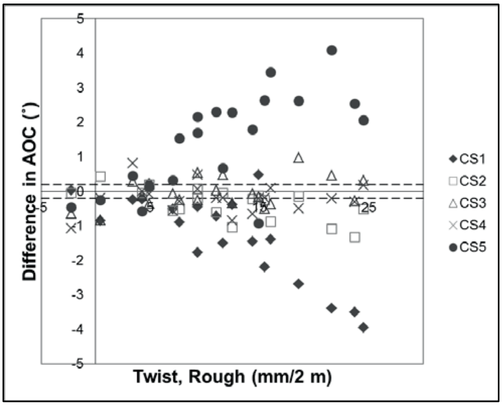

Figure 6: Difference in AOC between the two opposing faces of a cross-section as a function of twist for the rough plank. The dashed lines mark the interval where the maximum thickness variation is 0.2 mm, which is the difference allowed by the American Standard.

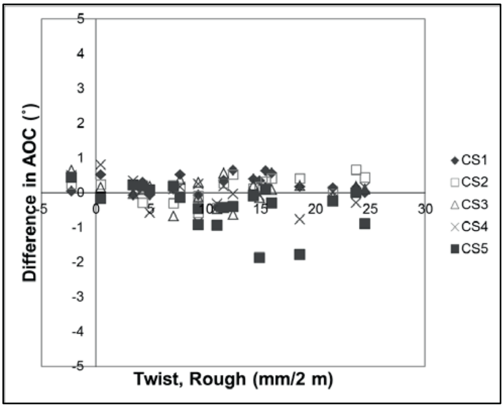

Figure 7: Difference in AOC between the two opposing edges of a cross-section as a function of twist for the rough planks.

AOCs on the opposing face or edge are equal and the corners of the cross-section are perpendicular.

In combination with the cutter arrangement in the planer, twist gave rise to differences in how the opposing faces and edges of a cross-section were aligned in relation to the cutters. As can be seen in Figures 6 and 7, twist gave a difference in AOC between the opposing faces and edges.

A limited number of planks with the same dry target cross-sectional dimensions were subjects in this study and they were all planed in a specific planer with specific settings. In order to get a more general view of how planing affects rectangularity, more tests with various planers, settings, and cross-sectional dimensions need to be done.

There are several possible ways to increase rectangularity and decrease the amount of planer misses. If the pressure on the planks is increased, the planks temporarily straighten during planing, which results in planed planks with high rectangularity and few planer misses but the same amount of twist after planing as before planing. However, pressure must not be so high that the cupped rough cross-sections flatten during planing, which will lead to recurring cup of the planed cross-sections when the plank is taken out of the planer.

If, on the other hand, the goal of planing is to obtain planks with low twist, oblique cutting is required, but the opposite cuts have to be parallel on opposite faces and edges, that is, the differences in AOC on opposing faces and edges must be low. In this case, low pressure on the planks during planing is a requirement so that the planks are not straightened during planing. To ensure a low number of planer misses, the cutting depths have to be increased with increasing twist. This in turn leads to a need for larger dry target cross-sectional dimensions for planks with large twist. Since the problem of planer misses will be larger in the top and butt end, an alternative is to cut off length at the ends of the planks instead of increasing the allowance for planing.

The rectangularity measure that was used in this study can indicate if there is a low value for a cross-section but not why or which cutter is responsible. Only four cross-sections had an acceptable rectangularity according to the American standard, while 41 cross-sections had differences in AOC that were acceptable. The two criteria have different sensitivities to cross-sectional defects, which explains the difference in approved cross-sections. Rectangularity is affected by planer misses and wane while the AOC is not.

There are many possible explanations for the general low rectangularity after planing. The rectangularity measure is sensitive to the noise present in the images (Rosin, 1999). Many planks in the study were extremely twisted and would be rejected in normal sawmill production. Also there is a possibility that the cutters of the planer were badly aligned and that this introduced differences in AOC on opposing faces and edges, resulting in a lower rectangularity.

Conclusions

In general, the rectangularity increased as a result of planing, mainly due to cup reduction. The lowest rectangularities of cross-sections after planing were present in the top and butt end of the planks. The mechanism that decreased rectangularity was misalignment between the planks' cross-sections and the cutters, which was caused by twist in combination with the planer's settings and cutter arrangements.

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References

AITC – American Institute of Timber Construction (2004). Standard specifications for structural glued laminated timber of softwood species: AITC117-2004.

Axelsson, A. (2012). Effect of planing on warp in Scots Pine (*Pinus sylvestris*). *Wood Material Science and Engineering,* DOI: 10.1080/17480272.2012.669408.

Coelho, C.L., Carvalho, L.M.H., Martins, J.M., Costa, C.A.V., Masson, D., & Méausoone, P. (2007). Method for evaluating the influence of wood machining conditions on the objective characterizations and subjective perception of a finished surface. *Wood Science and Technology, 42,* 181–195.

Ekevad, M., Salin, J, Grundberg, S., Nyström, J., & Grönlund, A. (2006). Modelling of adequate pretwist for obtaining straight timber. *Wood Material Science and Engineering, 1,* 76–84.

Ekevad, M, Lundgren, N., & Flodin, J. (2011). Drying shrinkage of sawn timber of Norway spruce (*Picea abies*): Industrial measurements and finite element simulations. *Wood Material Science and Engineering, 6,* 41–48.

Eriksson, J., Ormarsson, S., & Petersson, H. (2004). An experimental study of shape stability in glued boards. *Holz als Roh und Werkstoff, 62,* 225–232.

Franz, N. C. (1958). An analysis of the wood-cutting process. PhD Thesis, University of Michigan Press, Ann Arbor, United States of America.

Grönlund, A., Flodin, J., & Wamming, T. (2009a). Adaptive control of green target sizes. In: *Proceedings of the 19th Wood Machining Seminar,* Nanjing, China, October 2009 (pp. 120–129).

Grönlund, A., Flodin, J., Vikberg, T., Nyström, J., & Lundgren, N. (2009b). Monitoring of lumber size, shape and mismatch in double-arbour saws – development and validation of scanning equipment. In: *Proceedings of the 19th International Wood Machining Seminar.* Nanjing, China, October 2009 (pp. 293–299).

Hägglund, A. & Marklund, P. O. (1992). Glued material for windows and exterior doors – Nordic requirements for construction and control. [In Swedish: Limmade ämnen till fönster och ytterdörrar – Nordiska bestämmelser för tillverkning och kontroll.] Swedish Institute for Wood Technology Research, Report P 9208051 Skellefteå. ISSN: 1102-1021.

Jackson, M.R., Parkin, R.M., & Brown, N. (2002). Waves on wood. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 216, 475–497.

Johansson, G., Kliger, R., & Perstorper, R. (1994). Quality of structural timber-product specification system required by end-users. *Holz als Roh und Werkstoff*, *52,* 42–48.

Malkoçoğlu, A. (2007). Machining properties and surface roughness of various wood species planed in different conditions. *Building and Environment*, *42,* 2562–2567.

Perstorper, M., Johansson, M., Kliger, R., & Johansson, G. (2001). Distortion of Norway spruce timber. Part 1. Variation of relevant wood properties. *Holz als Roh und Werkstoff, 59,* 94–103.

Rosin, P.L. (1999). Measuring rectangularity. *Machine Vision and Application*, *11,* 191–196.

Skogsindustrierna (2011). The Swedish forest industries – facts and figures 2010. Stockholm, Sweden.

Swedish Standard SS-EN 1310 (1997). Round and sawn timber. Method of measurement of features. [In Swedish: Trävaror – Rundvirke och sågat virke – Mätning av särdrag.]

Wang, S.J. (1984). A new approach to calculating target sizes. *Forest Products Journal*, *34,* 53–60.

Warensjö, M. & Rune, G. (1999). Effect of compression wood and grain angle on deformations of studs from 22-year old Scots pine trees. *Scandinavian Journal of Forest Research, 19,* 48–54.