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Warp of Sawn Timber of Norway Spruce in Relation to End-user Requirements

Quality, sawing pattern and economic aspects

Lotta Woxblom

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

Warp of Sawn Timber of Norway Spruce in Relation to End-user Requirements - Quality, Sawing Pattern and Economic Aspects

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Abstract

Warp, i.e. twist, crook , bow and cup, has been identified as an important factor for sawn timber quality, especially for structural purposes. Twist, crook and bow affect the efficiency of construction and serviceability of wooden products. The prerequisites for improving the quality of solid timber products in terms of shape stability, with focus on the connection between end-user demands, raw material properties and processing methods, are studied in this thesis.

In the first study, acceptance levels for warp set by the building industry were compared with the properties of current production at five sawmills in southern Sweden. The quality of a product, wall studs, at time of delivery to the end-users was described, and an evaluation of fulfilment of the end-user requirements showed that one-third of the graded studs did not fulfil the requirements on warp. Twist was the most severe type of warp.

The effectiveness of altered sawing patterns to reduce warp was studied in the second study. Growth ring orientation and distance from pith considerably affected the shape stability of sawn timber. Removing the central part of the log greatly affected warp, especially twist, in the studs. The different forms of warp were also related to wood characteristics. Percentage of corewood in the studs, distance from pith and grain angle significantly affected twist. For crook and bow, no significant relationships with wood properties could be established. Stand age, tree height class and longitudinal position within the tree did not significantly affect warp.

In the third study, a sub-sample of studs from the second study was used to illustrate how a change in moisture climate affects sawn timber. There were differences in sensitivity to changes in moisture content for studs produced by different sawing patterns. Largest changes in twist and bow occurred in studs containing pith. Crook changed more in quarter-sawn studs than in flat-sawn studs.

The economic aspects of the possible reduction in warp through changed sawing pattern and an adapted choice of raw material are discussed in the final study.

Keywords: Warp, twist, sawing pattern, corewood, grain angle, moisture cycling, wood quality, end-user requirements, *Picea abies*.

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Preface

The work in this thesis covers the chain from forest to end-user - the starting point was customer requirements, and the connecting thought has been how to choose and manufacture wood so that the products become attractive to the end-users.

Financial support was provided by Södra Timber AB, Södra Skogsägarnas Stiftelse För Forskning, Utveckling och Utbildning, the Swedish Forestry and Agricultural Research Council (SJFR) and the Swedish University of Agricultural Sciences (SLU). The main part of the work was carried out within a research programme on Wood Properties and Timber Structures, established by Södra Timber AB.

Several persons have contributed, in various ways, to this work and I would like to express my gratitude to -

The sawmills involved in the first study, for letting me visit and providing me with material. My brother, Björn Woxblom, for assisting me during part of the sawmill survey.

Harald Säll and his co-workers at Asa research station, for providing me with suitable trees for the second study. Peter Johansson, for working with me in Hörle Bruk, and coping with "our" framesaw when it went on strike because of too large strain and Rolf Böhn for drying the boards and giving me accommodation. Cecilia Malmqvist, for helping me in the laboratory registering wood properties on never-ending piles of wood discs.

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Ulla Engstrand, for helping me with statistics, Hans Fryk for making the complicated drawings, Agneta Klahr , for editing the manuscript and Steve Scott-Robson, for correcting my English.

Last, but not least, I want to express my gratitude to my mentor and friend Britta Kaul for your support during the past years.

Uppsala, December 1999

Lotta Woxblom

Contents

1 Introduction

1.1 Background

The background to the studies included in this thesis is the problem with warping of sawn timber, especially for structural purposes. Market shares for wood in the building sector have steadily decreased during the last decades, and an interview study with Swedish building contractors concluded that warp must be reduced if timber is to continue as an important material in modern construction (Johansson et al. 1993). The geometric properties, i.e. dimensions and warp, influence the efficiency of construction and serviceability of wooden products. Other materials, especially steel, dominate the market for wall studs in Scandinavia today.

Wood, as a building material, is one of the most easily used products, but at the same time it is one of our most complex materials. The properties of wood are influenced during a whole rotation period, 70-150 years, i.e. during many years before the tree is finally sawn into planks and boards. Practical knowledge of the properties of wood and how they are influenced by production methods, such as sawing pattern and drying schedule, is necessary to be able to convert wood into products with specified properties, e.g. to be straight after drying.

The Swedish sawmilling industry produced 15 million cubic metres (m^3) of sawn wood in 1995. The market for sawn wood is highly dependent on construction activity and the amount of wood used in building (Anon. 1997). According to Baudin (1989), 70% of the sawn wood in Sweden is used within the building sector. Because of this, it is especially important to be aware of and adapt to the requirements of the end-users to maintain and regain market shares from other materials, such as concrete, steel and aluminium. During the last century the building sector has been restricted by the fire code to use timber in buildings more than two stories high. Today, the new building codes for timber construction in Sweden is performance based, and it is again permitted to build multi-storey houses, which means that timber construction has a good chance of experiencing a renaissance.

1.2 Objectives

The overall objective of this thesis was to study the prerequisites to improve the quality of solid timber products in terms of shape stability, by choice of raw material and production method. The focus is on the connection between end-user demands, raw material properties and processing methods.

The main objectives of the studies included can be summarized as follows:
- To describe the quality of a product at time of delivery to the end-users and evaluate the fulfilment of the end-user requirements.
- To compare the warp reducing effectiveness of altered sawing patterns.
- To relate different forms of warp to wood characteristics, such as spiral grain, growth ring orientation, corewood, compression wood and shrinkage parameters.
- To study how changes in moisture climate affects sawn timber and to study differences in sensitivity to changes in moisture content for studs produced by the different sawing patterns.
- To evaluate the possible reduction in warp and the subsequent economic gains if it were possible to increase quality through changed choice of raw material and sawing pattern.

A literature review was done to give a broad overview of the subject and provide a background to the empirical studies presented in later chapters.

1.3 General limitations

One product for the building industry, wall studs, was chosen to illustrate the (quality) process from forest to end-user. However, there is no reason to believe that the results may not be applicable for other products, for which shape stability is an important property.

Mechanical properties, i.e. strength and stiffness, which also are important for some sawn timber products used in the building industry, were not included in this thesis.

The studies included are based on Norway spruce (*Picea abies*) timber since this is the most common species for the structural timber produced in Sweden.

1.4 Chapter summary

Chapter 1 gives a background to the subject including a review of related literature.

In chapter 2, an evaluation of the quality of traditionally produced wall studs at five sawmills is presented.

Chapters 3 and 4 cover the experimental part of the thesis. Studies of sawing patterns and moisture cycling of the material are presented.

In chapter 5 the economic aspects on choice of raw material and sawing pattern adapted to end-user requirements are discussed.

An overall discussion and concluding remarks are found in chapter 6.

Appendices describe methods of measurements and also include a glossary of some terms used in the text.

1.5 Literature review

The purpose of this section is to give an overview of the research that has been carried out over the years to find the factors affecting drying properties of wood. Growth characteristics as well as processing methods have been studied.

The questions proposed to provide a background to the following chapters and the empirical studies reported in this thesis are:

- What is the meaning of the word "quality" and which parameters are best suited to describe the quality of structural timber products?
- Which growth characteristics affect the tendency to development of warp during drying?
- Which methods have been used to try to reduce or even prevent warp?

1.5.1 Quality

Definition of (wood) quality

During the formation of wood, numerous factors both inside and outside the tree lead to variation in the type, size, shape, physical structure and chemical composition of the wood elements. Larson (1969) relates *wood quality* to the variability in these characteristics, i.e. the result of the biological process occurring within the living tree. The *quality of wood products* is affected by wood characteristics as well as by the manner of harvesting, cross cutting, sawing and drying.

Because wood is used as a raw material for many different types of products, such as window frames, furniture, floors, beams and wall studs in houses, plywood and paper, there are many ways to express wood quality. Persons involved in the production chain from forest to end-product use different words to define quality, depending on at which stage they appear in the chain. Traditionally, foresters talk about high-quality trees as straight stems with few and small branches. For the sawmill industry, high quality means no knots, or other properties classified as defects on the sawn timber such as rot, spiral grain, pitch pockets and compression wood. The logs should be straight, have even growth rings, little tapering and contain a high percentage of heartwood. The users of sawn timber, e.g. the building industry, define quality in terms of strength, stiffness and shape stability (Johansson et al. 1994a and 1994b).

To avoid misunderstanding, it is important to find a uniform definition of the word "quality". In ISO 8402, quality is defined as "the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs" (Anon. 1986).

In 1959, Nylinder proposed that the quality of timber should be defined as "its degree of suitability for a certain specific conversion (plywood, sawn timber etc.)". Resch (1990) states that "the quality of wood is an expression of its basic nature or characteristics, the degree of excellence which wood possesses in relation to its many and diverse uses". Cown (1992) refers to quality as the suitability for a particular end-use. The same interpretation of the word is made by Johansson et al. (1994a) when they express quality as "the ability of timber products to satisfy intended applications".

Wood quality is often expressed as a level of a single characteristic, e.g. knot size or ring width whereas *product quality* must be expressed in terms of characteristics that make a product suitable for a specific end-use. The unique set of requirements for a certain end-product could differ substantially from those required by other products. If the sawn timber is intended for structural purposes shape stability in addition to strength and stiffness may be important whereas aesthetic characteristics and machinability may be significant for joinery products (Johansson et al. 1994a).

According to the expressions cited, quality should be defined with reference to the appropriateness of the wood for a particular end-use. This is also the definition used in this thesis.

Quality requirements for structural timber

From the definitions cited above it follows that wood quality can have a meaning only when the final product is known. To obtain a product that satisfies the customer, it is important to know what he or she means by quality, i.e. which properties are important for the use of the product.

The requirements for finished building elements, independent of materials, can be divided into the following categories: safety, function, desirable properties and irrelevant characteristics (Table 1).

Table 1. Matrix of requirements for structural timber (adapted from Johansson et al. 1994b).

Interested parties	Categories of requirements			
	Safety	Function	Desirable	Irrelevant
Society through codes	*	*		
Insurance companies	*	*		
Commissioner of buildings (owner)		*	*	*
Contractor		*	*	*
Element manufacturer		*	*	*

To prevent failure and damage, which might cause personal injury or heavy financial costs, requirements for safety are set by the society. The functional requirements are directly associated with the user's needs and expectations. Besides the basic needs, the desirable properties are those which give the product a greater value for the user. Finally, the properties which do not affect the function of a product, for example the colour of the wall studs, fall into the category of irrelevant characteristics.

In a study conducted at Chalmers University of Technology in Gothenburg, complaints made by end-users about the quality of structural timber products in Sweden have been documented (Johansson et al. 1994a). The interviews showed a general dissatisfaction with the shape stability of current products. This is in agreement with reports from e.g. the USA, where warp is pointed out as a problem and twist appears to be the most important problem (Senft et al. 1985, Beard et al. 1993).

Besides twist, crook and bow causing serious problems during assembly, problems can also occur after assembly when the timber warps during drying to equilibrium moisture content. The expected equilibrium moisture content is about 10-12%, but the timber may have a moisture content over 20% at delivery (Johansson et al. 1994a).

In a subsequent study, a systematic analysis of the requirements for structural timbers was made and acceptance levels regarding dimensions and warp were specified for different types of products, e.g. roof trusses, floor joists and wall studs. Demands for the timber components were derived from the requirements for the building elements. For example, a maximum limit for the curvature and inclination of a wall leads to a maximum level of acceptable crook for the stud, which also must have properties that make it possible to erect the wall in a rational and effective way (Johansson et al. 1994b).

1.5.2 Warp - definition

Warp has been identified as one of the most important quality factors for structural timber. The term warp is used to describe any deviation of a piece of sawn timber from a true or plane surface. It refers to defects such as twist, crook, bow and cup (Figure 1).

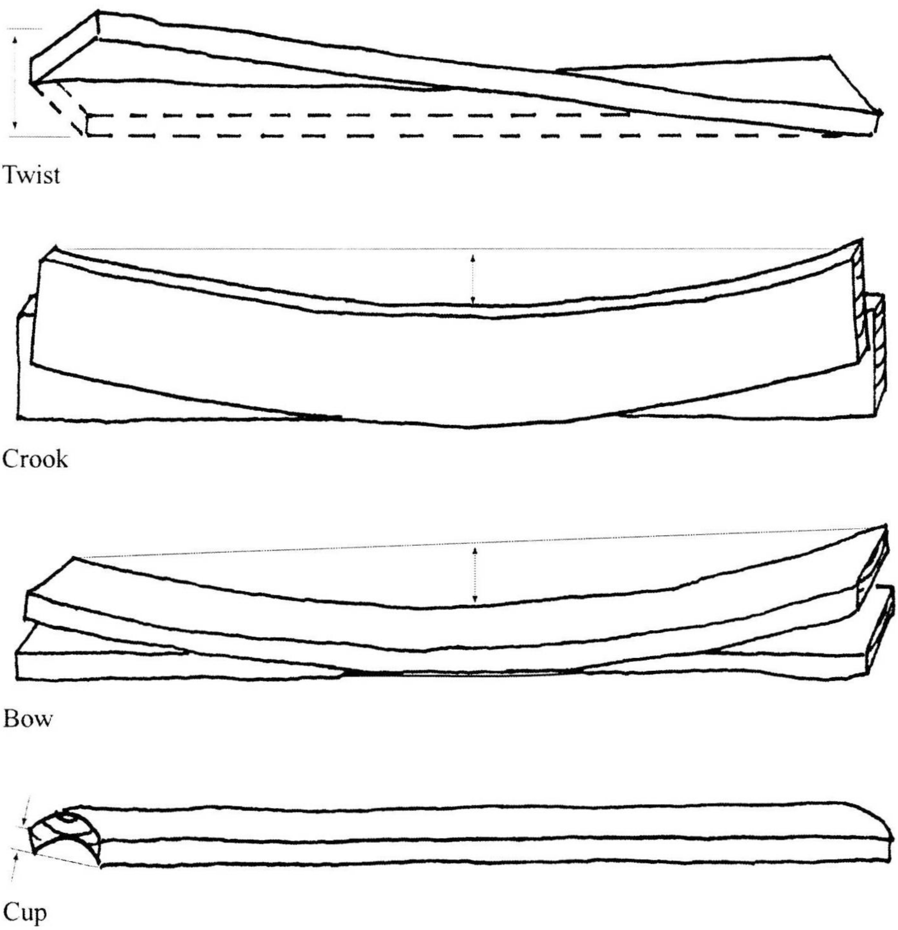

Figure 1. Illustration of the different forms of warp (adapted from Johansson et al. 1993).

The basic cause of warp is the anisotropic shrinkage of the sawn timber and is a consequence of changing moisture content in the piece of wood. Warp increases as the moisture content decreases.

<u>Twist</u>

Twist is defined as a lengthwise spiral distortion. It is generally related to a combination of large spiral grain and the anisotropic shrinkage in a piece of timber (Stevens 1961, Danborg 1991).

Bow and crook

The forms of warp usually referred to as bow and crook can be defined as simple curvature of a piece of wood in the direction of its length. Bow is the deviation flatwise from a straight line drawn from end-to-end of a piece, whereas crook is the edgewise deviation from a straight line (Stevens 1961, Simpson et al. 1988, Beauregard et al. 1992).

Bow and crook often occur when one face or edge of the board shrinks more in the longitudinal direction than the other (Panshin and de Zeeuw 1980, Skaar 1988). The difference in shrinkage is usually caused by the presence of corewood or compression wood (Esping 1992).

Cup

Cup may be defined as a deviation flatwise from a straight line across the width of the board (Hallock 1965). It is usually a consequence of tangential shrinkage exceeding radial shrinkage (Stevens 1961).

1.5.3 Grading rules for sawn timber - connection to structural timber

The most important grading rule for classification of sawn timber from pine and spruce used in Sweden, "The Green Book", was first published in the 1960's (Anon. 1982). It is a visual grading system which focuses on characteristics such as knots, pitch pockets, compression wood, decay, blue stain, checks and wane, properties important for the joinery industry, especially.

Before 1987 no acceptance levels for twist, crook, bow or cup were mentioned in The Green Book, it was only stated that "warp should be regarded during grading".

In 1994, new grading rules for sawn timber, called "Nordic Timber" (Anon. 1994), were published. The focus was still on properties such as knots, pitch pockets, grain angle, compression wood, checks, rot and wane. The Green Book was published by "The Association of Swedish Sawmill Men" and Nordic Timber is a result of cooperation between sawmill organisations in Sweden, Norway and Finland. In the introduction to Nordic Timber, it is stated that "the grades in Nordic Timber reflect qualities that the forest sector produces on a sustained basis and which the sawmills are able to continuously deliver to the markets". Thus, the grades are adapted to the raw material and not to the end-user requirements of the sawn products. However, there is an attempt to adjust the grading to the market by making it possible for customers and sawmills to agree on individual, customer and product related grades by creating a mixture of grades, which is based on the properties of the main grades. For example, a contract can specify purchase of grade A, but with seasoning checks according to grade A3, pitch pockets according to grade B, wane according to grade C, etc.

A consumer-adapted classification system with specifications for timber products used in the building sector has been developed at the Department of Steel and Timber Structures at Chalmers University of Technology. The purpose of this system is to guarantee a certain performance level for each product. These specifications are published in "Guidelines for Purchasing Building Timber" (Johansson et al. 1993) which covers wall studs, floor beams and boarding and in "Requirements for building timber - sill, girder, purlin, tiling batten, tongued - and - grooved timber, secondary spaced boarding and floor boards" (Engström et al. 1995).

In Table 2 the requirements for warp according to The Green Book, Nordic Timber and Guidelines for Purchasing Building Timber are shown.

Table 2. Maximum allowed warp(mm/3 m length) for 50 x 100 mm boards according to three different grading rules - The Green Book (GB), Nordic Timber (NT) and Guidelines for Purchasing Building Timber (GP). The requirements should be fulfilled at the moisture content shown in the respective column.

	GB[1]	NT[1]				GP[1]
GRADE	I - V	A1-A2	A3-A4	B	C	Wall studs
Bow (mm)	33.8	11.2	22.5	22.5	45.0	6
Crook (mm)	15.8	6.8	9.0	9.0	18.0	4
Cup (mm)	3.0	2.0	2.0	2.0	4.0	2
Twist (mm)	12.0	6.0	9.0	9.0	15.0	5
Moisture content (%)	≥ 17	20	20	20	20	15 ± 3 or 12 ± 3

According to Johansson et al. (1994b) the limits for warp, in The Green Book as well as in Nordic Timber, correspond very poorly to the requirements of the building industry. Other important properties are missing and some demands are irrelevant for this purpose.

1.5.4 Factors affecting the degree of warp

Anisotropy in shrinkage

Warping that occurs on drying of sawn timber can be caused by several different factors, but all types of warp, twist, crook, bow and cup, can be attributed to the anisotropic behaviour of wood, i.e. the degree of shrinkage is different in the three principal directions of growth: longitudinal, radial and tangential.

[1] The values are converted from 2 m to 3 m length according to conversion factors shown in appendix B6.

Average shrinkage values of Norway spruce wood dried from green to oven-dry condition are 0.3% in the longitudinal direction, 3.6% and 7.8% in the radial and tangential directions, respectively (Esping 1992).

Microfibril angle and fibre length

Shrinkage only occurs more or less perpendicular to the microfibril axis, thus the direction and magnitude of shrinkage is largely controlled by the fibril angle in the dominating layer of the secondary cell wall, the S2-layer (Dadswell 1958, Anon. 1960, Voorhies and Blake 1981, Voorhies and Groman 1982, Krahmer 1986). If the microfibril angles in the S2-layer were precisely parallel with the fibre axis, longitudinal shrinkage would be zero. However, there is always a small deviation from parallelism which makes wood shrink in the longitudinal direction.

Microfibril angles are inversely related to the fibre length, i.e. long fibres have small fibril angles and short fibres have large fibril angles (Panshin and de Zeeuw 1980, Krahmer 1986).

Cell length varies greatly both within and among trees. The fibres of Norway spruce are shortest in the wood near the pith. There is a rapid increase in length from the pith and outward during the first 10 to 20 years, after which the change is much less rapid and the length gradually stabilizes (Boutelje 1968, Atmer and Thörnqvist 1982, Kyrkjeeide 1990). Since the shortest fibres, with large fibril angles, are found close to the pith, the longitudinal shrinkage is also largest in this area and decreases outwards towards the bark. Shrinkage in the tangential and radial directions, however, is low in the pith area and larger in the wood close to the bark (Voorhies and Blake 1981, Cown and McConchie 1983, Krahmer 1986, Bendtsen 1986).

This is in accordance with observations made by Pedini (1990a) who measured the fibril angle in Sitka spruce (*Picea sitchensis*) grown in Denmark. At breast height (1.3 m) the largest angle (approximately 23 degrees) was found in ring number 3 and then decreased through ring numbers 9 to 12, where it stabilized at approximately 14 degrees. The same trend was noted by Kyrkjeeide (1990) on latewood of Norway spruce.

The length of fibres also varies within a growth ring. Earlywood fibres are shorter than fibres formed in the latewood. Because of this, different degrees of shrinkage can be found within the same growth ring. In normal wood close to the bark of conifers the microfibril angle of latewood is smaller than in the corresponding earlywood, 4-8 degrees and 20-25 degrees, respectively (Anon. 1960). Thus, latewood shrinks less in the longitudinal direction than earlywood, whereas tangential and radial shrinkage are larger in latewood (Trendelenburg and Mayer-Wegelin 1955).

For earlywood of Norway spruce Kyrkjeeide (1990) noted that there was a difference in development of microfibril angle between trees from three social classes. In suppressed trees the angle is about 45 to 50 degrees close to the pith and decreases to between 10 and 20 degrees in growth ring number 30. Intermediate and dominant trees start out with an angle about 45 to 50 degrees. A decrease to about 40 degrees appears around ring number 35 in the intermediate trees, whereas there is a slight increase to 55 degrees 28 to 30 growth rings from the pith. Thus, the dominant and intermediate trees had larger fibril angles than the suppressed trees.

Pedini (1990a) noted that the fibres of the fastest growing trees tended to have the largest microfibril angles, which was also observed by Kyrkjeeide in the earlywood of Norway spruce.

In the outer part of the stem, fibre length within a growth ring increases with height in the stem until 20% of the height after which it decreases. In spruce, the mean fibre length was about 2.5 mm at stump height and about 4.0 mm at 20% of stem height (Atmer and Thörnqvist 1982). Shorter fibre lengths at the base of the tree is a trend that has been shown for many conifer species such as Douglas fir (*Pseudotsuga menziesii*) (Megraw 1986), Japanese larch (*Larix leptolepsis*) (Shiokura 1982) and White spruce (*Picea glauca*) (Taylor et al. 1982). Pedini (1990a) found that in the longitudinal direction, the fibril angle decreased with increasing height in the stem when the same ring numbers were compared. This confirms the relationship between fibre length and fibril angle also in the longitudinal direction.

Saranpää (1994) however, studied Norway spruce and found that longitudinal shrinkage close to the pith increased with increasing height in the stem. The higher longitudinal shrinkage further up in the stem may be explained by a larger amount of compression wood found at the top of the tree.

Compression wood

Compression wood has long been recognized as an important cause of warp. The excessive longitudinal shrinkage of compression wood may cause the board to bend if one face of a board contains compression wood and the opposite face contains normal wood.

Only a few degrees of displacement from the vertical position is sufficient to activate formation of compression wood in the stem (Timell 1986). Hoffmeyer (1987) states that he has observed compression wood in cross-sections at breast height of 20-40 year old straight-grown Norway spruce trees, which would indicate that formation of some compression wood in the stem is normal. Compression wood is also formed to maintain a preferred angular orientation of branches (Timell 1986).

Compression wood behaves differently from normal wood with respect to physical and mechanical properties. Pronounced compression wood zones generally shrink more longitudinally and less transversely than normal wood during seasoning (Kollmann and Côté 1984). Niemz et al. (1993) studied shrinkage from green to oven-dry condition, of normal and compression wood of Norway spruce. Compression wood exhibited greater longitudinal shrinkage, whereas shrinkage in the tangential and radial directions were similar to that of normal wood. The longitudinal shrinkage of Norway spruce compression wood is between 0.7-3.5%, whereas normal wood of the same species only shrinks 0.1-0.3%. Tangential and radial shrinkage of compression wood have been reported to be 7.7-8.5% and 5.3-6.2%, respectively. The abnormally high longitudinal shrinkage is mostly a result of the large microfibril angle in the S2-layer of the fibre walls (Timell 1986).

Spiral grain angle

Large spiral grain angle together with anisotropic shrinkage is usually said to affect the shape stability during drying (Stevens & Johnston 1960).

Literature, e.g. Noskowiak (1963) and Harris (1989) report that, for conifers, the general pattern is that spiral grain angle varies with age of the tree and its position along the trunk. Close to the pith, the grain angle is almost negligible, then by the second or third growth ring, the prevailing orientation is in the left direction. The angle increases sharply in the first formed rings to reach a maximum deviation and then gradually decreases to a straight-grained condition. In the later formed wood, there is a gradual change to a right-handed spiral which tends to increase in magnitude as the ring number increases. Many investigations have found a large variation in the grain-angle patterns both between and within tree species.

Krempl (1970) investigated the occurrence of spiral grain on 120 Norway spruce trees from four plots in the mountain regions of Austria. All trees showed left-handed spirality at an early age and 95% of the sample trees changed to a right-hand spiral further away from the pith. The right-handed spiral grain angle in the outer wood of old trees (132-252 years) normally exceeded the angle of the left-handed spiral in the inner wood. He found that the correlation between the intensity of spiral grain and variables such as distance from pith, growth ring width and longitudinal position in the stem was very low. There was a large variation between trees.

The spiral grain angle of Norway spruce trees from five stands, 23-47 years old, in Denmark was measured by Danborg (1994b). The trees were planted on soils of high and moderate fertility. Danborg's findings corresponded to the typical patterns for a conifer; left-handed spirality in the inner growth rings which reached a maximum of 2.5-5 degrees in ring numbers 3 to 8, followed by a slow decline towards straight grain, or even right-hand spirality, near the bark. For individual rings right-handed spirals were observed as early as in ring number 12, but when average grain angles from the same diameter class and height were regarded, the change in direction appeared in ring number 38. However, both grain angle levels and patterns varied largely between individual radii and trees. Considerable tree-to-tree variation is also confirmed for Sitka spruce by Brazier (1967) and Pedini (1990c).

Danborg (1990) and Pedini (1990c) recorded the radial variation of grain angle in Norway spruce and Sitka spruce, respectively. In both studies the variation was divided into three different patterns of radial variation. The patterns were similar for both types of spruce. The dominating pattern was the one typical for conifers, mentioned above. Grain angle could be at maximum in the innermost ring and decrease immediately. In a few radii no interrelation between distance from pith and grain angle was found (Figure 2).

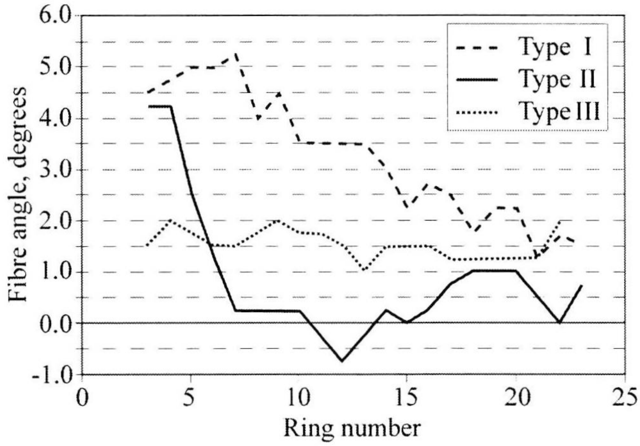

Figure 2. Three types of patterns of radial variation of grain angle in Norway spruce. Positive values are left-handed grain angles and negative values are right-handed grain angles (adapted from Danborg 1990).

Danborg (1994b) concluded that for Norway spruce no general interrelation exists between grain angle and height in the stem. However, within a stand there may be a specific pattern for grain angle in the longitudinal direction of the tree. For Sitka spruce Pedini (1990c) found that when the same ring numbers from the pith were compared, there was a decrease in grain angle with increasing height in the stem.

Perstorper et al. (1994a) studying fast-grown Norway spruce from southern Sweden found that grain angle of studs sawn from the pith region significantly decreased longitudinally from 4.1% in the butt logs to 3.2% in the top logs.

Results for species other than spruce show different results. In New Zealand, Cown et al. (1991) established strong patterns both in the radial and vertical directions in Radiata pine *(Pinus radiata)* trees. A general decrease in grain angle from pith to bark was found at all height levels in the stem. Grain angle increased in the longitudinal direction from base to top of the tree. Also for Radiata pine a strong individual tree effect was observed. For Honduras pine (*Pinus caribea*) grown in Fiji, on the contrary, no consistent pattern was found (Cown et al. 1983).

Only for trees from one of the five Norway spruce stands studied, did Danborg (1994b) find a consistent positive correlation between growth rate and spiral grain angle. Brazier (1967) recorded a tendency for larger grain angles in fast-grown Sitka spruce trees than in slower grown trees. Pedini (1990c) concluded that the fastest growing trees within a stand also had the largest grain angles. But, when two Sitka spruce stands were compared, grain angle was largest in the stand with the slowest average growth rate.

<u>Corewood</u>

Wood formed in a cylindrical column surrounding the pith has often been referred to as juvenile wood, a name that accurately describes its physiological development and refers to cambium age at time of wood formation. However, this term can be misleading because it implies that juvenile wood is only formed in the first years of the tree's life. In reality this type of wood is formed throughout the lifetime of the tree as it forms a cylinder up in the tree from the butt to the top of the tree in the 5-20 growth rings closest to the pith (Figure 3). Other terms used to describe these phenomena are pithwood, corewood, innerwood and crown-formed wood (Zobel et al. 1959, Larson 1969, Thomas 1984, Cown 1992).

Wood formed outside this cylinder is usually called mature or adult wood, analogously the names outer or stem-formed wood could be used (Zobel et al. 1959, Larson 1969, Thomas 1984, Cown 1992).

The terms *corewood* and *outerwood*, which describe the position of the zones in the stem, might be more suitable than juvenile wood. These terms will be used throughout this thesis, as they appear to be the most appropriate.

Corewood is characterized by progressive change in properties such as fibre length, fibril angle, density and strength, whereas the outerwood is relatively constant in cell size, has well-developed structural patterns and stable physical behaviour (Bendtsen 1978). A schematic illustration of the gradual change from pith towards cambium of certain properties in a conifer stem is shown in Figure 3. When studying the figure it should be noted that all these properties do not change from corewood characteristics to outerwood characteristics at the same time; many of the properties vary independently and transition periods may differ by a number of years.

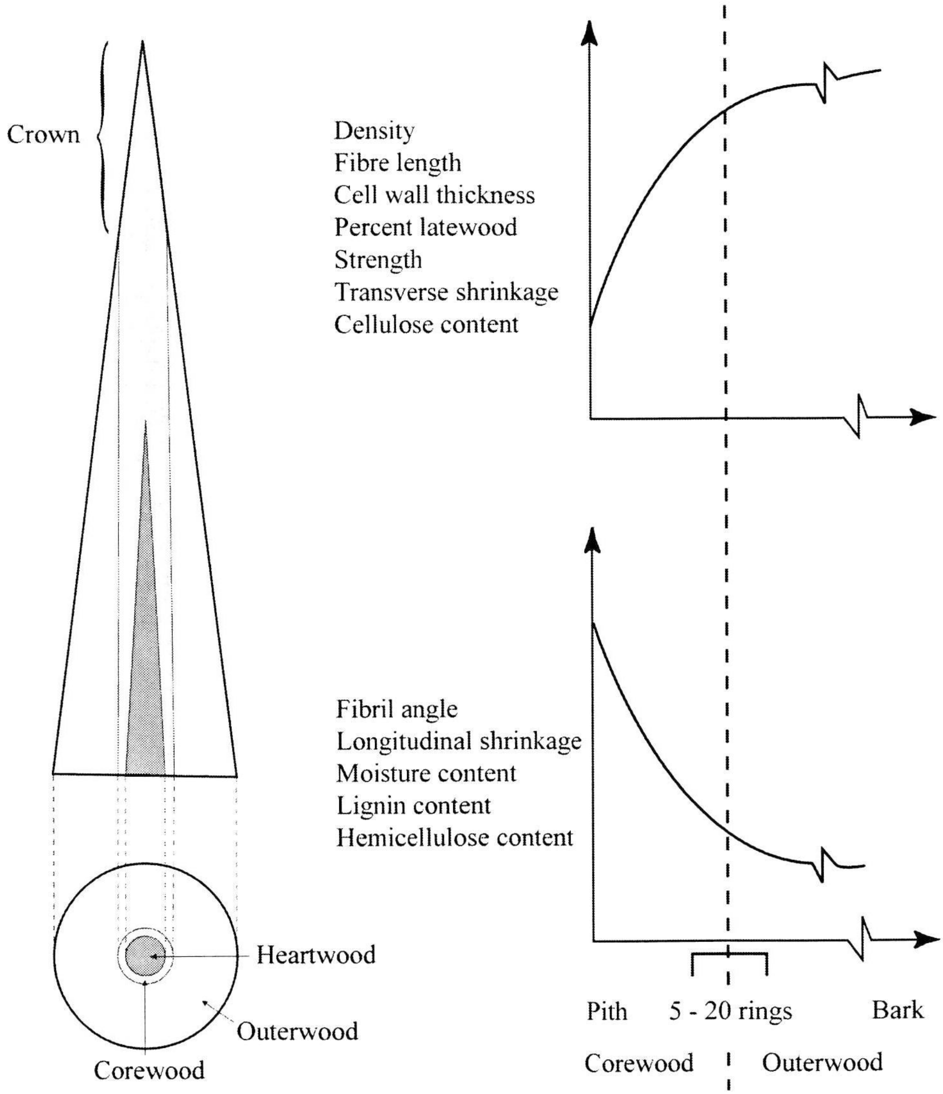

Figure 3. Schematic presentation of the location of corewood and outerwood in the stem and the gradual change of properties from corewood to outerwood (adapted from Bendtsen 1978).

Usually the location of the boundary between corewood and outerwood is defined as the growth ring number from the pith at which an important property stabilizes. This location, however, is not easily defined. Literature reports the duration of corewood formation varies from 5 to 30 years. The location of this boundary depends on the property or properties used to define the zone and also which species is studied. The gradual change in many wood properties makes it unclear as to where corewood ends and outerwood begins. The number of years with corewood production should be an evaluation of the age at which the properties cease to have significant negative influence on wood products.

For Norway spruce, the radial variation in some wood properties, shown in Table 3, have been studied to determine the boundary between corewood and outerwood. The property most frequently studied for radial variation is density.

Table 3. Duration of corewood formation in Norway spruce (*Picea abies*).

Property studied	Demarcation point - ring number from pith	Source
Microfibril angle		
- latewood	15 - 20	Kyrkjeeide 1990
Fibre length	15 - 20	Atmer & Thörnqvist 1982, Kyrkjeeide 1990
"	10 - 15	Kucera 1989
Fibre width	13	Danborg 1990
"	14	Kucera 1992
Latewood percentage	13-15	Kucera 1989
"	10	Kyrkjeeide 1990
Density		
- basic density		
- dense spacing	13 - 15	Kucera 1989
- wide spacing	18 - 20	Kucera 1994
- density (MC=10-13%)		
- earlywood	15 - 20	Kyrkjeeide 1990
- D5%[2]	10	Danborg 1994a
- density level[3]	10	Danborg 1994a
Presence of spiral thickenings in the fibre wall	20-30	Boutelje 1968

Danborg (1994a) states that the property used to demarcate the corewood should in some way reflect the systematical development in the fibre dimensions from pith to bark instead of the growth rate of the tree. This means that neither ring width nor latewood percentage can be regarded as suitable parameters. Instead Danborg studied variation in minimum density (1990, 1994a) and density levels (1994a) in very fast grown and moderately grown plantation trees in Denmark. He found that for both measures of

[2] The mean of the 5% lowest density records in a growth ring (kg/m^3)

[3] The whole ring average density as a function of the ring width

density and both stands the extent of corewood could be defined to ring number 10, irrespective of height level and growth rate. Ring numbers 11 and outward were defined as outerwood. In a previous study Olesen (1977) used density level as demarcation property and found that the basic density level reached a minimum value at rings 8 to 10 after which it increased steadily until the average level of the outerwood was reached at rings 15-20. Danborg (1994a) explains his choice of demarcation point on the fact that the decrease in density from pith until about ring number 10 always was found, whereas this was not the case for the increase in density until ring number 15 to 20. It was also within the ten inner rings that the changes in wood properties were most pronounced. Kyrkjeeide (1990) evaluated the earlywood density to attain a stable level between growth ring number 15 and 20, whereas latewood density seemed to be scattered around a certain level from pith and outwards.

Danborg (1990) stated that the minimum density is the density component that best reflects the development changes of the cambial initials and that it corresponds to the tangential fibre width. If defined in relation to tangential fibre width, Danborg (1990) found that the corewood on average included about 13 growth rings. No interrelation between ring number and fibre width variation was found and therefore annual variation in climate may slightly influence fibre width.

Fibre length has also been a major factor in defining the corewood, outerwood boundary. For the first 10 to 20 years there is a rapid increase in length. After this the change of fibre length is much less rapid, until a maximum length is reached. The number of years to attain a more or less constant length varies between species and is to some extent related to the expected lifespan of the species (Dadswell 1958, Panshin and de Zeeuw 1980). For example the Redwood (*Sequoia sempervirens*) which may live more than 1000 years, does not attain maximum fibre length until the tree is 200 to 300 years old (Panshin and de Zeeuw 1980).

Kyrkjeeide (1990) measured fibre length at 1-m height in 12 Norway spruce trees from three crown classes. Fibre length tended to increase with increasing growth ring number. The most rapid increase in length seemed to be finished between ring number 15 and 20 where it attained a level of about 2.8-3 mm. Trees from all crown classes showed the same level and an increase of length as function of growth ring number, but the variation in length was largest among suppressed trees and least among dominant trees. The results found by Kyrkjeeide is in good accordance with results for measurements at breast height (Atmer and Thörnqvist 1982). However, according to Atmer and Thörnqvist the transition period seems to change with height in the stem and involves a larger change in fibre length with increasing height level.

The microfibril angle which influences both strength, elasticity and longitudinal shrinkage has also been used to determine the boundary between corewood and outerwood. Pedini (1990a) studied the variation in microfibril angle in Sitka spruce. The boundary between corewood and outerwood was found in ring numbers 9 to 12, where the size of the angle stabilized. A very rapid decrease in microfibril angle was found from growth ring number 3 until number 9 to 12.

With reference to the mentioned studies on spruce, it can be concluded that the demarcation point occurs between ring number 10 and 20 from the pith.

1.5.5 Influence of growth characteristics on warp - previous studies

Many investigations have analysed the relationships between different types of warp and wood characteristics, but it has proved difficult to obtain good relationships that completely explain the development of warp e.g. Kloot and Page (1959), Du Toit (1963), Balodis (1972), Mishiro & Booker (1988), Perstorper et al. (1994b) and Forsberg (1997). Much of the variation is still unexplained and is probably due to differences between individual trees (Haslett et al. 1991).

Compression wood

Hallock (1965), studied sawn timber from southern pine, and found that logs containing compression wood tended to crook and bow, whereas compression wood had little or no effect on twist. This is in agreement with a study on the influence of growth characteristics on warp in relatively fast-grown Norway spruce by Perstorper et al. (1994b), who found that bow and crook increased significantly when the board contained easily visible compression wood. In the investigations by Hallock (1965) and Perstorper et al. (1994b), the butt log studs reacted much more to the presence of compression wood than the material from the top logs.

Other researchers, e.g. Gaby (1972) and Shelly et al. (1979) report that the degree of warp may be dependent on the proportion of compression wood present and have shown that small amounts of compression wood had no effect on warp. Du Toit (1963) collected material from Radiata pine and measured and correlated the extent of distortion with the relative amount of compression wood present. He also estimated the severity of compression wood from measurements of density. The results indicated that samples containing only compression wood or only normal wood did not exhibit bow, crook or twist during seasoning, whereas all specimens consisting of both normal and compression wood did. Maximum warp occurred in specimens with 40-70% compression wood by volume, and above 70%, warp decreased. The correlation between density and relative warp was most significant when compression wood constituted 50-60% of the total volume.

It is clear that as long as compression wood is associated with a much larger amount of normal wood, its presence in sawn timber is only moderately harmful. Its degree of development and its volume definitely affects the amount of warp which occurs.

Corewood and grain angle

The different shrinkage behaviour of corewood compared to outerwood contributes to the development of warp. The fact that corewood proportion has an important effect on twist has been shown by Haslett et al. (1991), who studied the effect of log characteristics on warp in young Radiata pine. Stöhr (1977) studied Patula pine (*Pinus patula)* and Milota (1992) studied Douglas fir and found that percentage corewood present in a board significantly affected twist, and is as such a criterion of log diameter and location of board in the log. Milota (1992) also reported that the effect on bow and crook was minimal.

Stevens and Johnston (1960) and Stevens (1961) assumed that logs can be represented by an assemblage of concentric cylindrical shells. Based on purely geometrical considerations they found that there is a relationship between spiral grain angle and the twist of the hollow shells. The model was obtained by calculating the degree of twist of one hollow cylinder composed of a very narrow growth ring containing spiral grain. From this, it was found that twist is proportional to the average ratio of spiral grain angle and the distance from the pith, i.e. for a given grain angle, twist decreases with increasing distance from pith. To test the validity of the theoretical model, actual measurements were made on a number of wooden cylinders from Sitka spruce trees containing spiralled grain. There was a good agreement between the theoretical and the actual measurements of the wooden shells, except for very small diameters. In that sample, which twisted more than the amount calculated by the model, the grain angle on the convex face was 4.5 degrees, and 1.5 degrees on the concave side, a distance of only 6.35 mm. Because of the large variation of spiral grain angle from point to point circumferentially, radially and longitudinally within a tree, the authors concluded that in practice it becomes almost impossible to estimate the extent of twist that will occur in a log, board or plank during drying from grain angle only.

The principles of the model was confirmed also by Balodis (1968, 1972) who studied the tendency of boards sawn from Australian coniferous species to twist during drying. Empirical analysis of the results showed that twist is proportional to the ratio of grain angle and distance from the pith to the centre of the specimen. In practice, this would mean that twist is a serious problem only in boards cut from stems that exhibit large spiral grain angles close to the pith, since the magnitude of this ratio for a given grain angle decreases rapidly with increasing distance from the pith.

Heartwood and sapwood

The formation of heartwood introduces further heterogeneity in material being dried. In the corewood zone, variable proportions of heartwood, depending on age and species, can be found. A hypothesis, saying that the large amount of extractives in the heartwood fibres would affect the shrinkage and stability of wood on drying and stabilizing the warp-prone corewood and prevent excessive warp, has been put forward by Hillis (1984) and Perstorper et al. (1994b).

As an example to support this hypothesis, Hillis (1984) refers to the highly dimensionally stable Redwood, that has a high amount of extractives in the cell wall. Perstorper et al. (1994b) compared warp in studs from a thinning stand of Norway spruce, representing corewood with only minor heartwood formation, with studs from spruce butt logs harvested in a 65-year-old stand that had developed heartwood. However, they found no stabilizing effect of heartwood on warp and the hypothesis, that heartwood formation prevents excessive warp of corewood, was rejected.

Presence of both heartwood and sapwood in the same piece of sawn timber has been shown to cause warp in Ponderosa pine (*Pinus ponderosa*). The degree of crook was affected by the location of the sapwood-heartwood boundary in a board. Presence of a heartwood layer along the narrow face tended to increase the severity of crook. However, no apparent relationship between warp and amount of heartwood in the stud could be found (Shelly et al. 1979).

Knots, growth rate and wood density

The major wood quality factor considered in most grading rules for sawn timber is knots. Fibre irregularities around the knots and compression wood on the underside of branches are properties known to affect warp. However, studies on the relation between knots and warp have not found any relationship of practical importance between the variables studied (Kloot and Page 1959, Shelly et al. 1979, Beard et al. 1993, Perstorper et al. 1994b).

Growth ring width has not showed any correlation with warp (Mishiro and Booker 1988, Beard et al. 1993, Perstorper et al. 1994b). The tendencies for increased twist, crook and bow with increasing growth ring width found by Mishiro and Booker (1988) are explained by the fact that usually growth rings are widest in the region close to the pith where the largest spiral grain and longitudinal shrinkage also appear.

Contradictory results have been reported on the effect of wood density on warp. Both Shelly et al. (1979) and Simpson et al. (1988) found that density slightly influenced crook. Shelly et al. reports that studs with density larger than the average for the material studied exhibited nearly twice as much crook as studs less dense than the average. This is because of the larger shrinkage in heavier wood. However, Simpson et al. for Loblolly pine (*Pinus taeda*) found that more crook occurs in lightweight boards than in heavier boards. The lightweight boards are supposed to contain a greater proportion of warp-prone corewood with large longitudinal shrinkage.

Mishiro and Booker (1988), Beard et al. (1993) and Perstorper et al. (1994b) all concluded that density did not significantly affect warp.

1.5.6 Influence of processing factors on warp - previous studies

The anisotropic behaviour of wood makes it difficult to eliminate development of warp completely. Several investigations aimed at finding practical methods for preventing or at least reducing warp in sawn timber have been carried out over the years. However, most of the methods tried have yielded only partial success.

Five general approaches have been used in the efforts to prevent or reduce warp:
- altered sawing patterns
- modified drying schedules
- use of mechanical restraint during drying
- steaming of sawn timber before and after drying
- segregation of material prior to drying

Methods of sawing

Warping that occurs on drying of conifer sawn timber can, as indicated in the sections before, be caused by several different factors. Koch (1986) has shown that crook of Yellow-poplar (*Liriodendron tulipifera*) boards is positively related to growth ring orientation, a characteristic influenced by the sawing pattern used. Crook increased with increasing growth ring angle, being minimum in flat-sawn pieces and maximum in quarter-sawn pieces. The reverse is the case for bow.

Kloot and Page (1959) suggested that sawing patterns should be designed to eliminate the central part of the log, as this part seems to be the major source of warp. As an alternative method they suggested that the boards could be sawn so that the percentage of pith-associated wood of any one piece would be small. To find evidence for their recommendations, Radiata pine logs were sawn according to different sawing patterns. The results showed that all three types of warp: twist, crook and bow, were at maximum in the pith-region.

When boards of Sitka spruce were dried to 8% moisture content, it was found that quarter-sawn boards containing the pith twisted on the average 4 degrees more on a length of 0.6 m than the corresponding flat-sawn boards sawn away from the pith (Stevens 1961). Also, Gaby (1972) confirmed the findings of Kloot and Page (1959). Boards of Shortleaf pine (*Pinus echinata*) and Loblolly pine (*Pinus taeda*) containing pith warped approximately twice as much as pith-free boards.

A hypothesis put forward by Voorhies (1971) suggests that if wood of the same fibril angle is evenly distributed within the cross section of individual pieces, warping would be reduced, because the longitudinal and transverse shrinkage are kept in balance. In practice, this means that a sawing pattern that results in boxed pith should be used. A study that contradicts this was made by Cech and Huffman (1972) where boxed-pith studs of Red pine (*Pinus resinosa*) developed greater twist than studs sawn with split-pith technique. This result was valid irrespective of growth-rate and drying schedule used.

Hallock (1965, 1969) and Hallock and Malcolm (1972) investigated the relation of sawing method to warp for Loblolly pine, Lodgepole pine (*Pinus contorta*) and Red pine, respectively. Four methods were tested and a sawing method was developed, whereby a cant of about 102 mm is ripped into studs parallel to and immediately adjacent to both bark edges, and the centre wedge is discarded. Thus, the taper is removed from the corewood rather than from the high quality wood immediately under the bark. This method reduced the volume of corewood in the studs, and the percentage of accepted studs increased. The results led to the recommendation that split-pith sawing-technique combined with parallel sawing to the bark should be used.

The effect on warp of a process in which logs are live sawn into flitches, kiln-dried and then cut into boards, called Saw-Dry-Rip (SDR), has been investigated for some species. Studies by Kloot and Page (1959), Beauregard et al. (1983), Maeglin and Boone (1983) and Kyrkjeeide et al. (1994) all show a reduction in warp with the SDR-method compared to the conventionally used Saw-Rip-Dry (SRD) method, where studs are cut green from the log and then dried. Three sawing methods, conventional cant system, around- and SDR-methods, were compared for producing structural timber from Trembling aspen (*Populus tremuloides*) (Bearegard et al. 1983). Methods tested differed significantly, especially for development of crook, where SDR showed lowest crook-value and the cant system the highest values. However, the SDR-studs showed significantly lower strength properties than the other groups. A hypothesis for this is given: as the SDR flitches are dried full width, it is possible that the internal stresses developed are higher and are relieved through the formation of micro checks, which causes a decrease in modulus of elasticity (MOE) and modulus of rupture (MOR).

Maeglin and Boone (1983) found that the effect of SDR-method on Ponderosa pine (*Pinus ponderosa*) was significant only for twist, whereas no difference for crook and bow were obtained between treatments. The authors suggest that the SDR-method should be supplemented with some modifications of the drying schedule in combination with heavy top load to achieve better results.

In Sweden, Kyrkjeeide et al. (1994) studied the effect of production method on warp in studs from fast-grown and slow-grown Norway spruce. The flitches and the studs were dried to 12% moisture content, after which the flitches were ripped into studs. When using the SDR-method the amount of twist decreased significantly compared to studs produced the conventional way. As in the study by Maeglin and Boone (1983) the production method did not affect the average values for crook and bow.

Methods of drying and restraint

The fact that boards near the bottom of a stack generally come out of the kiln straighter than those in the upper layers has raised the idea that restraint could be a means to prevent warping. Boards dried in carefully built stacks warp less than boards dried singly.

Stevens (1961) and others, e.g. Stöhr (1983), has done experiments to find out to what extent warp could be reduced by imposing mechanical restraint on the stacks of sawn timber during drying. The ultimate final warp recorded were much less for the restrained specimens than those dried without restraint. Restraint seemed to be more effective in reducing cup than bow. It was concluded that the greatest benefit from imposing mechanical restraint was obtained when the timber was dried from a high moisture content at relatively high temperatures and/or subjected to a short high temperature treatment when almost dry.

High-temperature drying techniques make use of the plastic-elastic properties of wood under the influence of heat and moisture. Wood dried under restraint at temperatures above 100°C softens, i.e. the fibres move in relation to each other and, when dry, remain in their new positions so that the extent of twist that would result from spiral grain is reduced greatly (Hillis and Rozsa 1985).

A comparison of the effect of conventional low-temperature drying and high- temperature drying with and without restraint on warp in Norway spruce and Scots pine (*Pinus sylvestris*), grown in Sweden, was made by Morén and Sehlstedt-Persson (1990). As in other studies, e.g. Stevens (1961) and Arganbright et al. (1978), they found that mechanical restraint was more effective in the reduction of twist than in preventing longitudinal warp. The effect of restraint on twist only showed on the high-temperature dried material, whereas restraint had a reducing effect on bow irrespective of drying temperature. Crook was not affected by restraint at all. No significant difference between the species was found.

Koch (1971) studied the behaviour of studs exposed to severe moisture change after drying, a situation that resembles that of studs at the building site and studs incorporated in buildings. Warp of studs dried at high temperature with restraint were compared with studs dried conventionally without restraint. After a 20-day dry cycle following a 20-day humid cycle, average warp was severe in all studs, but less extreme in the wood dried under restraint at high temperature. The effect was most obvious for twist. The improved stability in high-temperature dried wood in service is also commented on by Hillis (1984).

Pre- and postdrying treatments

Pre-treatment with steam makes the wood more plastic, reduces the elastic modulus, and therefore allows the loads to be more effective in reducing distortion during the subsequent drying process in which a set occurs. Steaming of green Radiata pine studs prior to high-temperature drying led to a higher yield in terms of studs meeting three grade specifications for twist (Mackay and Rumball 1972).

Methods directed at reducing twist in dried boards have been studied with varying results, by e.g. Dost and Arganbright (1972), Visser and Vermaas (1988) and Taylor and Mitchell (1990).

Sorting of boards prior to drying

Also, by sorting of boards before drying it is possible to minimize the range in green moisture content within the stack (Quarles and Wengert 1989). Bester (1983) states that twist can be reduced by sorting boards with pith-associated wood and putting them at the bottom of the stack, where they will be under maximum restraint, whereas outer boards, which twist much less than boards from the pith area, can be placed in the top five or six layers of the stack where most twisting occurs.

1.5.7 Concluding remarks to the literature review

- The most suitable definition of *quality* for the purpose of this thesis refers to the appropriateness of the wood for a particular end-use, i.e. the term quality can only have a meaning when the final product is known.
- The major quality parameter for structural timber has been identified as shape stability.
- The limits for twist, crook and bow in "The Green Book" as well as in "Nordic Timber" correspond poorly to the requirements of the building industry.
- A consumer-adapted classification system with specifications for different timber products to attain better quality of products intended for the building market has been developed. The specifications are published in "Guidelines for Purchasing Building Timber" and "Requirements for Building Timber".
- All types of warp can be attributed to the anisotropic behaviour of wood during drying and to the different anatomical characteristics of wood near the pith.
- Wood formed in a cylindrical column surrounding the pith is characterized by progressive change in properties such as fibre length, fibril angle and density.
- The term commonly used for this kind of wood, *juvenile wood*, can be misleading because it implies that juvenile wood is only formed in the first years of a tree's life.

Instead, the term *corewood* which describes the position of the zones in the stem, will be used throughout this thesis. For the same reason, *outerwood* instead of mature wood will be used to describe the zone surrounding the corewood.

- With reference to the mentioned studies on spruce, it can be concluded that the boundary between the corewood and the outerwood occurs somewhere between ring number 10 and 20 from the pith.
- It has proved rather difficult to obtain good relationships that explain the development of warp and much of the variation is still unexplained. One explanation for the difficulties in finding good relationships could be due to the substantial tree-to-tree variation of many wood properties, for example spiral grain pattern and occurrence of compression wood.
- Several studies have reported that high-temperature drying and mechanical restraint imposed onto the boards during drying are effective ways of reducing twist, but less effective on the longitudinal distortions, i.e. crook and bow.
- An improved stability in high-temperature dried wood in service has been established, and the effect is most obvious for twist.
- A steaming phase of green studs prior to drying makes the wood more plastic and has led to higher yield in terms of studs meeting grade specifications for twist and bow.
- It has been shown that the tendency of a board to twist when drying as a consequence of spiral grain decreases as distance from the pith increases.
- Sawing patterns designed to eliminate the central part of the log have been used to prevent drying defects. Studs containing pith usually warp more than pith-free boards.
- A hypothesis put forward suggests that if wood of the same fibril angle is evenly distributed within the cross-section of individual pieces, warping could be reduced because the longitudinal and transverse shrinkage are kept in balance. In practice, this means that a sawing pattern that results in boxed pith should be used.
- The Saw-Dry-Rip-method has shown promising results in reducing twist, but did not affect the average value of crook and bow.

2 Quality variations in wall studs

2.1 Introduction

2.1.1 Background

In the middle of the 1980's the building sector consumed 65 to 87% of the sawn timber in Western Europe (Baudin 1989). Competition between wood and other materials has increased during recent years and an interview study by Johansson et al. (1994a) showed that the building industry is not fully satisfied with the quality, in terms of warp, of the sawn timber products. However, no study quantifying this problem has been found in the literature.

2.1.2 Aim of the study and limitations

The main purpose of this study was to describe a product at time of delivery to the end-users, to see if the product fulfills the requirements given in "Guidelines for Purchasing Building Timber" (Johansson et al. 1993). For this study, one specific product, i.e. wall studs, was chosen.

The study was designed to obtain an indication of the percentage of studs that fail to meet the requirements proposed. The studs were also graded according to "The Green Book" (Anon 1982) and "Nordic Timber" (Anon 1994). The study was carried out at five sawmills situated in southern Sweden.

The sawmills chosen for the study were of average size for Swedish conditions, producing 50 000 - 100 000 m^3 sawn timber per year. Although the sawmills were not chosen as a stochastic sample from the population of all Swedish sawmills, the results of the study were expected to indicate the quality of studs produced and sold today and how the quality varied within and between sawmills.

2.2 Material and methods

2.2.1 Material

The material was sampled from a large amount of sawn timber of Norway spruce produced in southern Sweden. A total of 1800 boards were obtained from the five sawmills visited. The sawing pattern used was typical of Nordic sawing practice (Appendix B1) i.e. a single or double cant sawing pattern, 2 or 4 ex log with split-pith. The boards had been kiln-dried to an average moisture content of 18% (shipping dry). Two sawmills used circular saws, two sawmills had band-sawing technique and one sawmill had a frame-saw. All sawmills used progressive kilns for drying structural timber.

The dimension after planing was 45 x 95 mm. However, at one sawmill, that dimension was not available at time of observation, therefore two other stud-dimensions, 45 by 120 mm and 45 by 145 mm, were chosen.

The sampling process was similar at each sawmill (Figure 4). The boards were randomly sampled at two different steps in the production chain at the sawmills, after drying (*sample packages*) and from the normal production stock in trade (*delivery packages*).

For each sample package, boards were taken from three vertical levels: top, middle and bottom, in the kiln stacks. Each sample package contained a total of 150 boards.

The boards in the delivery packages had been planed and graded to be sold as wall studs, thus representing the wall stud quality of the sawmill. Number of studs in the delivery packages varied between 184 and 264.

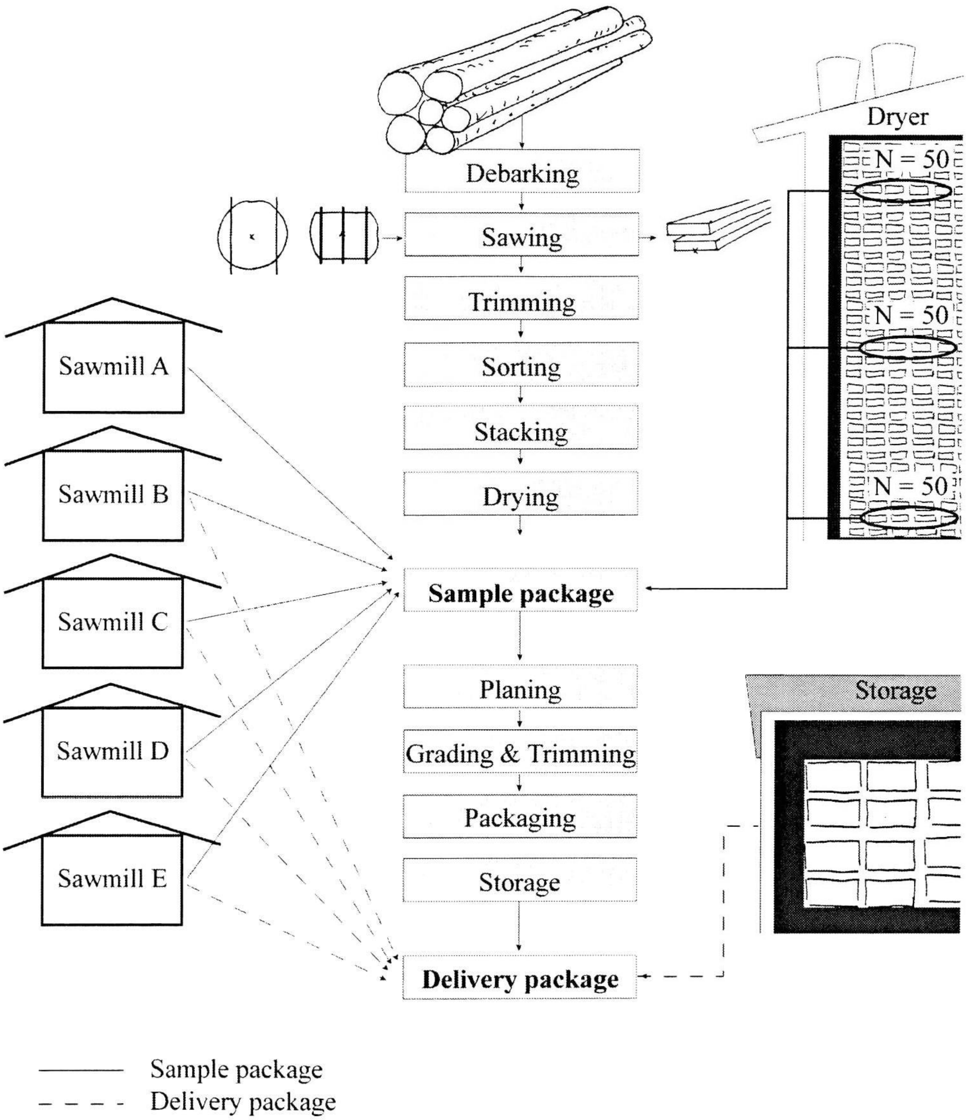

Figure 4. Sampling design.

At sawmill A, two sample packages but no delivery package were taken. From the other sawmills, one sample and one delivery package were collected. The number of pieces in each package and their dimensions are presented in Table 4.

Table 4. Number of studs in each package and stud dimensions.

SAW-MILL	SAMPLE PACKAGES				DELIVERY PACKAGES			
	Package number	Dimension after planing (mm)	Number of studs		Package number	Dimension after planing (mm)	Number of studs	
			before planing	after planing and grading			before planing	after planing and grading
A	1	45 x 95	150	117	-	-	-	-
A	2	45 x 95	150	149	-	-	-	-
B	3	45 x 95	150	61	7	45 x 95	-	210
C	4	45 x 95	150	126	8	45 x 95	-	264
D	5	45 x 95	150	29	9	45 x 95	-	242
E	6	45 x 145	150	150	10	45 x 120	-	184
	Total number of studs		900	632	Total number of studs		-	900

2.2.2 Procedure

Sample packages

The boards in the sample packages were measured for moisture content and warp directly after kiln-drying. Then the boards were graded according to the grading system used at each sawmill, trimmed and planed. At grading, 268 pieces were removed for other uses or because of defects. Remaining boards, graded as wall studs, were remeasured for moisture content and warp. In addition, width and thickness after planing were measured. To identify the sawing pattern used, growth ring orientation and approximate distance from pith were registered.

One package was stored in an open shed for three months and then remeasured for warp and moisture content to determine the changes during storage.

Delivery packages

Only warp was measured on studs in the delivery packages. Moisture content was not registered for these studs because marks caused by the moisture metres were not allowed in the final product.

2.2.3 Measurements

Warp

The actual amount of twist, crook and bow was measured, on every board, to the nearest mm over a span of 3 m.

Measurements were made using a mm-graded wedge. Crook and bow were measured as the greatest horizontal deviation from a straight line drawn from end-to-end. Twist was measured by fixing one end of the board to a plane table and measuring the greatest distance a corner at the other end of the board was raised above the flat surface. Cup was measured as the maximum concave deviation of the small end to the flat plane (Appendix B2).

Moisture content

Moisture content was determined with an electrical resistance moisture metre (Bollman H-DI-3.10) at three points in every board. Two readings were taken at positions 0.3 m from each end of the board and one at its centre. Average moisture content of the board was determined as the mean value of the three measurements.

Dimensions

Measurements of width and thickness, using slid callipers, were performed on every piece left in the sample packages after grading and planing. Three measurements were taken, near each end and at the middle of the stud, and the smallest of the readings for each board were recorded (Appendix B 3).

Location of the stud in relation to the pith

The boards were classed as split-pith, boxed-pith or side-boards, according to the sawing pattern used. Most boards belonged to the first category and came from logs split through the pith.

2.2.4 Statistical evaluation

The data collected were analysed for significant patterns and trends. The statistical analyses were made using the SAS software 6.12 (Anon. 1990). General Linear Models (GLM) procedure was used to evaluate data. For frequency data, the chi-square test was used to evaluate differences between groups.

2.3 Results and discussion

2.3.1 Quality of the wall studs

The studs were graded according to the requirements shown in Table 5. Those exceeding these limits for any one type of warp were classed as out-of-grade.

Table 5. Summary of proposed requirements on dimension, warp and moisture content on wall studs according to "Guidelines for Purchasing Building Timber" (Johansson et al. 1993).

<table>
<tr><th colspan="4">DIMENSION</th></tr>
<tr><td colspan="2">Width (mm)</td><td colspan="2">Thickness (mm)</td></tr>
<tr><td colspan="2">45 ± 1</td><td colspan="2">70, 95, 120, 145, 170 ± 1</td></tr>
<tr><th colspan="4">SHAPE - limits are set for the whole stud or for 3 m length</th></tr>
<tr><td>Cup</td><td>Bow</td><td>Crook</td><td>Twist</td></tr>
<tr><td>max 2% of width</td><td>max 6 mm</td><td>max 4 mm</td><td>max 4% of width,
5 mm is allowed</td></tr>
<tr><th colspan="4">MOISTURE CONTENT</th></tr>
<tr><td colspan="4">1) The timber should be delivered kiln-dried to a moisture content of 15 ± 2%, alternatively at moisture content class 12 (i.e. 9-15%) according to SS232740 (Anon. 1991).

2) Moisture content of 18 ± 2%, maximum 22%, could be accepted if the warp requirements when dried to equilibrium moisture content are fulfilled and guaranteed by the supplier.</td></tr>
</table>

Dimensions

The requirements for dimensions fall into the category of functional requirements. According to Johansson et al. (1994b), some contractors claim that the dimensions of the products bought are smaller than those expected by the standards. However, the end-users usually have no serious problems with the dimensions.

The necessary thickness is determined from the strength and stiffness requirements and from the need for sufficient support for splicing the cladding boards. The width should not differ between or within studs, i.e., the wall should not become bent (Johansson et al.1994b).

According to the requirements shown in Table 5, width and thickness are not allowed to deviate more than ± 1 mm from the specified measurements. On average, 94% of the studs in the sample packages met this requirement. However, in one of the packages the requirements were fulfilled by only 66% of the studs. The result for the other packages varied between 91 and 100% accepted studs (Figure 5). The reason for rejection of studs was that the measures were lower than the minimum value for width or thickness.

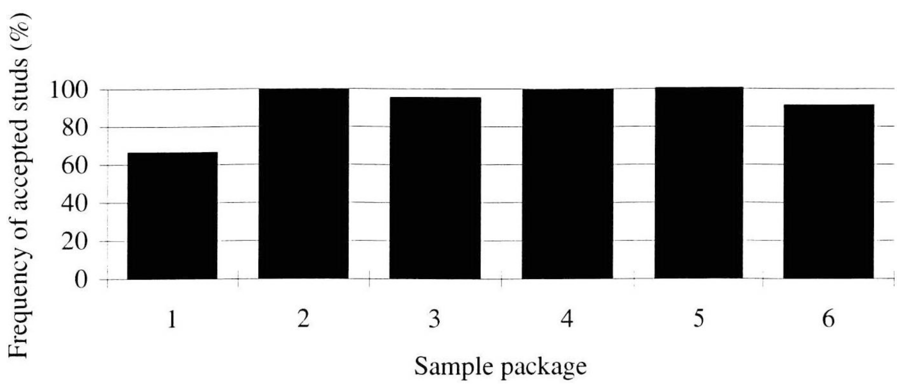

Figure 5. Percentage of the studs in the sample packages from each sawmill that was accepted with regard to dimensions (width x thickness).

Moisture content

The moisture content itself is not an important measure for the user, but many of the wood properties change as moisture content decreases or increases. If moisture content is too high at the time of building, studs will warp when drying to the equilibrium moisture content (EMC) and the wall risks becoming bent. The best way to avoid these problems is to deliver timber with the correct EMC. However, a prerequisite is that the wood is handled and stored in such a way that it is not exposed to moisture at the building site.

Today, sawn timber is usually dried to a moisture content class 18, i.e. 18 ± 6% (Anon. 1991). This limit is set primarily to avoid attack by microorganisms during transportation. The EMC for interior wall studs in Sweden varies over the year from approximately 8% in the winter to 13% in the summer (Bergström 1981). The requirement for moisture content of the sawn timber at time of delivery proposed in Guidelines for Purchasing Building timber (Johansson et al. 1993) is 15 ± 2%. A maximum moisture content of 20% is accepted *if* the supplier guarantees that the limits for twist, crook, bow and cup are not exceeded when EMC is reached.

Figure 6 shows the distribution of moisture content of the boards in the sample packages. The frequency distribution shows that the target moisture content, 18%, is rather well reached by the sawmills. Average moisture content was 18% for three of the packages, 16% for two packages and 19% for one package.

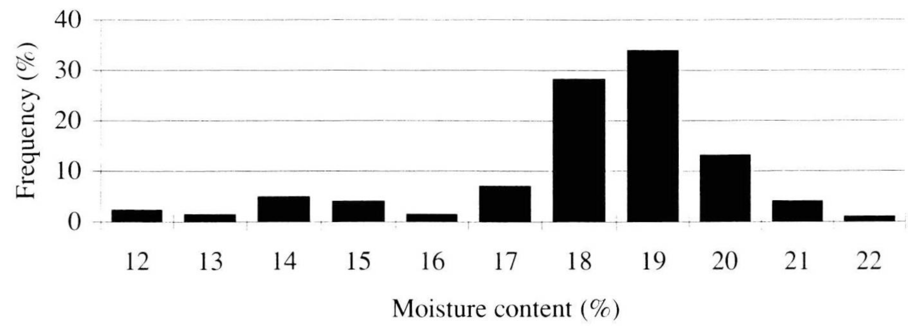

Figure 6. Frequency distribution of moisture content after planing for studs in the sample packages.

Almost all (91%) studs had a moisture content of 20% or less after planing. However, in one package only 46% of the studs were accepted. The variation in moisture content among the rejected studs in that package was low and ranged between 20.1-21.5%. In the other packages between 93 and 100% of the studs were accepted.

If the limit 15±2% moisture content was used instead, the variation between packages was statistically significant and much larger. In four packages, less than 20% of the studs fulfilled the requirement of a moisture content between 13 and 17%. The remaining two packages had 74 and 87% studs that were accepted.

Table 6. Percentage of studs in each sample package that was accepted with regard to the requirements on moisture content.

Sawmill	Package number	Percentage (%) of studs accepted with regard to moisture content	
		< 20	15 ± 2
A	1	46	0
A	2	95	1
B	3	97	87
C	4	100	12
D	5	93	17
E	6	100	74

Warp

The proposed grading rules, shown in table 5, are valid on dried and planed studs. Therefore, percentage of accepted studs is shown for planed and graded studs from the sample and delivery packages.

To be fully accepted the studs are not allowed to exceed any of the warp limits. Since the sawmills usually dry structural timber to a higher moisture content than that recommended in the Guidelines for Purchasing Building Timber (Johansson et al. 1993), moisture content was not considered in the following evaluation of warp.

Of the total number of studs in this study, i.e. sample studs after planing and delivery studs, 66% fulfilled the requirements for all four types of warp. This means that as much as approximately one-third of the studs graded, *did not* pass the warp requirements and should be rejected as wall studs at the building site.

According to the interview study by Johansson et al. (1994a and b) twist is the most prevalent problem in building timber today. Also, crook is considered as a serious problem, whereas bow often can be adjusted during erection of the wall. Figure 7 shows the percentage of studs accepted or rejected for each type of warp.

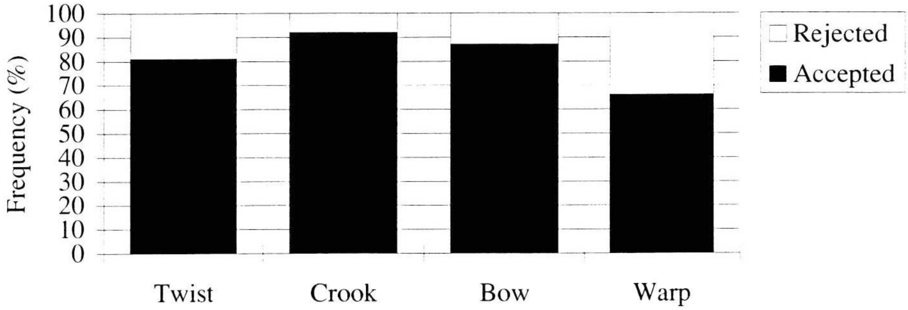

Figure 7. Percentage of studs accepted or rejected for each type of warp and for the combination of twist, crook and bow (warp).

When only twist was considered, about 80% of all studs in the material fulfilled the requirement of maximum 5 mm twist. According to Figure 7, 92% of the total number of studs fulfilled the requirement of maximum 4 mm crook. Bow was less than 6 mm in 87% of the studs.

Maximum cup allowed is set to 2% of the width of the stud, i.e. 1.9, 2.4 and 2.9 mm for the 95-, 120- and 145-mm wide studs, respectively. In this study, the largest cup measured was 1 mm and this only for few of the studs. Therefore, cup was not considered a problem for the dimensions studied and will not be discussed further in this chapter.

Comparison of individual studs

Figure 8 shows the types of warp of individual studs. Only a few studs exceeded the limits for more than one type of warp.

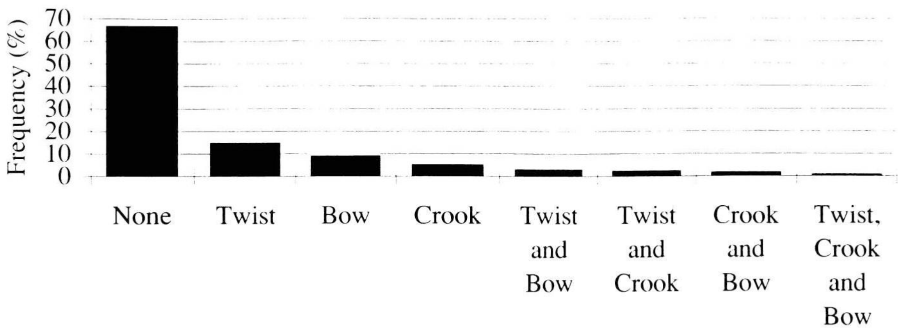

Figure 8. Number of warp defects exceeding the maximum limit, per stud in both the sample and the delivery packages.

The most common single form of warp was twist, followed by bow and crook. When two types of warp were present in one single stud the combination of twist and bow was most frequent. Crook and bow appeared together in only 1% of the studs.

Comparison of sawmills and packages

A comparison of the sawmills showed that there were large differences between sawmills concerning the percentage of studs that fulfilled the proposed limits for warp (Table 7).

Table 7. Percentage of studs in each sample and delivery package that was accepted with regard to the requirements on twist, crook and bow and the percentage of studs in each package that fulfilled all the requirements on warp. S=sample package, D=delivery package.

Sawmill	Package number	Percentage (%) of studs accepted with regard to			
		Twist	Crook	Bow	Warp
A	1 (S)	96	91	92	80
	2 (S)	80	94	78	61
B	3 (S)	72	88	77	48
	7 (D)	58	89	83	42
C	4 (S)	87	86	95	71
	8 (D)	90	96	93	81
D	5 (S)	72	62	66	34
	9 (D)	90	93	89	76
E	6 (S)	65	96	77	47
	10 (D)	87	95	95	79

At the best sawmill (C), 78% of the total number of studs fulfilled the requirements for warp. Only 44% of the studs from sawmill B were accepted, whereas sawmills A, D and E had 65-71% accepted studs in their packages.

In the best package, 81% of the studs were accepted whereas in the package with the lowest quality, only 34% of the studs were accepted when twist, crook and bow were considered together.

A pairwise comparison of the packages from each sawmill (Figure 9) shows that there were also differences between packages within the same sawmill.

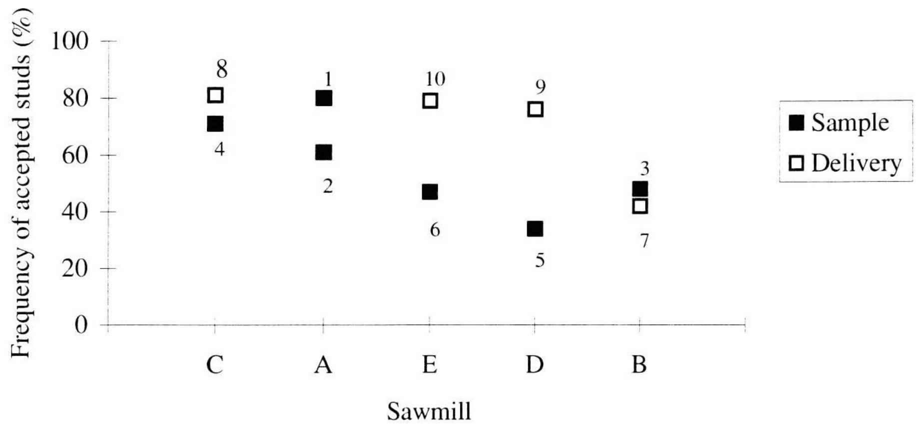

Figure 9. Comparison of the percentage of accepted studs in the sample and delivery packages from each sawmill.

Delivery packages from sawmills C, D and E had significantly more accepted studs than the sample packages. The opposite was true for sawmill B. Also, at sawmill A, where both packages were sampled at the same step in the production chain, there was a significant difference in percentage of accepted studs between the packages.

Both Table 7 and Figure 9 show that there was a significant difference in yield between sawmills and between packages within the sawmills. Large variation in warp between packages has also been noted in an evaluation of stud quality at two building sites in Sweden (Lindvall 1996). This variation could probably be attributed to differences in raw material, as well as processing factors.

2.3.2 Influence of grading rules on quality of the final product

Some of the difference in final quality between the sawmills may be attributed to the fact that different sawmills apply different grading criteria. Three of the packages, number 3, 5 and 7, differed significantly from the other packages. These packages came from two sawmills, B and D, which graded studs as "better VI grade" according to The Green

Book, whereas all other sawmills graded studs as V. The studs in package number 7 were rejects from a visual strength grading, but were, according to the sawmill, good enough for wall studs.

The requirements for twist, crook, bow and moisture content differ between the grading systems used today and the ones proposed by Johansson et al. (1993). The limits on warp proposed in Guidelines for Purchasing Building Timber are more rigorous than the regulations set in The Green book (Anon. 1982) and in Nordic Timber (Anon. 1994), the most commonly used grading rules in Sweden (Table 2).

Grades I-V, in The Green Book, allow maximum values for twist, crook and bow of 12 mm, 16 mm, and 34 mm, respectively, when they are converted to a span over 3 m. Grading according to these requirements resulted in a rejection of only 1% of the studs, whereas the limits proposed in Guidelines for Purchasing Building Timber led to a rejection of 34% when all studs were included. Thus, the classification at the sawmills seemed to be done according to The Green Book. Nordic Timber recommends grades A3, A4, B and C for structural purposes. The highest grades, A1 and A2, intended for joinery, allowed more warp than the rules proposed by Johansson et al. (1993) and therefore had a lower percentage of acceptable studs, between 49 and 97% among the packages. When graded according to class C, 100% of the studs were accepted in all packages. The difference between grading systems is illustrated in Figure 10, where quality yield for studs in sample and delivery packages are shown.

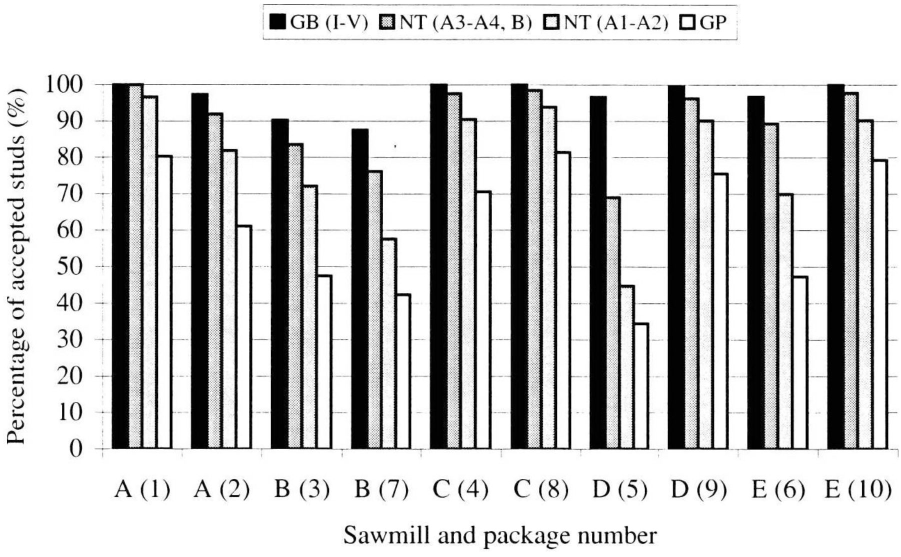

Figure 10. Comparison of stud yield for three grading systems - The Green Book (GB), Nordic Timber (NT) and Guidelines for Purchasing Building Timber (GP).

2.3.3 Influence of processing factors on warp

Position in the kiln-drying stack

To study the effect of top load on warp during drying, the studs were sampled from three levels, top, middle and bottom, of the kiln stack at each sawmill (Figure 4). To avoid the influence of planing, values of twist, crook and bow directly after drying were used for the evaluation. In all packages, twist was significantly larger for studs from the top level than from the bottom of the stack (Figure 11). The amount of bow and crook was not significantly influenced by top load.

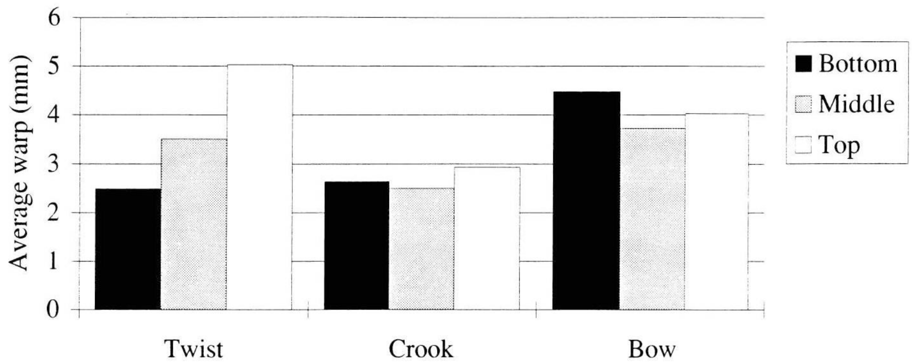

Figure 11. Influence of level in stack during drying on twist, crook and bow.

The findings here are in agreement with results from a study by Morén and Sehlstedt-Persson (1990), where the amount of warp in two groups of sawn timber, one with restraint and one without restraint, was compared. However, in their study, bow tended to increase further up in the pile. Danborg (1994a) also found a small, but statistically significant twist-reducing effect of restraint during drying.

Planing

All boards from the sample packages graded as studs, were planed and the changes in twist, crook and bow were registered. Twist and crook decreased in about 50% of the studs, increased in 25% and 25% of the studs remained as before drying. Bow changed in 75% of the studs, in 35% bow increased and bow decreased in 40% of the studs. As for twist and crook, in 25% of the studs bow were the same as before planing. There was no significant relationship between change in twist, crook and bow, and change in moisture content during the period between first warp measurements and measurements after planing.

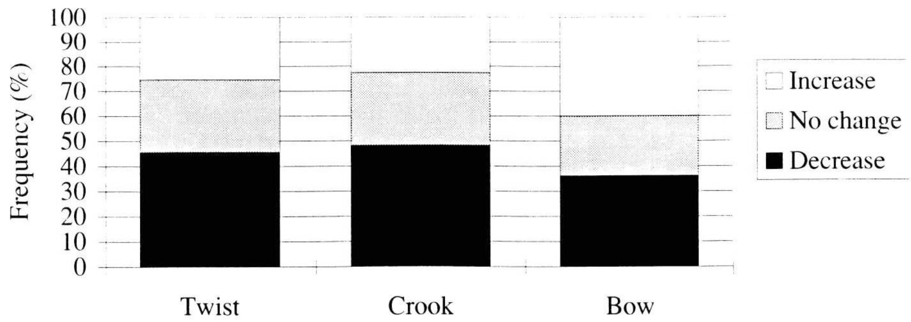

Figure 12. Effect of planing on warp - percentage of studs for which twist, crook and bow increased, did not change or decreased by planing.

Storage

One package (no. 2) was stored in an open shed during three months (late autumn). For most studs, twist increased whereas bow decreased during storage. Crook did not change to any particular extent. This trend was also found in the study by Morén and Sehlstedt-Persson (1990). Moisture content decreased significantly during the storage period, which can explain the increase in twist; there was a significant correlation between twist and moisture content for the studs in this package.

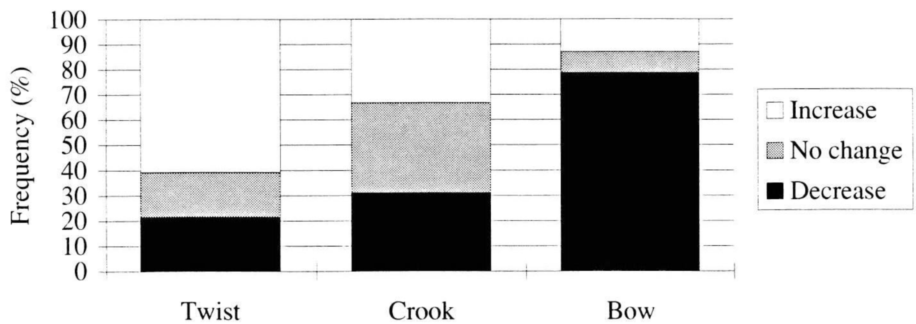

Figure 13. Percentage of studs for which twist, crook and bow decreased, did not change or increased during storage.

Final moisture content

Although final moisture content varied in this material, no significant correlation could be found between moisture content and twist, crook or bow after drying when all studs were compared. This was probably due to the fact that moisture content for almost 90% of the studs were between 16 and 20%. Thus, the few studs with extremely low or high moisture contents did not influence on the overall result. Only in one package changes in twist were related to changes in moisture content, the studs that were stored.

2.4 Concluding remarks

This study verified the conclusions from the interview study by Johansson et al. 1994a. The proportion of studs not meeting the requirements for warp was very high; 34% of all studs were rejected because of too large bow, crook or twist. Twist was the most severe warp problem. The large differences in quality of the final product between sawmills indicate that there is potential for the sawmills to improve shape stability of structural timber. Processing methods and grading criteria probably greatly influence the quality of the final product at time of delivery. Further knowledge of the connection between wood properties, sawmill processes and consumer requirements would make more efficient conversion possible.

3 Influence of sawing pattern and wood properties on the final quality of Norway spruce studs

3.1 Introduction

3.1.1 Background

The study on quality variations in wall studs, presented in chapter 2, showed that there was a significant variation in percentage of rejected studs between sawmills. This indicates that processing methods, and grading criteria as well as wood properties, influence the percentage of boards accepted as wall studs.

Many studies aimed at finding practical methods to prevent or reduce warp in sawn timber have been carried out over the years. Mainly pine-species have been studied. Different drying schedules together with mechanical restraint, have been tested with varying results (e.g. Kloot and Page 1959, Stevens 1961, Gaby 1972, Stöhr 1983, Morén and Sehlstedt-Persson 1990, Simpson et al. 1992, Kyrkjeeide et al. 1994). In the Nordic countries, studies on relationships between the properties of Norway spruce wood and warp have been made by, e.g. Danborg (1994c), Perstorper et al. (1994a, 1994b) and Forsberg (1997, 1999). They have all used logs from fast-growing trees and the logs were sawn according to the Nordic sawing practice, i.e. split through the pith (Appendix B1).

3.1.2 Aim of the study

The main objective of this study was to evaluate the effect of sawing pattern on the final quality of wall studs. The influence of pith location and ring orientation on the various types of warp was examined. The radial and longitudinal variation of raw material properties in the material and their influence on warp were also studied, as well as the effect of tree height class and stand age.

3.2 Material and methods

3.2.1 Stand description and sampling of trees

The sample trees originated from Asa research station, situated in the province of Småland in southern Sweden (latitude 57^0). Two stands, a 91-year-old mixed stand and a 55-year-old thinning stand consisting only of Norway spruce, both with site index G28[4], were chosen for the study. The stands were considered representative of Norway spruce grown on

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[4]Site index G28 means that the average height of the 100 largest trees per hectare (ha) will be 28 m in 100 years and the estimated average annual increment is about 7.1 m^{3}sk per hectare and year (Anon. 1984).

forest land in the south of Sweden and site index G28 is the average index in this part of the country. Data for the stands are given in Table 8.

Table 8. Description of stands according to the Forest Management Plan.

	Thinning stand	Final felling stand
Latitude (^{0})	57	57
Site index	G28	G28
Stand age (years)	55	91
Volume (m^3/ha)	241	323
Stems per hectare	1200	392
Proportional distribution of tree species (%)		
- Norway spruce	100	55
- Scots pine	-	45
Basal area (m^2/ha)		
- Norway spruce	25.3	17.1
- Scots pine	-	14.9
Average height (m)	19	22

A total of 120 trees were included in this study. From the 91-year-old stand, trees from two height classes were harvested: 30 dominant and 30 intermediate trees. In addition, 30 dominant and 30 co-dominant trees were sampled from the thinning stand. Because the intermediate trees in the younger stand were too small to make sawn timber, trees from the co-dominant height class were chosen instead of intermediate class. The trees sampled for the study did not have any major defects. Before felling, each tree was numbered and total height, green crown height and diameter at breast height were measured. The north-south direction was also marked on each tree. Data for sample trees are given in Table 9.

Table 9. Description of the sample trees - average values.

	Thinning stand		Final felling stand	
	Dominant	Co-dominant	Dominant	Intermediate
Number of trees	30	30	30	30
Diameter at breast height (cm)	21.3	17.8	33.9	21.7
Height (m)	18.6	15.0	24.7	15.9
Green crown height (dm)	76	80	75	63
Ring width (mm)	2.2	1.9	1.9	1.3

3.2.2 Selection of logs

The trees were cut with a chain saw and the stems were bucked into 3.1-m long logs. Butt logs and top logs were cut from each tree. The position of the top logs was defined by the top end diameter, which was set to 150 mm, and the logs were cut 3.1 m downwards from that point. From larger trees a third log, i.e. lower middle log, close to the butt log, was cut. Discs, 50 mm thick, were taken in connection to the upper and lower end of each log. The discs were frozen and transported to Uppsala, where the amount of corewood and heartwood of each log were measured. Growth ring width of each tree was measured on discs from the butt logs. Figure 14 shows the experimental design.

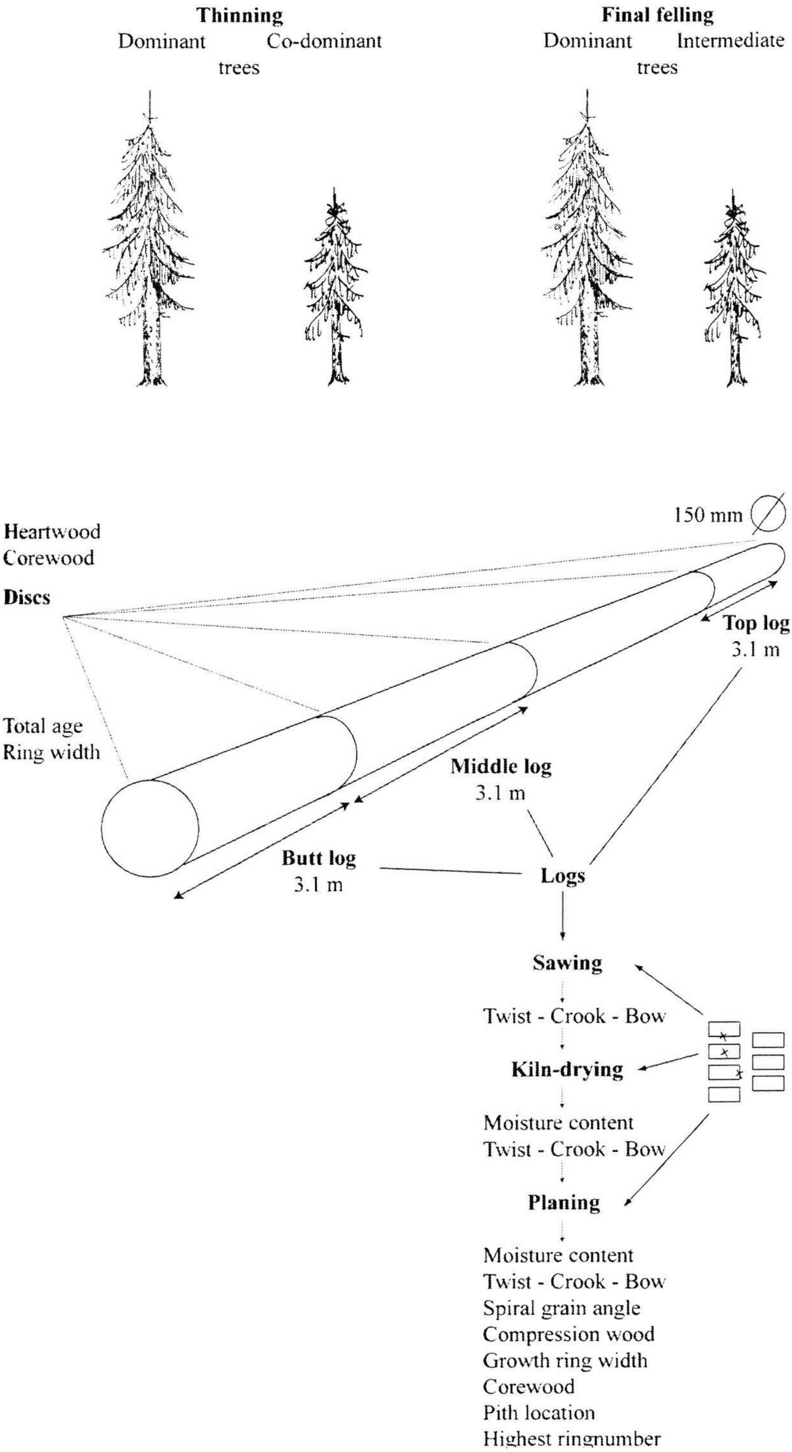


Figure 14. Experimental design.

3.2.3 Sawing

At the sawmill the logs were sorted into diameter classes and split according to four different sawing patterns, illustrated in Figure 15.

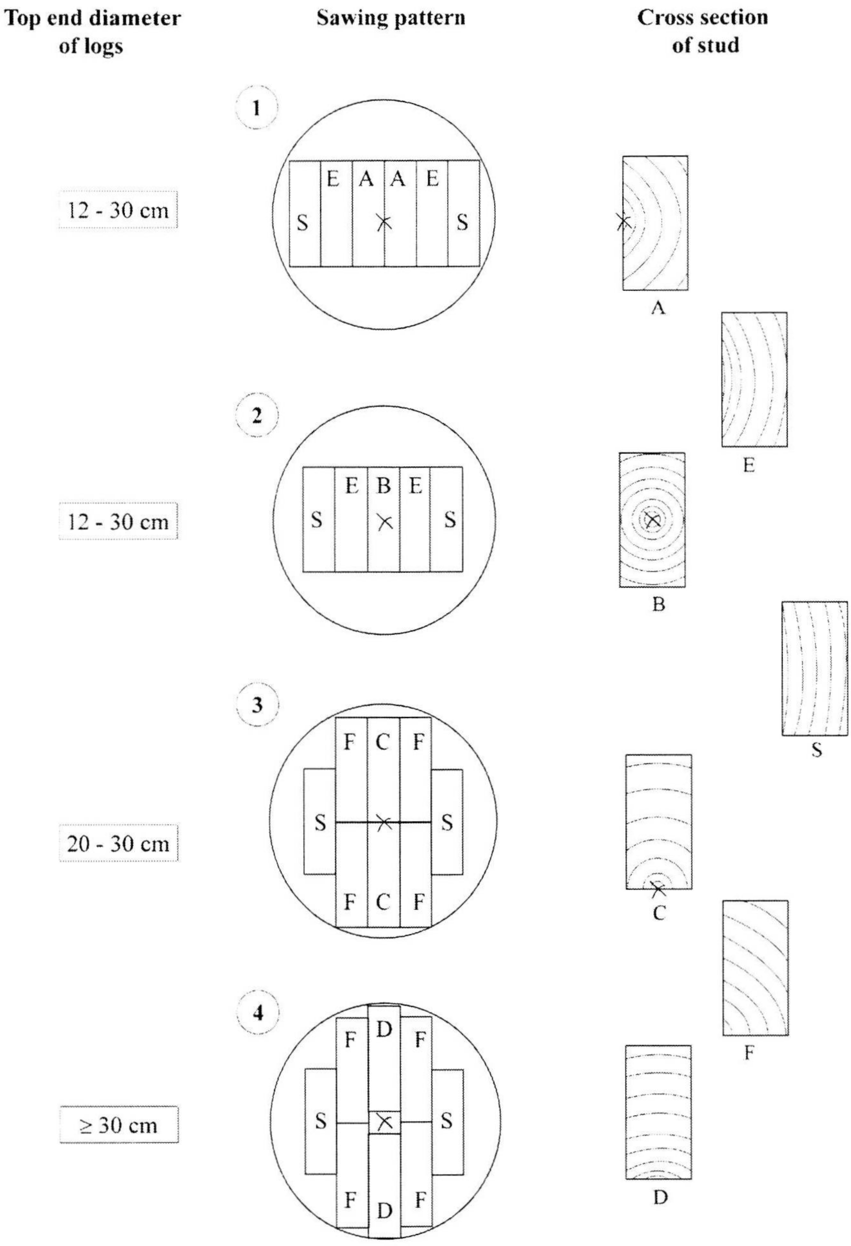


Figure 15. Sawing patterns used and cross-sections of studs - A; pith at face - flat-sawn, B; boxed pith, C; Pith at edge - quarter-sawn, D; No pith - quarter-sawn, E; No pith - flat-sawn, F; No pith - quarter-sawn, S; No pith - flat-sawn.

All types of logs were sawn by methods 1 and 2, whereas only the middle and butt logs were sawn in accordance with sawing patterns 3 and 4. Top logs had small diameters and they could not be used for all the sawing patterns. In method 4, a square of 50 x 50 mm centred around the pith was removed. This square was chosen so that the ten growth rings closest to pith were not included in the stud.

All logs were sawn into 50 x 100 mm studs. Logs with a top-end diameter less than 250 mm were sawn in a small frame-saw, whereas larger logs were sawn in a circular saw. In total 306 logs were sawn into 690 studs. The source of stand, tree height class, longitudinal and radial position were registered for each stud.

Total number of studs in different groups are presented in Table 10.

Table 10. Total number of studs in each group - by stand, log type and stud type.

Group	Thinning stand			Final felling stand			Total number of studs
	Top log	Middle log	Butt log	Top log	Middle log	Butt log	
B	34	18	26	32	19	13	142
A	48	30	49	49	26	27	229
C	-	-	16	-	6	14	36
E	-	-	20	-	45	57	122
D	-	-	-	-	11	28	39
F	-	-	-	-	32	54	86
S	-	-	-	-	4	32	36

To study the effect of sawing pattern the studs, produced by the four sawing patterns used here, were grouped according to ring orientation and absence or presence of pith. Stud types A, E and S were flat-sawn, i.e. growth rings tangent to the wide face and types C, D and F were quarter-sawn, i.e. growth rings tangent to the edge. Studs of type B were boxed-pith, i.e. pith was located approximately in the centre of the cross-section of the stud. Studs A, B and C contained pith on the wide face, in the centre and on the edge respectively, whereas studs D, E, S and F were completely free of pith.

3.2.4 Drying and planing

After sawing, the green studs were measured for twist, crook and bow over a span of 3 m and location of the pith was registered at both ends of studs.

Next, the studs were piled by hand and kiln dried to a moisture content of 12-14%. Drying was done in progressive kilns according to a conventional program used at the sawmill. The studs were divided into different packages according to sawing pattern. In the kiln-drier the experimentation packages were placed as number two from the top in the stack. Drying conditions were the same for all studs. A few days after drying the studs were measured for moisture content and remeasured for warp.

Finally the studs were planed to 45 x 95 mm and measured for moisture content and warp a last time. Furthermore, grain angle and presence of compression wood were registered.

Specimens, 50 mm wide, for use in measurements of growth ring width, pith location, proportion of corewood and number of growth rings in studs were cut from both ends of the boards.

3.2.5 Measurement of wood properties on logs

<u>Ring width</u>

Mean growth ring width was measured on discs cut from the top end of each log along a radius from pith to bark in the north-south direction. The measurements were made on discs in green condition. Also the radial development, in 20-mm intervals from pith to bark, was registered.

<u>Proportion of corewood in logs</u>

In this study, corewood was defined in accordance with Danborg (1990), i.e. the 10 innermost growth rings were defined as being corewood, whereas rings from number 11 and outward to the bark were defined as being outerwood.

Proportion of corewood in the logs was measured on discs cut from the top end and was determined as a percentage of the total cross-section of the log.

<u>Heartwood</u>

The proportion of heartwood in the logs was also measured, but as this parameter did not affect warp, it will not be discussed further here.

3.2.6 Measurement of wood properties and warp on studs

<u>Average ring width</u>

Average ring width of the single studs was measured on pieces cut from the top end of each stud.

Proportion of corewood in studs

Percentage of corewood in each stud was estimated as the approximate area of the corewood, defined as the 10 rings closest to pith, in relation to the area of the whole cross-section of the board.

Cambial age of the outermost growth ring included in the stud

Another way to express the proportion of corewood in studs is to register the number of the growth ring with the highest cambial age included within the cross-section of the stud. This was done from the top-end-pieces of the studs.

Grain angle

Grain angle was measured on the face closest to the bark, representing the tangential face of the studs, using a scribe in accordance with BS 4978 (Anon. 1973) (Appendix B4). Two lines were scribed on knot-free wood in the top end on every stud. Grain angle was determined as the deviation from parallel alignment with the edge of the studs on a length of 200 mm. The deviation divided by the length represents grain angle expressed as percent. Grain angle for the stud was calculated as the mean of the two measurements.

Compression wood

Estimation of compression wood percentage is difficult without splitting the board. Therefore, presence of compression wood was estimated visually into two classes: YES if compression wood was visible on the surfaces or small ends of the boards, and NO if not.

Warp and moisture content

Warp and moisture content were measured as described in chapter 2, section 2.2.3.

3.2.7 Grading of studs

To evaluate the effects of sawing pattern on the quality of the final product, the studs were graded according to the requirements in "Guidelines for Purchasing Building Timber" (Johansson et al. 1993). For comparison, the studs were also graded according to current grading systems, "The Green Book" (Anon. 1982) and "Nordic Timber" (Anon. 1994). Those exceeding limits in any one type of warp was classified as out-of-grade. The limits for warp according to these systems are shown in Table 2, section 1.5.3.

To clearly observe the effect of sawing pattern on the development of warp during drying, the values of twist, crook and bow before planing was used for the evaluation.

3.2.8 Statistical evaluation

Data analyses were made using SAS software, version 6.12 (Anon. 1990). General Linear Models (GLM) procedure as well as the MIXED procedure were used to evaluate data. For skewed data a non-parametric test (NPAR1WAY procedure) was also used to test significance. Because results from the different procedures used led to the same conclusions, only GLM results are presented. The chi-square test was used to evaluate differences in frequency data between groups.

3.3 Results and discussion

3.3.1 Variation of wood properties measured on logs

Ring width

Average ring width differed significantly between the two stands and also between height classes within each stand. The dominant trees from the thinning stand had the widest growth rings, 2.2 mm, and intermediate trees from the old stand the most narrow rings, 1.3 mm. Average ring width was 1.9 mm for both co-dominant trees in thinning stand and dominant trees from the final felling stand.

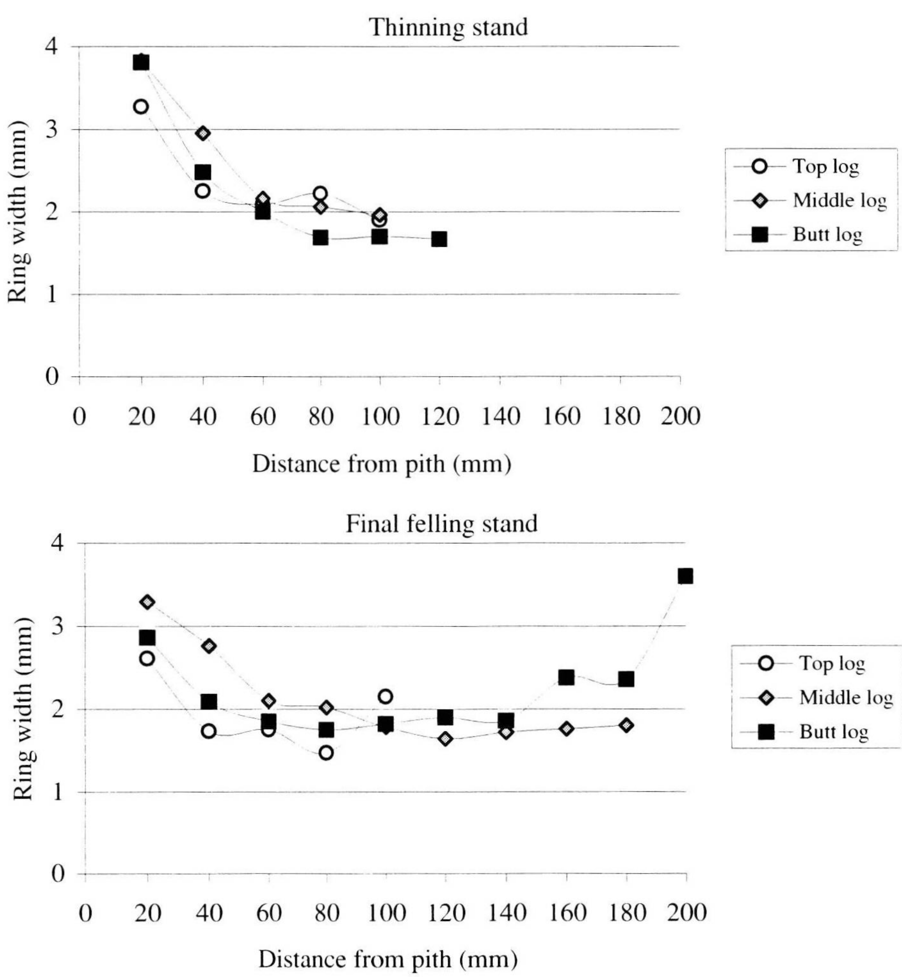


Figure 16. Radial variation in ring width for logs from the thinning and the final felling stand.

As expected, ring width was largest close to the pith and decreased towards the bark. For butt and top logs from the final felling stand, ring width increased rapidly at a distance of 80 and 180 mm from pith, at a cambial age of approximately 40 years. The increase was probably caused by a thinning at that time. The difference between stands was largest in the corewood (Table 11).

Proportion of corewood in logs

Corewood proportion was higher in co-dominant and intermediate trees than in dominant trees within each stand. This difference was, however not significant.

All logs from the thinning stand contained about twice as much corewood as the logs from the older stand. Top logs contained the largest proportion, whereas butt logs had the smallest. The differences between stands and the longitudinal variation were highly significant.

Summary of growth characteristics for logs

In Table 11, characteristics measured on the logs are summarized.

Table 11. Summary of growth characteristics for logs from the two stands. Average values for logs (LOG), average values for corewood=10 rings ($CORE_{10}$), proportion of heartwood in logs (HW). Number of observations (N), arithmetic mean value and standard deviation ().

Group	N	Ring width (mm)		Proportion in log (%)	
Stand and Log		LOG	$CORE_{10}$	$CORE_{10}$	HW
Thinning					
- Top	58	2.3 (0.5)	2.8 (0.4)	21.8 (5.1)	22.9 (16.8)
- Middle	33	2.5 (0.4)	3.5 (0.4)	19.3 (4.0)	31.5 (11.7)
- Butt	59	2.1 (0.3)	3.2 (0.5)	13.9 (3.5)	33.4 (13.0)
Final felling					
- Top	55	1.7 (0.4)	2.3 (0.7)	14.3 (8.1)	26.4 (13.6)
- Middle	40	1.9 (0.4)	2.9 (0.7)	6.8 (2.3)	40.5 (12.9)
- Butt	49	1.6 (0.4)	2.6 (0.6)	5.5 (2.8)	43.2 (11.6)

3.3.2 Variation of wood properties measured on studs

The properties measured on the studs, i.e. ring width, corewood proportion, highest ring number, spiral grain angle and presence of compression wood, are presented by stud-group (A-S). Comparisons between stands, tree height classes within stands and between logs were made only for studs from groups A and B (corestuds) as these studs occurred in all categories. Average values of properties measured are summarized in Table 12 at the end of this section. In tables and figures the studs are ordered in relation to approximate distance from pith, i.e. B, A, C, E, D, F and S.

Ring width

Average ring width was significantly larger in corestuds from the thinning stand than those from the final felling stand. Within stands, ring width was smaller in studs from co-dominant and intermediate trees than dominant trees in each stand. However, the difference was significant only for top- and butt log, split-pith studs from the thinning stand and boxed-pith studs from the final felling stand. Studs from middle logs had wider growth rings than studs from top and butt logs. When studs from trees for which all three log types were present were compared, ring width was equal for middle and butt logs. The difference between stud type A and B was significant only for co-dominant top logs from the thinning stand and dominant top logs from the final felling stand.

Proportion of corewood in studs

In accordance with the result for ring width variation for studs containing pith, there was a significantly larger amount of corewood in studs from the thinning stand than from the final felling. Figure 17 shows the significant radial trend of corewood proportion.

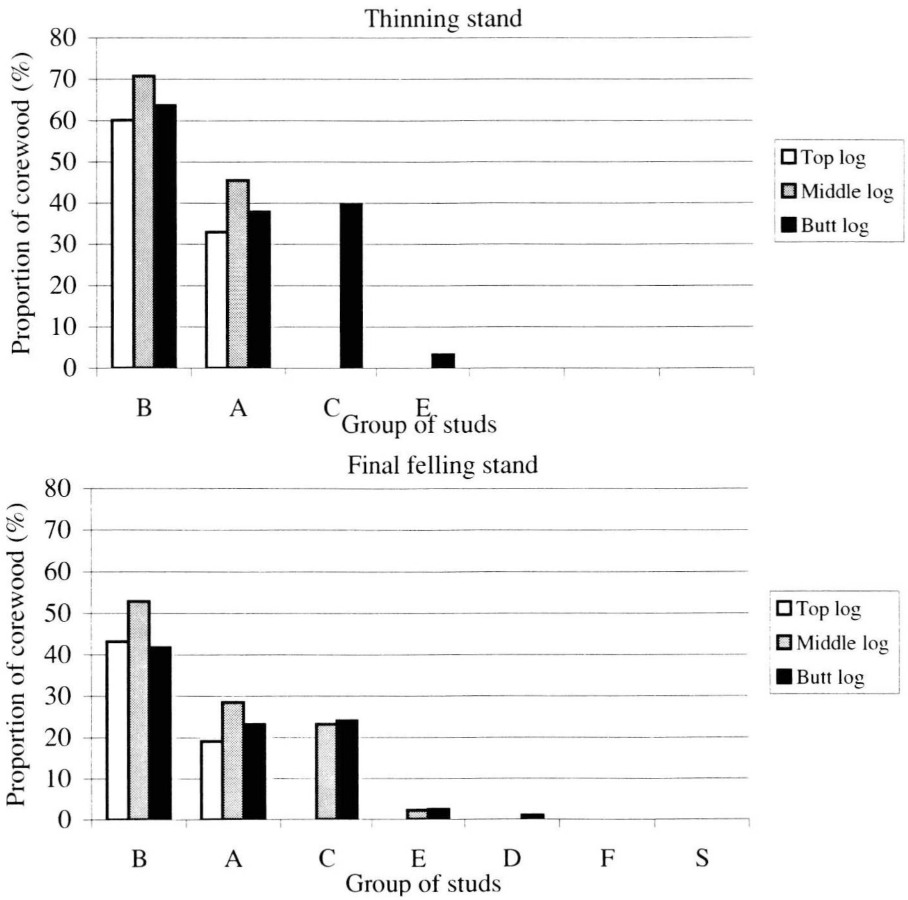


Figure 17. Percentage of corewood, defined as 10 rings closest to the pith, for different groups of studs from the thinning stand and the final felling stand.

Within both stands, studs from dominant trees had larger percentage of corewood than studs from co-dominant and intermediate trees. This difference was, however, not significant. Middle log studs had the largest and top logs studs the smallest amount of corewood. The larger corewood proportion in studs from middle logs could be explained by the fact that middle logs were cut only from the fastest growing trees in each stand. When only studs from trees with all three types of logs were compared corewood proportion was about equal for middle and butt logs.

Cambial age of the outermost growth ring included in the studs

This parameter was negatively correlated to growth ring width and studs from the thinning stand included significantly fewer rings in each stud group than studs from the final felling. Middle log studs included fewer growth rings than top and butt logs. There was also a significant radial variation, the further away from the pith, the higher the number of the last ring.

Grain angle

No significant variation in grain angle between stands or height classes was found. Radial and longitudinal grain angle variation differed between trees which could explain the non-significant relationships between different groups of the material. Neither the longitudinal variation nor the variation in the radial direction was consistent. The between-tree variation has been observed by several authors, e.g. Danborg (1990), Perstorper et al. (1999).

Compression wood

Compression wood occurred in 36% of the studs. Studs from the final felling stand had significantly higher frequency of studs with visible compression wood than those from the thinning stand. Significant differences were also found between studs from different height classes within each stand. Within the thinning stand, butt log core-studs from co-dominant trees had a larger frequency of studs containing compression wood than dominant trees. The same relationship existed within the final felling stand, but for studs from middle logs. Studs from top logs showed no significant difference with respect to tree height class. Longitudinal and radial variation of the occurrence of compression wood is shown in Figure 18.

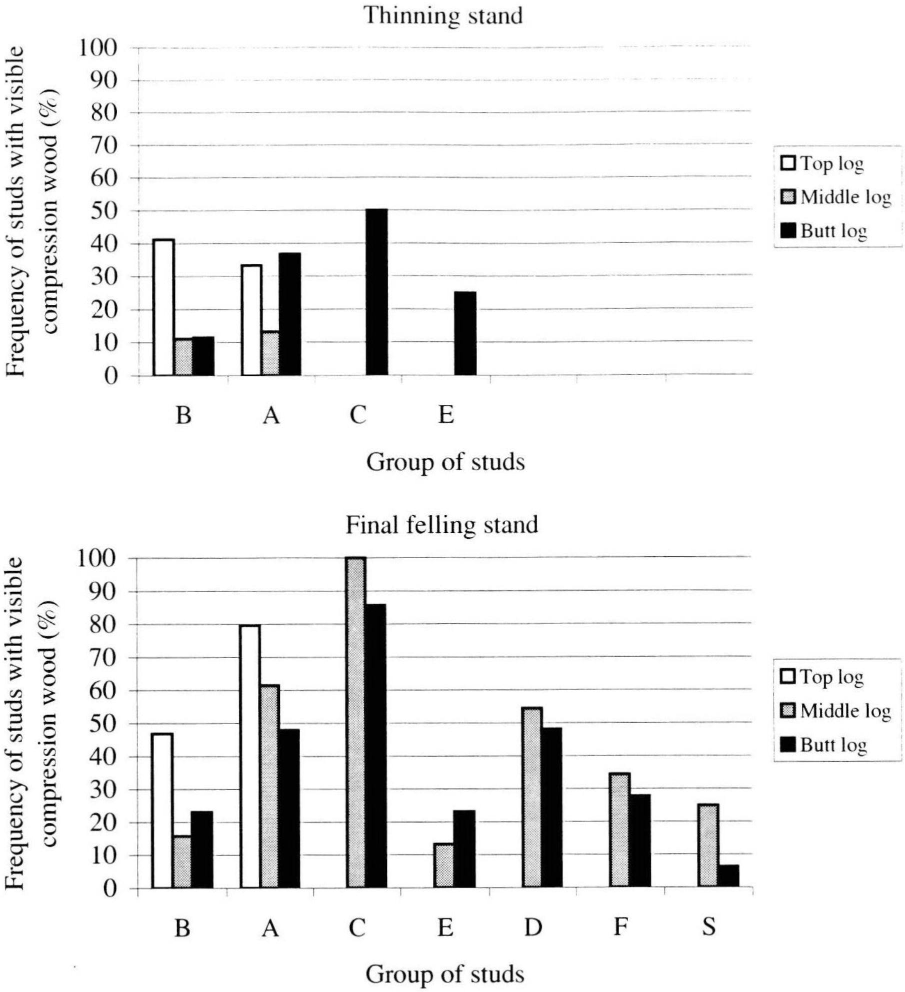


Figure 18. Longitudinal and radial variation of occurrence of visible compression wood in different groups of studs from the thinning stand and the final felling stand.

Comparison of all studs revealed that there was a significant difference between stud types. The highest percentage of studs containing visible compression wood was found in stud group C from both stands. In the old stand the frequency of split-pith studs containing compression wood increased from butt to top logs. In split-pith studs from the thinning stand compression wood was more frequent in top and butt log studs than in studs from middle logs. Percentage of boxed-pith studs from top logs containing visible compression wood were significantly larger than studs from middle and butt logs. In logs from the final felling, compression wood seemed to be situated at a distance of about 25-50 mm from the pith on the southern side of the stem.

Summary of material data for studs

Growth characteristics for studs are summarized in Table 12.

Table 12. Summary of growth characteristics for stud groups. Number of observations (N), ring width (RW), ring number from pith (RNR), proportion of corewood=10 rings in studs ($CORE_{10}$), grain angle (GA) and frequency of studs with presence of visible compression wood (CW). Arithmetic mean value and standard deviation ( ).

Group Stand Log	Stud	N	RW (mm)	RNR	$CORE_{10}$ (%)	GA (%)	CW (%)
All		668	2.3 (0.6)	32 (17)	24 (24.4)	2.2 (1.7)	36
Thinning							
- Top	B	33	2.6 (0.4)	19 (5)	60 (9.4)	1.9 (1.5)	41
	A	46	2.5 (0.5)	18 (3)	33 (8.1)	2.4 (1.6)	33
- Middle	B	18	3.0 (0.7)	15 (3)	71 (9.7)	2.4 (1.8)	11
	A	30	2.9 (0.5)	15 (2)	45 (12.5)	2.1 (1.3)	13
- Butt	B	26	2.5 (0.4)	19 (4)	64 (7.2)	2.5 (1.7)	12
	A	49	2.5 (0.5)	17 (3)	38 (12.0)	2.3 (1.6)	37
	C	16	2.7 (0.4)	35 (4)	40 (12.1)	2.4 (1.9)	50
	E	20	2.6 (0.4)	23 (4)	3 (14.8)	3.0 (2.3)	25
Final felling							
- Top	B	31	1.8 (0.5)	23 (7)	43 (15.7)	2.4 (1.9)	47
	A	43	1.7 (0.4)	29 (7)	19 (7.6)	2.3 (1.6)	80
- Middle	B	18	2.4 (0.9)	16 (5)	53 (18.1)	2.3 (1.2)	16
	A	22	2.2 (0.5)	22 (3)	29 (9.6)	2.4 (1.3)	62
	C	6	2.1 (0.1)	47 (3)	23 (11.4)	1.1 (0.9)	100
	E	45	2.4 (0.9)	31 (10)	2 (11.0)	2.1 (1.7)	13
	D	11	2.2 (0.2)	53 (6)	0 (0)	2.8 (1.3)	55
	F	32	2.5 (0.4)	56 (5)	0 (0)	2.9 (1.8)	34
	S	4	2.2 (0.2)	-	0 (0)	2.1 (0.5)	25
- Butt	B	12	1.6 (0.4)	29 (14)	42 (12.8)	2.1 (1.4)	23
	A	24	1.7 (0.7)	29 (11)	23 (13.3)	2.9 (2.3)	48
	C	14	1.6 (0.2)	59 (6)	24 (9.2)	2.5 (1.8)	86
	E	54	2.0 (0.6)	36 (11)	3 (13.0)	1.8 (1.6)	23
	D	27	2.2 (0.4)	54 (6)	1 (3.6)	1.9 (1.5)	48
	F	54	2.3 (0.5)	60 (8)	0 (0)	2.1 (1.7)	28
	S	32	2.2 (0.6)	57 (12)	0 (0)	1.7 (1.4)	6

3.3.3 Variation in moisture content within the material

The frequency distribution in Figure 19 shows that as much as 41% of the studs had a moisture content less than 13%, i.e. the lower limit according to Guidelines for Purchasing Building Timber (Johansson et al. 1993). However, 98% of the studs had a moisture content of 17% or less, which is more important to note when studying warp. In fact, the moisture content should be as close to the equilibrium moisture content as possible at time of building to avoid damage caused by shrinkage in the studs after they are built in.

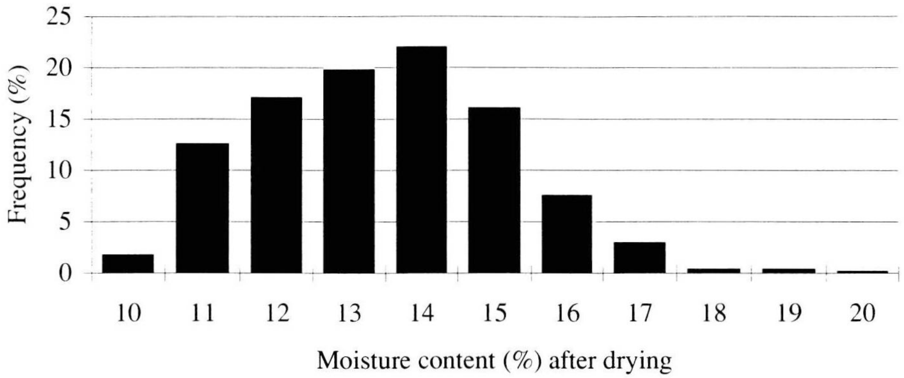


Figure 19. Variation in moisture content of the studs.

A comparison of average moisture content in the different groups of studs showed that there was a significant difference between the groups. Lowest moisture content was measured in groups A and B and highest in groups C and S (Table 13).

3.3.4 Influence of sawing pattern and moisture content on warp

The difference in moisture content between stud groups indicated that the effect of sawing pattern on warp could be difficult to study. However, an analysis of the influence of moisture content on twist, crook and bow, with moisture content, stud group and moisture content within stud group as independent variables, showed that stud group was highly significant whereas there was no significant effect of moisture content on warp. Neither for the whole material, nor within groups of studs. Thus it was concluded that differences in moisture content was not large enough to explain differences in warp in this material.

In Table 13, average values of moisture content, twist, crook and bow for the different groups of studs are summarized.

Table 13. Summary of moisture content (MC), twist, crook and bow after drying for different groups of studs. Number of observations (N) arithmetic mean value and standard deviation ().

Group	N	MC (%)	Twist (mm)	Crook (mm)	Bow (mm)
B	142	12.3 (1.2)	10.1 (5.6)	2.1 (2.2)	3.5 (2.2)
A	228	12.9 (1.4)	3.2 (3.1)	2.2 (2.1)	2.5 (1.7)
C	36	15.0 (1.5)	2.9 (3.4)	1.6 (1.4)	2.3 (1.5)
E	123	13.5 (1.6)	1.0 (2.0)	2.3 (2.7)	2.2 (2.2)
D	39	14.7 (1.3)	0.2 (0.7)	1.5 (1.4)	1.9 (1.5)
F	86	14.5 (1.3)	0.8 (1.4)	1.4 (1.5)	1.6 (1.5)
S	36	15.4 (1.6)	0.4 (0.8)	1.8 (1.5)	1.5 (1.3)

The sawing pattern greatly affected the geometrical properties of the studs after drying. Especially twist was influenced by the sawing pattern.

Twist decreased significantly with increasing distance from pith. The core-studs, A and B, had mean values of 3.2 and 10.1 mm respectively. Mean values for the outer studs, varied between 0.2 and 1.0 mm for twist (Table 13 and Figure 20).

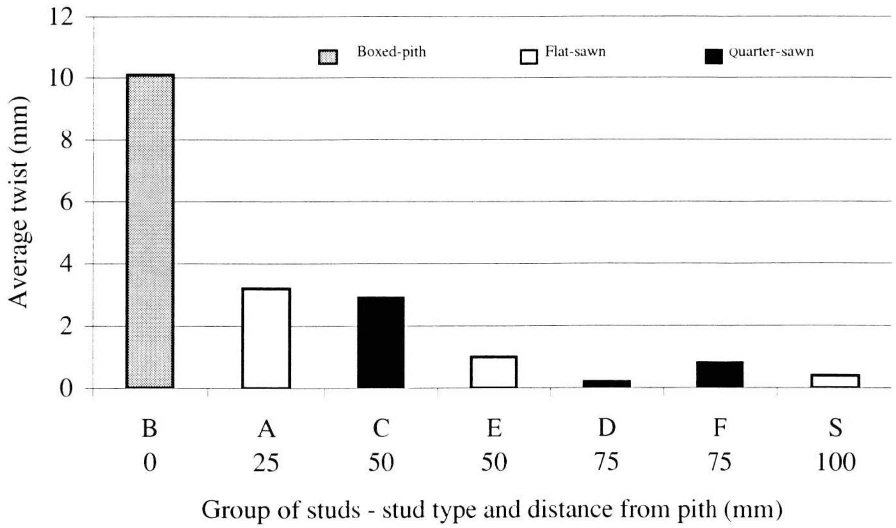


Figure 20. Influence of pith location and ring orientation on twist.

Crook did not vary significantly with distance from pith when flat-sawn studs were compared. Crook was larger in quarter-sawn studs containing pith than in pith-free studs, but the difference was not significant.

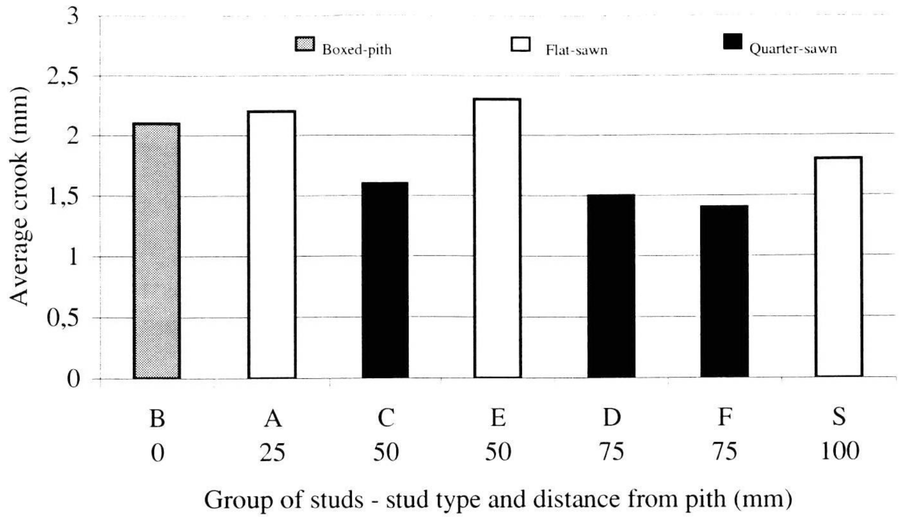


Figure 21. Influence of pith location and ring orientation on crook.

Within each group of studs, there was a significant radial variation for bow, whereas ring orientation had no significant effect. Bow decreased with increasing distance from pith.

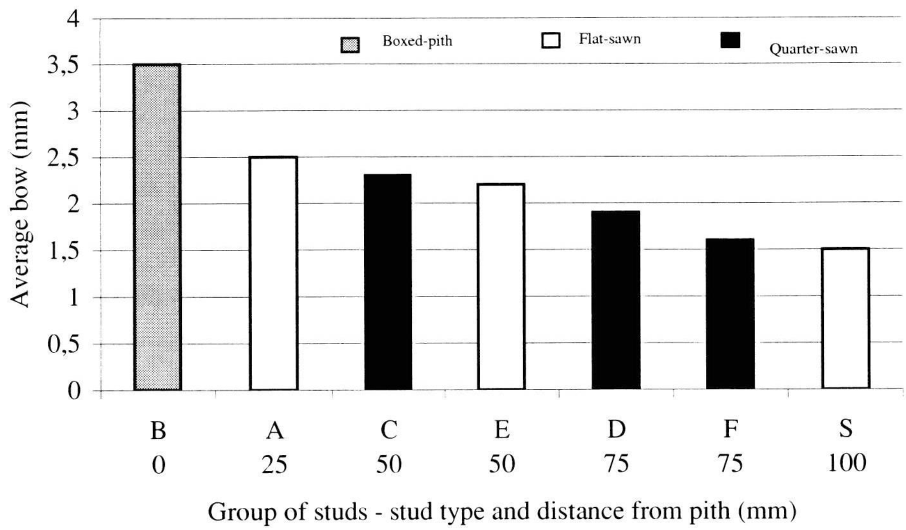


Figure 22. Influence of pith location and ring orientation on bow.

3.3.5 Influence of sawing pattern on the final quality of studs

The percentage of studs accepted according to the requirements in Johansson et al. (1993) was 67%, but there were substantial differences between groups depending on the sawing patterns (Figure 23).

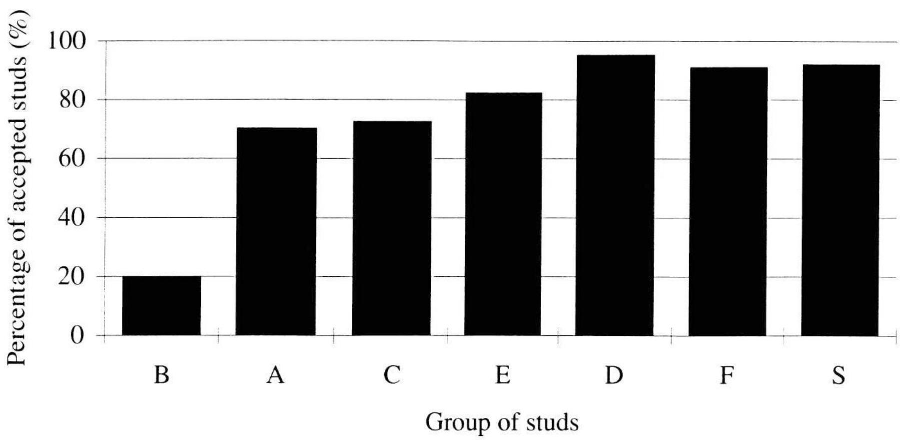


Figure 23. Percentage of accepted studs when requirements for twist, crook and bow are fulfilled.

Warp was more pronounced in studs close to the pith than those sawn closer to the bark. Studs of type B, boxed-pith, differed significantly from the other studs, only 20% of the boxed-pith studs were acceptable, whereas 95% of those belonging to group D met the warp requirements. Groups A and C were equal, about 70% of the studs sawn according to these patterns were acceptable. There was only a minor difference between the percentage of acceptable studs among the outer boards. Between 80 and 90% of the intermediate and outer studs met the requirements. About 90% of the pith-free studs, flat-sawn as well as quarter-sawn, fulfilled the requirements after drying (Table 14). Only 53% of the studs including pith were accepted. Kyrkjeeïde et al. (1994) and Perstorper et al. (1994b) found the same radial pattern for core, intermediate and outer flat-sawn studs from butt logs of fast-grown Norway spruce trees.

Comparison of the types of warp (Figure 24) clearly shows that twist was the most serious problem. Only 75% of the total number of studs met the requirement of maximum 5 mm twist. About 90% of the studs met the requirement for crook and 97% of the studs had a bow of less than 7 mm and would thus be accepted by the end-users, the builders.

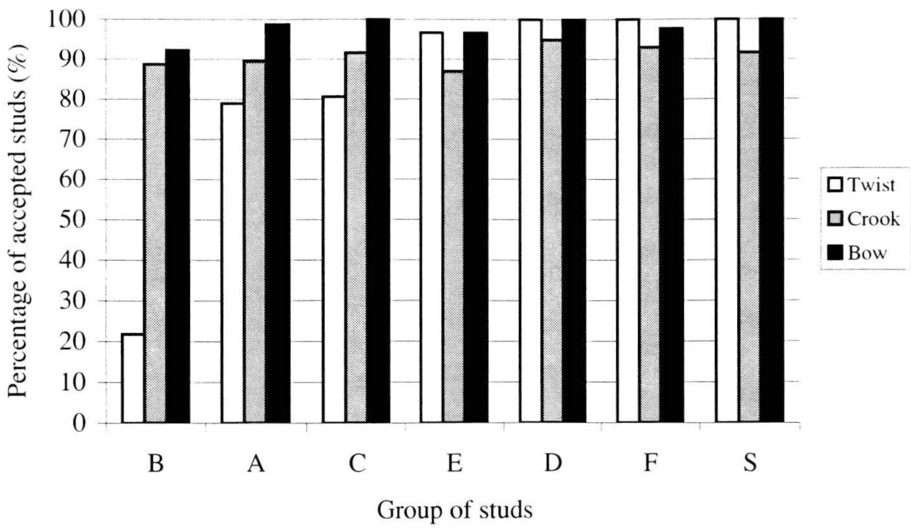


Figure 24. Percentage of accepted studs according to "Guidelines for Purchasing Building Timber" (Johansson et al. 1993).

The limits for maximum allowed warp and moisture content set in The Green Book (Anon. 1982) and in its replacement Nordic Timber (Anon. 1994) are much more generous than the rules derived from the requirements of the building industry. Table 14 shows the effects of the three standards on final yield.

Table 14. Comparison of stud yield for three grading systems: The Green Book - grades I-V (GB), Nordic Timber - grades A-C (NT) and Guidelines for Purchasing Building Timber - wall studs (GP). The requirements on warp are shown in Table 2.

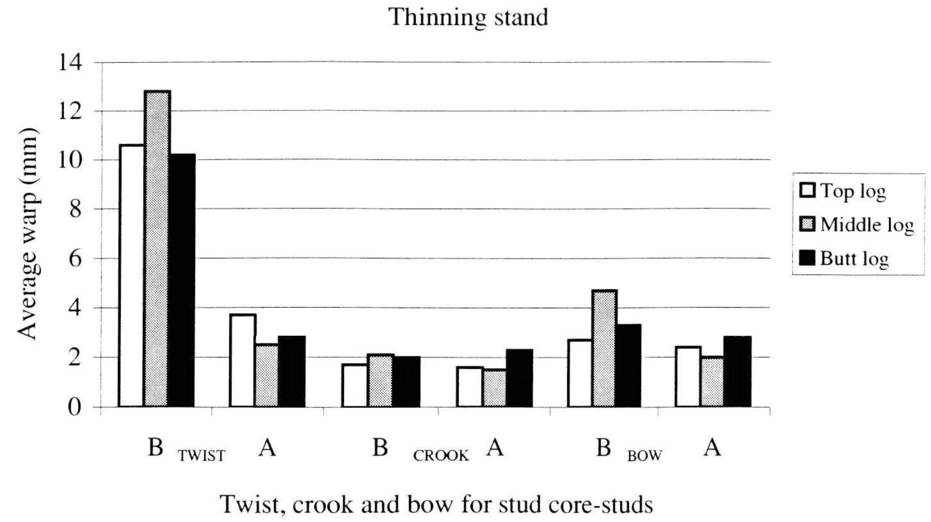
Group		Percentage of accepted studs with regard to											
		Warp			Twist			Crook			Bow		
		GB	NT	GP	GB	NT	GP	GB	NT	GP	GB	NT	GP
All		93	75-97	67	93	78-97	75	100	96-100	90	100	100	97
B	Boxed pith	68	26-85	20	68	27-85	22	100	98-100	89	100	100	92
A	Pith at face - flat-sawn	99	80-100	70	99	83-100	79	100	95-100	90	100	100	99
C	Pith at edge - quarter-sawn	97	86-100	72	97	86-100	81	100	100	92	100	100	100
E	No pith - flat-sawn	100	88-100	82	100	97-100	97	100	92-100	87	100	99-100	97
D	No pith - quarter-sawn	100	100	95	100	100	100	100	100	95	100	100	100
F	No pith - quarter-sawn	100	99-100	91	100	100	100	100	99-100	93	100	100	98
S	No pith - flat-sawn	100	100	92	100	100	100	100	100	92	100	100	100

When graded according to The Green Book (Anon. 1982), there were no differences in percentage of accepted studs for the different group, except for boxed-pith studs of which as much as one third were rejected.

The warp limits in Nordic Timber (Anon. 1994) where somewhat stricter than in the Green Book. Between 80 and 100 % of the studs, irrespective of which sawing pattern used, were accepted. The only exception is for grades A1-A2, which is recommended for visible joinery, that accepted only 26% of the boxed-pith studs.

3.3.6 Influence of longitudinal position on warp and final quality of studs

Neither average twist, nor percentage of down-graded studs seemed to be affected by the longitudinal position in the tree. Bow and crook showed a longitudinal variation in stud groups A and B. For split-pith studs, largest bow and crook were found in studs from butt logs. This difference was significant for average values of bow and crook, but affected the percentage of accepted studs only for crook. For split-pith studs, largest crook and bow in butt logs have been reported by Danborg (1994c) and Forsberg (1997), whereas Perstorper (1994b) found longitudinal variation only for crook. Largest bow in boxed-pith studs were found in studs sawn from middle logs and smallest bow was found in top log studs. The difference was significant for average values as well as for final quality for studs from the thinning stand. Quarter-sawn studs and flat-sawn outer studs were present only in middle and butt logs. For these studs, no significant differences in warp were found between the logs compared.



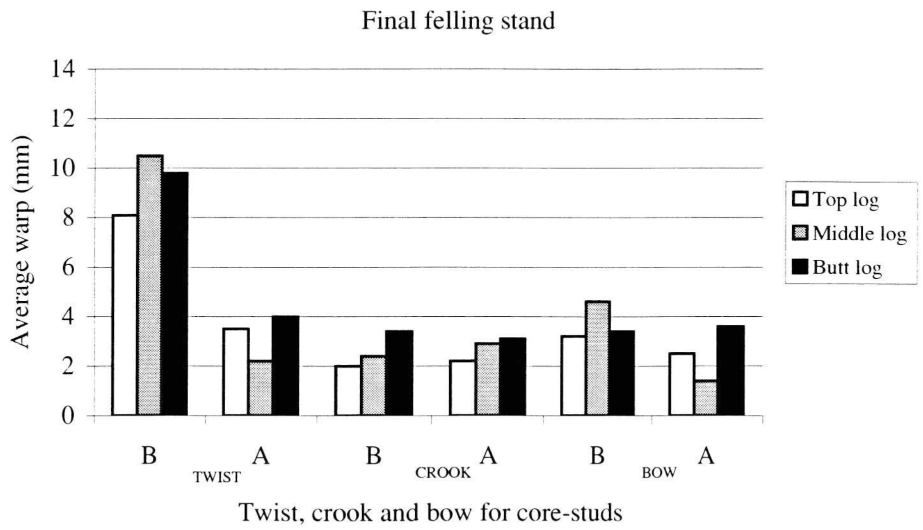


Figure 25. Longitudinal variation of twist, crook and bow in studs from the thinning stand and the final felling stand.

3.3.7 Influence of stand and tree height class on warp and final quality of studs

When core-studs, A and B from different stands and tree height classes within stands were compared for twist and bow, no significant differences between either stands or height classes were found. Studs from the final felling stand had significantly larger crook than studs from the thinning stand. However, the difference was significant only for split-pith studs from middle logs. Tree height class had no effect on crook. Forsberg (1997) concluded that neither site index nor tree height class had any significant influence on warp.

3.3.8 Influence of wood properties on twist, crook and bow

Percentage of corewood in the stud and distance from pith to the centre of the stud are the most important factors for the development of twist (Table 15). Cambial age of the last growth ring included in the stud also had a fairly high correlation coefficient. None of the parameters substantially explained the variation in crook and bow. This is in accordance with studies by e.g. Danborg 1994c, Perstorper 1994b and Forsberg 1997.

Table 15. Coefficients of correlation (R) for twist, crook, bow and material parameters (N=485). Spiral grain angle (GA), ring width (RW), corewood -10 rings ($CORE_{10}$), ring number from pith (RNR) and distance from pith (DIST).[5]

	Twist	Crook	Bow	GA	RW	$CORE_{10}$	RNR	DIST
Twist	1.00	-	-	-	-	-	-	-
Crook	0.02	1.00	-	-	-	-	-	-
Bow	0.32^{***}	0.12^{**}	1.00	-	-	-	-	-
GA	0.24^{***}	0.04	0.10^{*}	1.00	-	-	-	-
RW	0.09^{*}	-0.01	0.02	0.008	1.00	-	-	-
$CORE_{10}$	0.61^{***}	0.009	0.22^{***}	0.04	0.33^{***}	1.00	-	-
RNR	-0.38^{***}	-0.10^{*}	-0.18^{***}	-0.06	-0.40^{***}	-0.63^{***}	1.00	-
DIST	-0.58^{***}	-0.07	-0.24^{***}	-0.06	-0.06	-0.77^{***}	0.77^{***}	1.00

In the multiple regression analysis, grain angle, presence of compression wood, growth ring curvature, growth ring width, distance from pith to centre of stud, last growth ring number and proportion of corewood in stud were tested as independent variables.

<u>Twist</u>

Growth ring width and presence of compression wood did not affect twist. The best individual variables to explain the variation in twist were the proportion of corewood in the stud, distance from pith to centre of stud and grain angle.

Figures 26 and 27 show the relationship between twist and proportion of corewood and between twist and distance from pith, respectively.

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[5] Levels of significance: $p>0.05$ NS, $p\leq 0.05^{*}$, $p\leq 0.01^{**}$, $p\leq 0.001^{***}$.

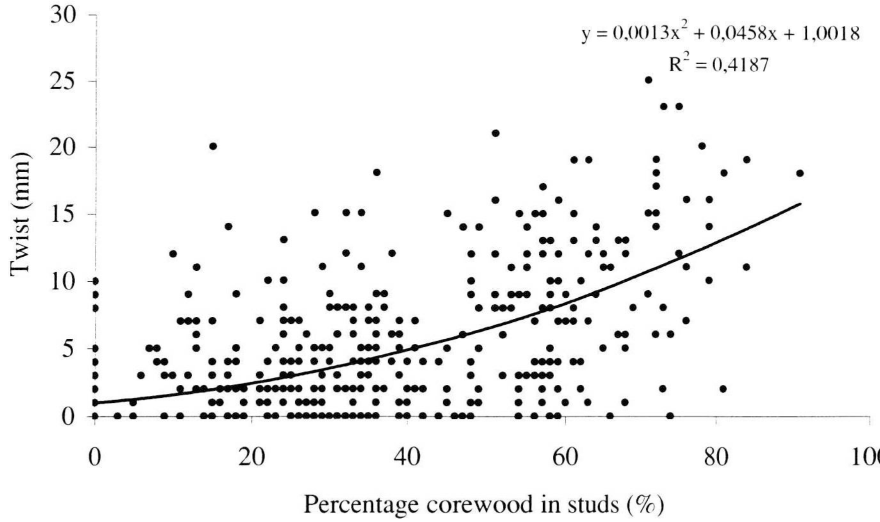


Figure 26. The relationship between twist and proportion of corewood, defined as 10 rings closest to the pith - all studs in the material.

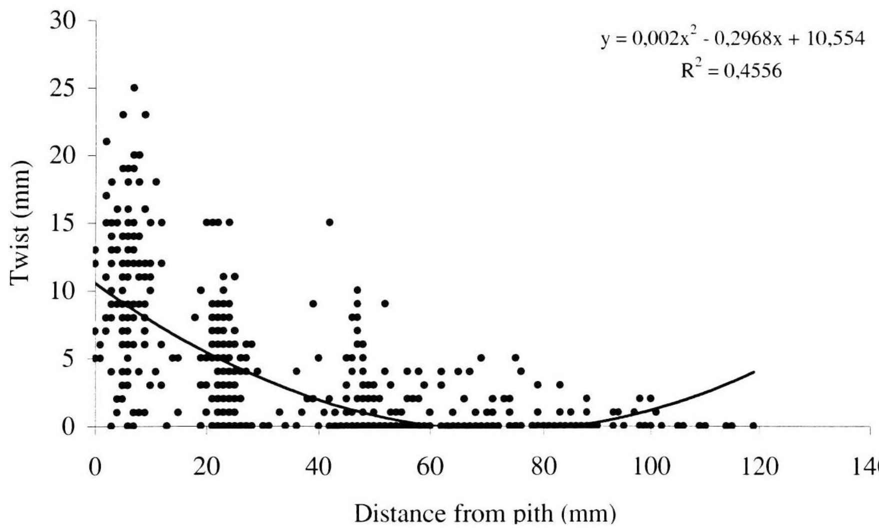
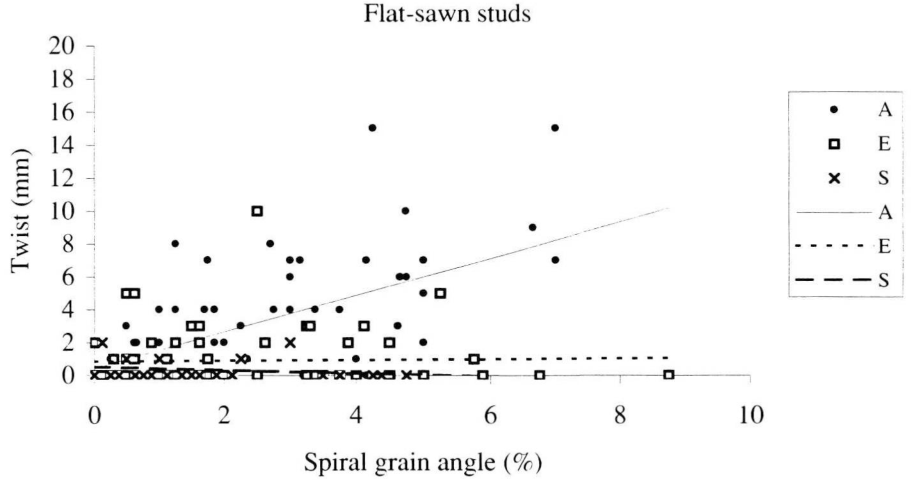


Figure 27. The relationship between twist and distance from pith - all studs in the material.

Twist increased with the proportion of corewood in the studs, whereas twist decreased with increasing distance from pith.

The relationship between twist and grain angle was weak if all types of studs were included in the same regression (R^2=0.09). For studs from butt logs, R^2 was 0.14 and 0.11 for flat-sawn and quarter-sawn studs, respectively. Forsberg (1997), studied flat-sawn boards of Norway spruce, and found that grain angle accounted for 40% of the variation in twist, whereas Perstorper (1994b) could explain only 14% of the variation in twist by grain angle in flat-sawn studs from butt logs.

The influence of grain angle on twist was highly dependent on distance from pith to centre of stud. The relationship between twist and grain angle was stronger closer to pith than further out. This indicates that the combination of corewood properties, e.g growth ring orientation and grain angle, affect the development of twist (Figure 28 and Table 16).



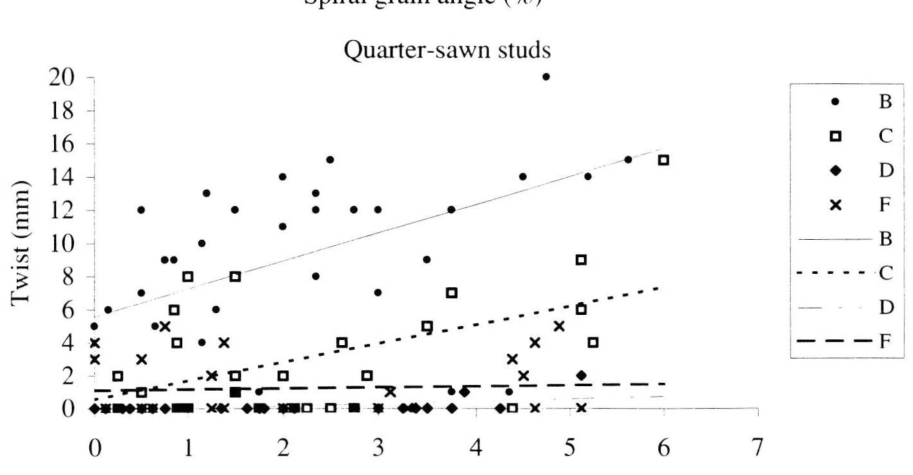


Figure 28. The relationship between twist and grain angle for different groups of butt log studs.

Table 16. Relationships between twist (T) and grain angle (GA) for different groups of butt log studs (T = a + b * GA).

Group	N	Regression equation	R^2
B	31	T = 6.67 + 1.42 * GA	0.20^{*}
A	62	T = 0.40 + 1.12 * GA	0.35^{***}
C	29	T = 0.85 + +.95 * GA	0.23^{**}
E	69	T = 0.85 + 0.02 * GA	0.0007
D	27	T = -0.16 + 0.14 * GA	0.27^{**}
F	30	T = 1.10 + 0.06 * GA	0.004
S	26	T = 0.51 - 0.10 * GA	0.04

The models for stud groups A, B, C and D were highly significant, whereas twist in outer studs, E, F and S was not significantly affected by the size of the grain angle. Studs from the different groups showed different twist for the same spiral grain angle, twist in boxed-pith studs was severe even for small grain angles. According to the models, boxed-pith studs will have a twist of 14 mm, whereas average twist of flat-sawn studs without pith will be less than 1 mm for a grain angle of 5%. This is in accordance with Balodis (1972) who concluded that the magnitude of twist is proportional to the ratio of grain angle and distance from pith. Thus, serious twist should occur only in boards cut close to the pith.

Table 17 shows the result of the final regression analysis for twist. From the table it can be seen that grain angle was included in every model together with amount of corewood or distance from pith (R^2=0.43-0.53 and 0.41-0.78, respectively). The low coefficients of correlation between grain angle and amount of corewood (R=0.03) and grain angle and distance from pith (R=-0.07) show that the variables were independent (Table 15).

Table 17. Results of final regression analysis showing material parameters that significantly affected twist and proportion of twist explained by the model (R^2). Spiral grain angle (GA), corewood - 10 rings ($CORE_{10}$) and distance from pith (DIST).

Group of studs	N	Variables in model	Model R^2
All	532	GA, $CORE_{10}$, GA*$CORE_{10}$	0.47^{***}
Thinning stand studs	206	GA, DIST	0.41^{***}
Final felling stand studs	326	GA, $CORE_{10}$, GA*$CORE_{10}$	0.49^{***}
Top log studs	140	GA, DIST, GA*DIST	0.41^{***}
Middle log studs	106	GA, DIST	0.44^{***}
Butt log studs	271	GA, $CORE_{10}$, GA*$CORE_{10}$	0.46^{***}
Thinning stand			
- top log studs	71	GA, DIST, GA*DIST	0.44^{***}
- middle log studs	40	GA, DIST, GA*DIST	0.78^{***}
- butt log studs	95	GA, DIST	0.38^{***}
Final felling stand			
- top log studs	69	GA, DIST, GA*DIST	0.39^{***}
- middle log studs	84	GA, $CORE_{10}$, GA*$CORE_{10}$	0.65^{***}
- butt log studs	160	GA, DIST, GA*DIST	0.39^{***}

The importance of distance from pith has also been demonstrated by Perstorper (1994b), in the model for flat-sawn, butt-log studs the value of R^2 varied between 0.49 and 0.64 when both grain angle and distance from pith were included.

In this study, highest values of R^2 were found for groups of studs from middle logs. One reason could be that these logs only came from the largest trees in each stand and had the largest variation in wood properties.

Crook and bow

Neither the simple linear regressions with one independent variable, nor the stepwise multiple regression analyses showed any strong significant relationships between the variables tested and crook or bow.

Of the parameters studied, presence of compression wood was the only one that had an effect on the development of crook and bow. Studs from middle or butt logs in the final felling stand containing compression wood had on average larger crook than compression wood studs from top logs (Figure 29).

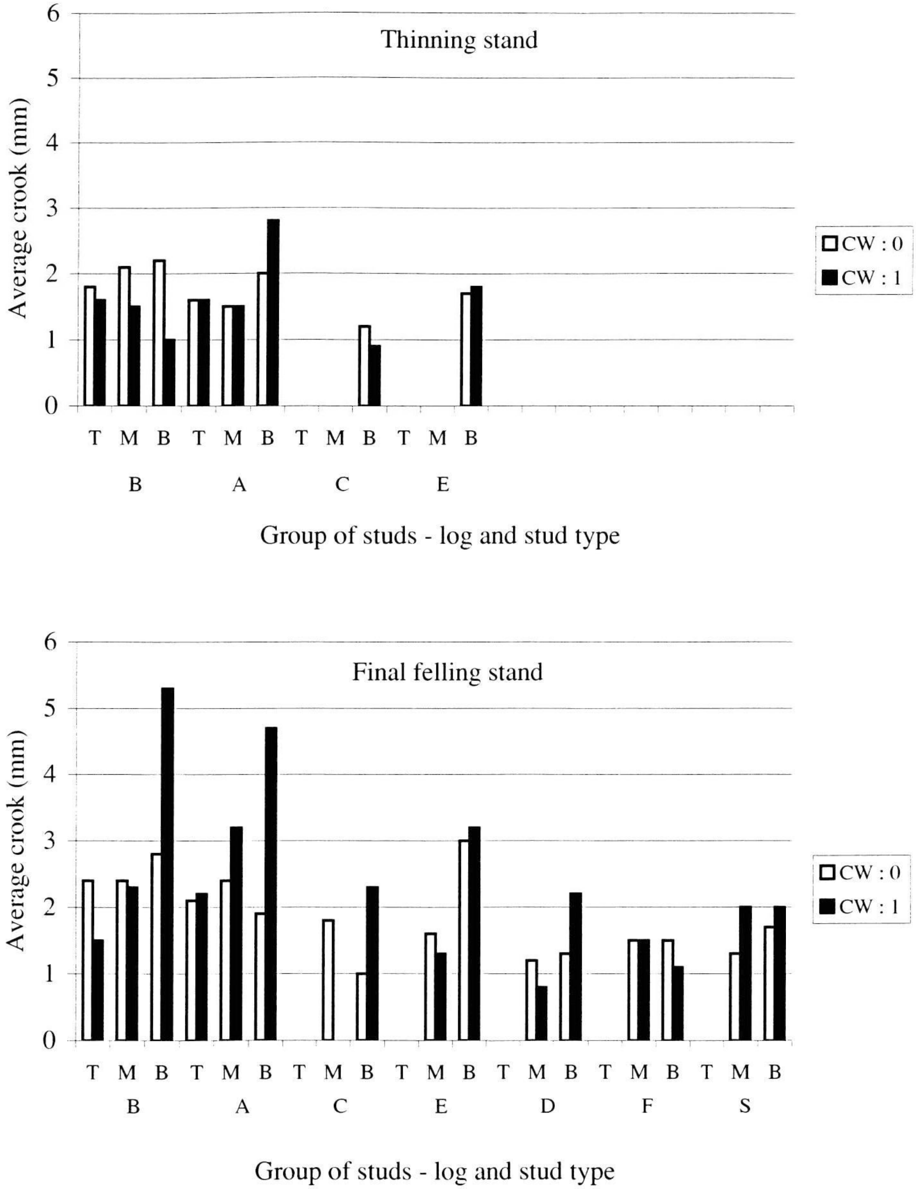
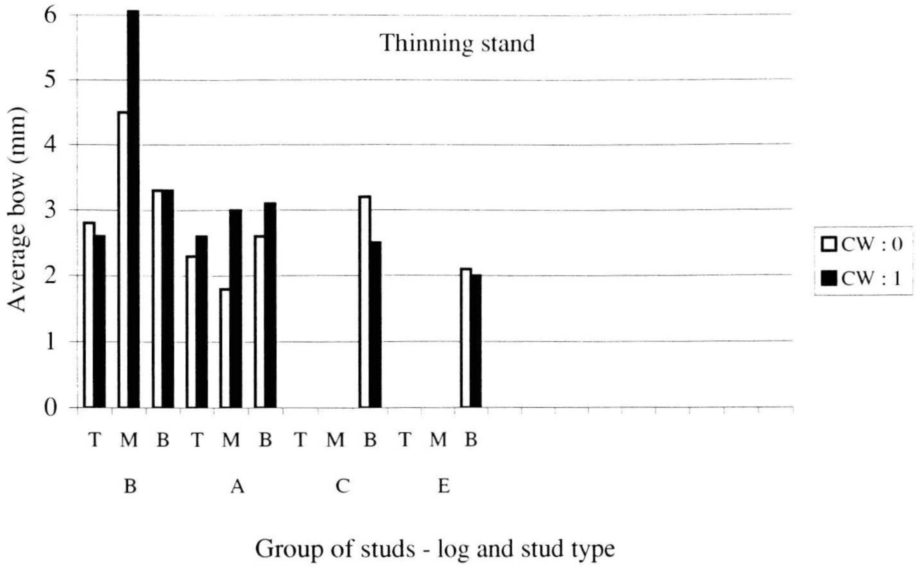


Figure 29. Influence of compression wood (CW) on the amount of crook for stud groups from the thinning stand and the final felling stand (T=top log, M=middle log, B=butt log).

Middle log studs from the final felling stand with visible compression wood had larger bow than studs where no compression wood was visible (Figure 30). Studs from the thinning stand did not show any of these differences.



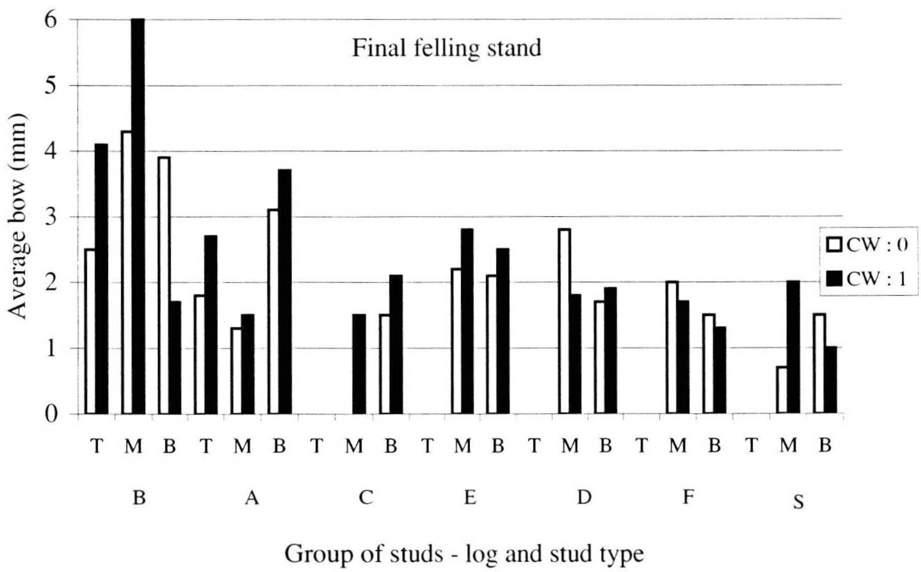


Figure 30. Influence of compression wood (CW) on the amount of bow for stud groups from the thinning stand and the final felling stand (T=top log, M=middle log, B=butt log).

For both crook and bow there was also an effect of type of stud: studs from the core, group A and B, were influenced by compression wood more than studs further from the pith.

Warensjö and Lundgren (1998), studied split-pith studs from butt logs of Norway spruce and found that compression wood accounted for about 20% of the variation in crook and bow.

3.4 Conclusions

Based on the results of this study, the following conclusions can be drawn:

- Sawing pattern, i.e. ring orientation and distance from pith, had the largest impact on final quality of the sawn timber.
- By using a sawing pattern where the ten innermost rings were excluded almost all studs were accepted according to the end-user requirements after drying.
- Warp development was much lower in studs not including pith irrespective of whether the stud was quarter-sawn or flat-sawn.
- Stand age, tree height class and longitudinal position had no significant effect on warp development.
- Percentage of corewood in the studs significantly affected development of twist during drying. As corewood is defined as a certain number of rings from the pith, growth rate in the corewood cylinder plays a major role in identifying logs not suitable for products that need to be stable.
- Crook and bow was affected by presence of visible compression wood in the stud.
- Compression wood in butt logs seemed to have a larger negative effect than this type of wood developed further up in the tree.

4 Influence of changes in moisture content on warp

4.1 Introduction

4.1.1 Background

After kiln-drying at the sawmill sawn timber is stored, transported and handled at, for example, a building site and may be stored outside in rain, snow or sunshine. Finally, the studs are incorporated in buildings where they are exposed to low relative humidities (RH) when the heating is activated. During these stages, moisture content in the air changes and because wood is a hygroscopic material, it strives to reach the equilibrium moisture content.

4.1.2 Aim of the study

The aim of this study was to illustrate what happens to wood exposed to severe moisture changes after drying, and also to study differences in sensitivity to changes in moisture content for studs produced by the different sawing patterns.

4.2 Material and methods

4.2.1 Material and preparation of specimens

A sample of studs from the original material described in chapter 3 was used in this study. Studs of six types, three flat-sawn and three quarter-sawn, from the original material were exposed to four different moisture stages in a climate room. In total, 143 butt log studs were included, the experimental design is shown in Figure 31[6]. Experimental work was done by researchers at Division of Steel and Timber Structures at Chalmers University of Technology in Gothenburg.

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[6]This experimental setup was originally described in Johansson et al. 1999.

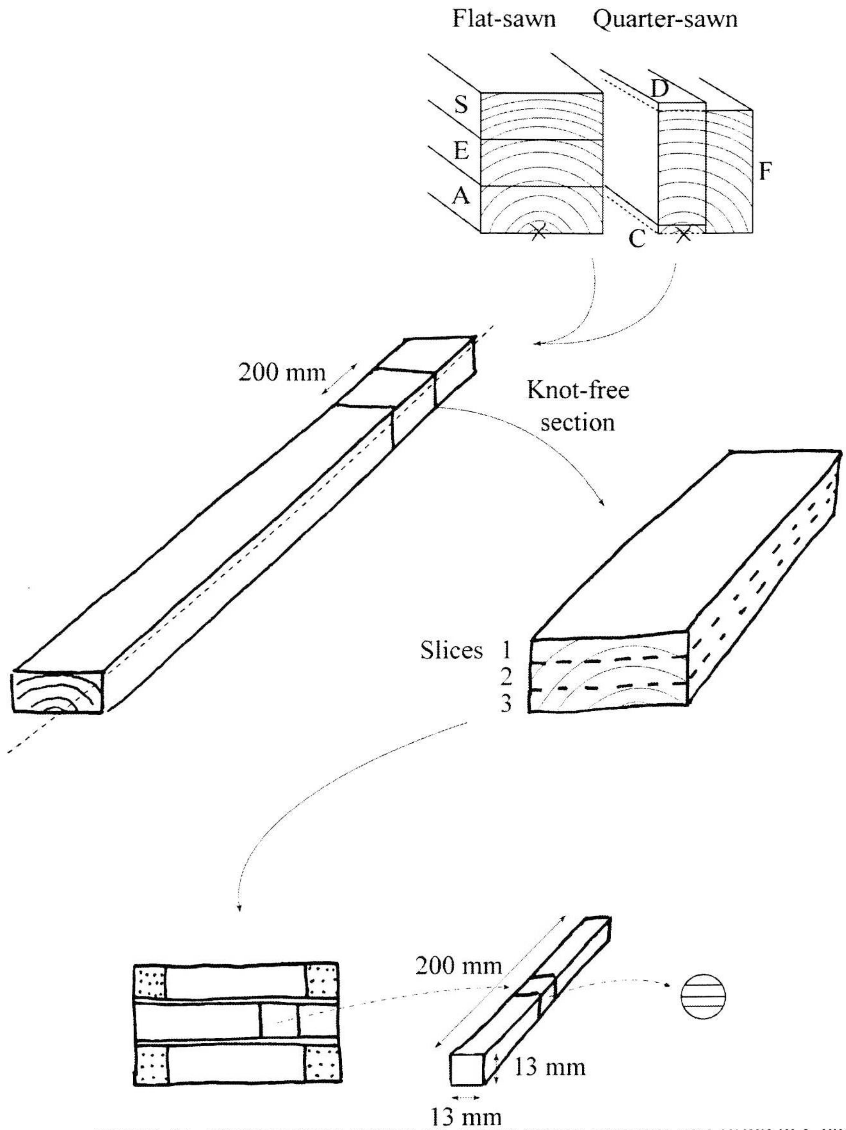


Figure 31. Experimental design for the moisture cycling test done at Chalmers University of Technology (adapted from Perstorper et al. 1999).

From the top-end of each stud, a 200-mm long, more or less, knot-free section was cut. This section was ripped into three slices (1, 2 and 3) each 13 mm thick. The slices were cut into five sticks, measuring 13 x 13 x 200 mm, i.e. one from each corner and one in the middle. The sticks from the middle slice (2) were cut at a position were the edges coincided well with the radial and tangential directions. A small rivet with a rounded head was mounted on the end of each stick to create a distinct measurement point for the longitudinal shrinkage. A small part of the stick from slice 2 was turned to increase precision and to facilitate measurement of the radial and tangential shrinkage.

4.2.2 Moisture stages

The studs and sticks were placed in a climate room and measured at four moisture stages (Table 18). Every stud was weighed at the end of each moisture stage to determine the moisture content. The studs were hung vertically to eliminate restraint on the material.

Table 18. Average moisture contents at the four moisture stages.

Moisture stage	Temperature	Relative humidity	Duration	Moisture content at the end of conditioning period
1	20°C	85%	6 months	15.6 %
2	20°C	30%	5 months	7.2 %
3	20°C	85%	4 months	14.4 %
4	20°C	30%	3 months	7.8 %

Due to the hysteresis effect and that the relative humidity in the climate room was not exactly the same as at the starting point, the original moisture content was not reached in the second moisture cycle (Perstorper et al. 1999).

4.2.3 Measurement of warp

On studs, twist, crook and bow were measured at the end of each moisture stage when equilibrium was reached. A device for warp measurements based on digital transducers has been developed at Department of Steel and Timber Structures at Chalmers University of Technology (Appendix B5).

Warp in all studs was measured four times, i.e. at the end of each moisture stage.

The total change in warp between the moisture stages is a function of the magnitude and the direction of the warp. Positive and negative directions were therefore defined as described by Mishiro and Booker (1988).

4.2.4 Measurement of material parameters

<u>Density and ring width</u>

Density, ρ, was determined on the basis of the weight and volume of the sticks according to the following equation:

$$\rho = m_u/(L_l * L_r * L_t) \qquad (kg/m^3) \qquad (4.1)$$

where m_u = mass at moisture content u
L_l = longitudinal length
L_r = radial length
L_t = tangential length.

The sticks were measured for weight, length, tangential and radial width at the end of the first two moisture stages. Tangential and radial width were measured only on the centre stick. All sticks were finally dried at 103° C and weighed to determine the moisture content.

Compression wood and knots

Because it was not always possible to cut out a perfectly "clear" section from the studs, the sticks were visually examined for compression wood and knots. The sticks were classified into three groups: 0 - "no compression wood"; 1 - "widened latewood-like band in one or several growth rings" and 2 - "dominating latewood-like bands in one or several growth rings" (Perstorper et al. 1999). Presence of knots were registered as 0 - "no knots" and 1 - "knots present".

Shrinkage

All five sticks were used to determine shrinkage properties in the longitudinal direction. The sticks from section 2, with a clear radial and tangential face, were used to determine transverse shrinkage properties.

A device based on digital displacement transducers was used for the shrinkage measurements. Effort was made to ensure that the position of the stick should be the same for each measurement. A high degree of repeatability was therefore reached. The maximum deviations for repeated recordings were about 0.003 mm and 0.010 mm for the longitudinal and transverse measurements, respectively. The device is described by Bengtsson (1997).

The sticks were weighed at moisture stages one and two as well as after oven-drying. The moisture content, u, was determined according to the following equation:

$$u=\left((m_u - m_0)/m_0\right) \times 100 \quad (\%) \tag{4.2}$$

where m_u = mass before drying
m_0 = mass after drying at 103° C.

The shrinkage strain, ε, was obtained from the changes in the dimensions between moisture stages one and two as:

$$\varepsilon = \left((L_1 - L_2)/ L_1 \right) \times 100 \quad (\%) \tag{4.3}$$

where L_1 = size at moisture stage 1
L_2 = size at moisture stage 2

To determine the average shrinkage coefficients, α, between any two moisture stages, i.e. percentage of shrinkage per percentage of change in moisture content, the shrinkage strains were divided by the change in moisture content and determined as:

$$\alpha = \varepsilon / (u_1 - u_2) \qquad (\%/\%) \qquad (4.4)$$

where u_1 = moisture content at stage 1
u_2 = moisture content at stage 2

4.2.5 Statistical evaluation

As in chapters 2 and 3, the SAS system was used to evaluate data (Anon. 1990). The General Linear Models (GLM) and MIXED procedures as well as chi-square test were used.

4.3 Results and discussion

4.3.1 Moisture content

There was no significant difference in moisture content among stud types at any of the moisture stages.

Table 19. Average values of moisture content (MC) at the four moisture stages. Number of observations (N), arithmetic mean value and standard deviation ().

Stud group	N	Moisture content (%) at stage			
		1	2	3	4
All	137	15.5 (0.5)	7.0 (0.4)	14.1 (0.5)	7.6 (0.5)
Flat-sawn					
- A	20	15.4 (0.3)	7.2 (0.3)	14.2 (0.3)	7.7 (0.3)
- E	42	15.5 (0.2)	7.0 (0.2)	14.1 (0.2)	7.6 (0.3)
- S	15	15.4 (1.2)	7.0 (1.1)	14.0 (1.2)	7.6 (1.1)
Quarter-sawn					
- C	23	15.5 (0.3)	7.0 (0.3)	14.0 (0.4)	7.7 (0.4)
- D	15	15.4 (0.2)	7.0 (0.3)	14.0 (0.2)	7.6 (0.3)
- F	22	15.4 (0.3)	7.0 (0.3)	14.0 (0.4)	7.5 (0.5)

4.3.2 Density and ring width

Average ring width in logs from the thinning stand was significantly larger than ring width in logs from the older stand, 2.5 mm and 1.8 mm, respectively. Density measured on sticks at moisture stage 2 was, as expected, significantly larger in the slow-grown final felling stand than in the thinning stand, 517 and 481 kg/m^3, respectively.

There was small radial increase in density from pith to bark, which relates to the decrease in ring width from pith to bark in logs from both stands.

4.3.3 Compression wood and knots

17% of the sticks contained wood classified as compression wood, according to the definition in section 4.2.4. However, the classification of compression wood was very rough and no severe compression wood was found in the sticks. Knots, mostly pin knots, were present in one-third of the sticks.

4.3.4 Shrinkage parameters

Longitudinal shrinkage

There was no significant difference in longitudinal shrinkage for the material from the two stands. The mean value of the longitudinal shrinkage coefficient was 0.0072 (Table 20). This value is in agreement with other studies of Norway spruce, e.g. Niemz et al. (1993), Persson (1997) and Perstorper et al. (1999).

According to Figures 32a and b there was a small, but significant decrease in longitudinal shrinkage from pith to bark. A decrease in longitudinal shrinkage from pith to bark has been reported by several authors e.g. Persson (1997), Perstorper et al. (1999).

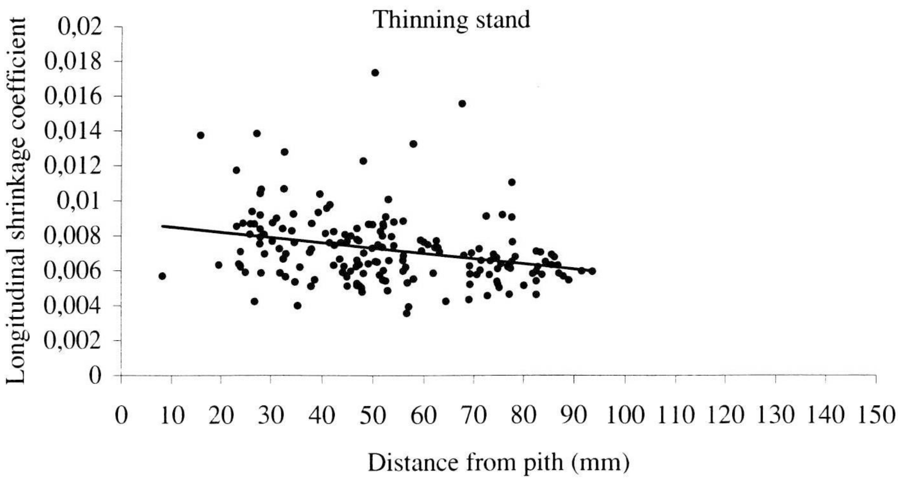


Figure 32a. Radial variation of longitudinal shrinkage coefficient measured on sticks from the thinning stand.

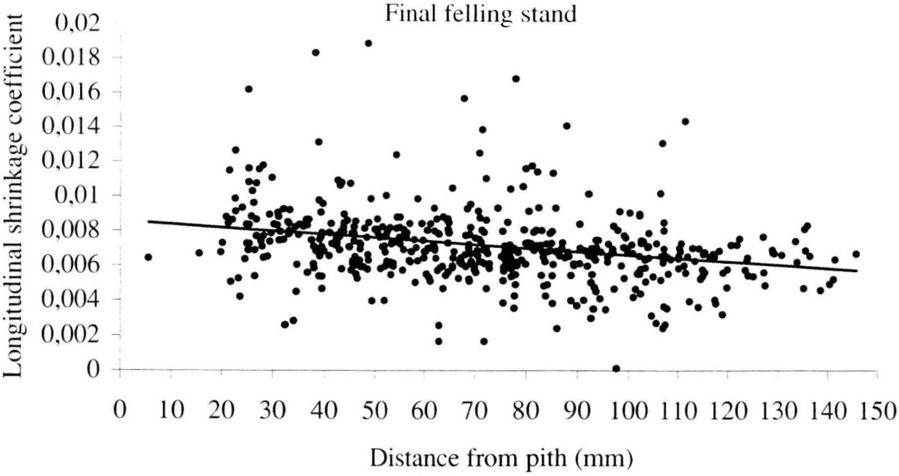


Figure 32b. Radial variation of longitudinal shrinkage coefficient measured on sticks from the final felling stand

Since the direction and magnitude of shrinkage is largely controlled by the microfibril angle in the S2-layer, which is largest close to the pith, the longitudinal shrinkage is also largest in this area and decreases towards the bark. The smaller microfibril angle in the latewood compared to the earlywood in the same growth ring makes latewood shrink less in the longitudinal direction (Trendelenburg and Mayer-Wegelin 1955, Kyrkjeeide 1990). As ring width decreases towards the bark the proportion of latewood increases, which also contributes to this radial trend in longitudinal shrinkage.

Radial and tangential shrinkage

There was a significant difference for both radial and tangential shrinkage coefficients between sticks from the two stands. Shrinkage was larger in sticks from the older stand compared to the thinning stand. Radial shrinkage coefficients for sticks from the thinning stand and final felling stand were 0.17 and 0.20, respectively. The average tangential shrinkage coefficient for sticks from the thinning stand was 0.35 and for sticks from the final felling stand 0.38. These findings are in accordance with e.g. Perstorper et al. (1999). Persson (1997) showed that radial and tangential shrinkage coefficients decreased with increasing microfibril angle and the difference between stands could be explained by the larger percentage of latewood in the slower-growing final felling stand, which leads to a smaller average fibril angle.

Radial shrinkage showed no significant variation from pith to bark, but there was a tendency for radial shrinkage to increase towards bark. Sticks from the final felling stand showed a significant increase in tangential shrinkage coefficient from pith to bark. No radial trend was found for sticks from the thinning stand.

4.3.5 Summary of material data

Average values for the material in this study are summarized in Table 20.

Table 20. Summary of material data - measured on sticks. Number of observations (N), arithmetic mean value and standard deviation ( ). Measurements on all sticks - moisture content and longitudinal shrinkage coefficient. Measurements on the middle stick - radial and tangential shrinkage coefficients.

Property	N	All	Thinning	Final felling
- at moisture stage 2	140	508 (58)	481 (32)	517 (62)
Moisture content (%)				
- at stage 1	700	15.5 (1.1)	15.8 (0.4)	15.4 (1.2)
- at stage 2	700	7.0 (0.9)	7.0 (0.4)	7.0 (1.0)
Shrinkage coefficients (% / %)				
- longitudinal	700	0.007 (0.003)	0.007 (0.002)	0.007 (0.003)
- radial	140	0.19 (0.04)	0.17 (0.03)	0.20 (0.05)
- tangential	140	0.38 (0.05)	0.35 (0.05)	0.38 (0.05)
Shrinkage ratio (-)				
- α_t / α_r	140	2.1 (0.4)	2.1 (0.4)	2.0 (0.4)
- α_r / α_l	140	29.5 (15.6)	24.2 (8.1)	31.3 (17.0)
- α_t / α_l	140	58.6 (26.0)	50.4 (15.1)	61.4 (28.3)

In Table 21, coefficients of correlation (R) for the material parameters are shown. Radial and tangential shrinkage were highly correlated to density. Also longitudinal shrinkage was related to density, but the relationship was weaker. Density is associated to the amount of latewood in growth rings, and transverse shrinkage is larger in latewood than in earlywood whereas longitudinal shrinkage is larger in earlywood. The ratio of tangential and radial shrinkage decreased with increasing density, i.e. wood of higher density had a lower degree of anisotropy. Distance from pith also influenced tangential shrinkage coefficient.

Table 21.Coefficient of correlation (R) for material parameters- only values from the centre stick was used and sticks with knots were omitted (N=94). DENS = density based on weight and volume at moisture stage 2 (u~7%) [7], DIST = distance from pith and MC-DIFF = Difference in moisture content between moisture stage 1 and 2.

	α_l	α_r	α_t	α_t / α_r	α_r / α_l	α_t / α_l	DENS	DIST	MC-DIFF
α_l	1.00	–	–	–	–	–	–	–	–
α_r	–0.36***	1.00	–	–	–	–	–	–	–
α_t	–0.29**	0.54***	1.00	–	–	–	–	–	–
α_t / α_r	0.25*	–0.80***	0.03	1.00	–	–	–	–	–
α_r / α_l	–0.73***	0.56***	0.30**	–0.45***	1.00	–	–	–	–
α_t / α_l	–0.79***	0.37***	0.39***	–0.18	0.94***	1.00	–	–	–
DENS	–0.35***	0.69***	0.52***	–0.44***	0.58***	0.51***	1.00	–	–
DIST	–0.12	0.08	0.32**	0.12	0.22*	0.31**	0.29**	1.00	–
MC-DIFF	0.14	–0.08	–0.21*	–0.01	–0.13	–0.19	–0.19	–0.34***	1.00

[7] Levels of significance : ns p>0.05, * p≤ 0.05, ** p≤0.01, ***p≤0.001

4.3.6 Influence of moisture cycling on warp

Twist

Warp, especially twist, was influenced by changes in relative humidity in the environment where the studs were stored. Average values for twist increased from 1.7 to 4.0 mm when RH changed from 85% at moisture stage 1 to 30% at stage 2. As RH increased from stage 2 to 3, twist decreased to 2.5 mm and finally increased again to 4.2 mm at the last stage in the moisture cycle. However, stud types differed significantly. Studs containing pith, i.e. A and C, showed the largest change in twist as moisture content changed. Within each group of studs, flat-sawn and quarter-sawn, there was a radial trend, decreasing twist towards bark. In Table 22, average values of twist for the studs are shown.

Table 22. Average values for twist (absolute value) at the four moisture stages. Number of observations (N), arithmetic mean value and standard deviation ( ).

Stud group	N	Twist (mm) at moisture stage			
		1	2	3	4
All	137	1.7 (1.5)	4.0 (3.5)	2.5 (2.3)	4.2 (3.7)
Flat-sawn					
- A	20	2.6 (2.0)	6.3 (4.8)	3.8 (3.2)	6.4 (5.0)
- E	42	1.6 (1.4)	3.8 (3.3)	2.3 (2.2)	4.0 (3.4)
- S	15	0.9 (0.5)	2.1 (1.2)	1.2 (0.7)	2.2 (1.2)
Quarter-sawn					
- C	23	2.5 (1.7)	5.6 (4.2)	3.8 (2.7)	6.2 (4.6)
- D	15	1.0 (0.8)	2.5 (1.6)	1.4 (1.4)	2.6 (1.7)
- F	22	1.2 (0.7)	3.0 (1.5)	1.8 (1.3)	3.1 (1.6)

The size of the changes in twist between the moisture stages were significant for all stud types. When moisture content decreased (first and last cycle) average twist increased by more than 3 mm for studs containing pith and varied between 1.0 and 2.1 mm for outer studs. During the second moisture cycle, when moisture content increased, twist decreased by 1.0-2.5 mm.

The effect of sawing pattern on changes in twist during drying and rewetting is shown in Figure 33.

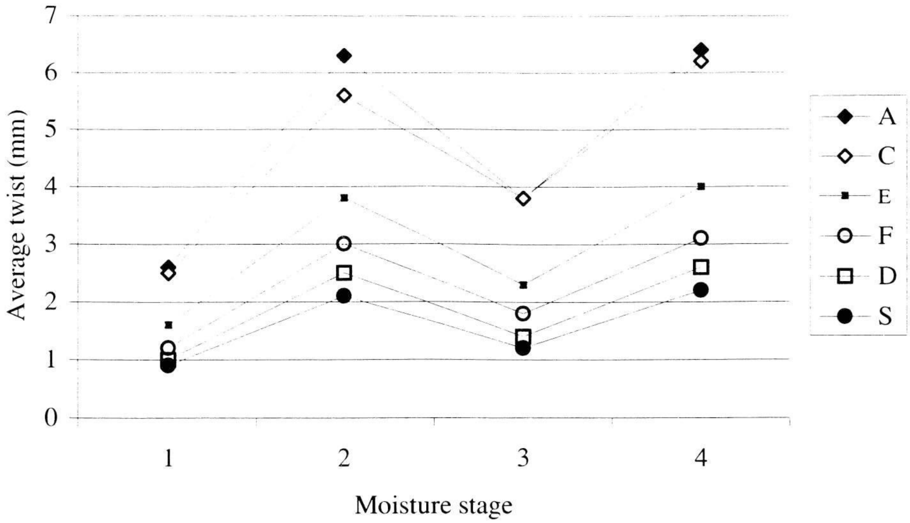


Figure 33. Average twist for different groups of studs at each moisture stage.

Clearly the largest changes occurred in studs containing pith (A and C), approximately equal for flat-sawn and quarter-sawn studs.

There were very strong correlations between twist at the different moisture stages for all studs and for each type of stud through the whole moisture cycling. The relationship between twist at moisture stage 1 and 2 for all studs is illustrated in Figure 34. Correlations of about equal strength were also found by Johansson et al. (1999).

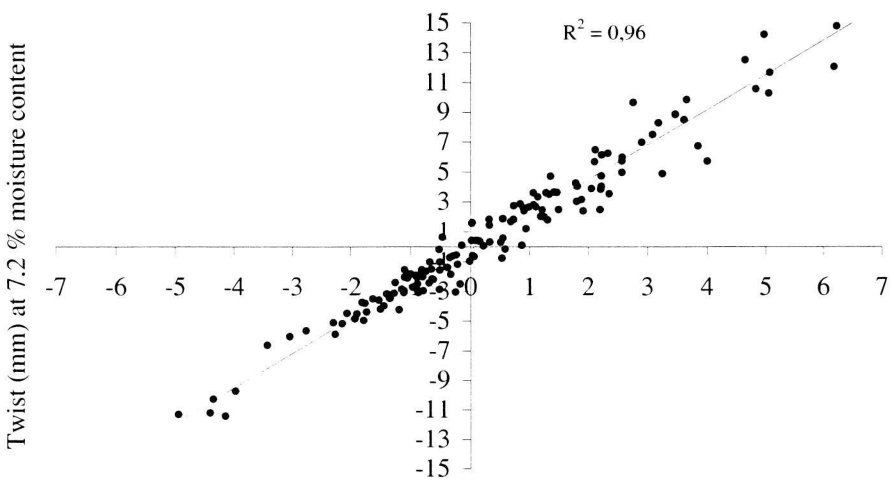


Figure 34. Relationship between twist measured at the first and second moisture stages (R^2=0.96***).

There was no significant correlation between twist in green condition and twist after drying, (values from chapter 3), i.e. twist directly after sawing could not be used as a criterion for sorting out twist-prone studs before drying. This was also concluded by Forsberg (1997).

Total change in twist, i.e. when direction of twist was considered, was of the same size as the change in absolute values. Thus, twist did not seem to change direction during the moisture cycling.

Crook

Crook was also affected by changes in the surrounding climate, but not as much as twist. Mean values for crook measured at the four moisture stages, are shown in table 23.

Table 23. Average values for crook (absolute values) at the four moisture stages. Number of observations (N), arithmetic mean value and standard deviation ( ).

Stud group	N	Crook (mm) at moisture stage			
		1	2	3	4
All	137	1.7 (1.5)	2.1 (1.9)	1.6 (1.4)	2.0 (1.7)
Flat-sawn					
- A	20	2.3 (1.8)	2.9 (2.4)	2.3 (1.7)	2.7 (2.0)
- E	42	1.7 (1.5)	2.1 (1.8)	1.6 (1.5)	1.9 (1.7)
- S	15	1.3 (1.0)	1.6 (1.3)	1.3 (0.8)	1.5 (1.1)
Quarter-sawn					
- C	23	1.8 (1.6)	2.4 (1.9)	1.8 (1.4)	2.4 (1.8)
- D	15	1.6 (1.5)	2.2 (2.1)	1.6 (1.3)	2.0 (1.9)
- F	22	1.3 (1.0)	1.6 (1.6)	1.1 (1.1)	1.5 (1.6)

Crook increased with decreasing moisture content and decreased when moisture content increased. Changes in absolute values of crook were too small to be important for the product quality of studs and was not statistically significant. Largest changes appeared in quarter-sawn studs. In Figure 35 the effect of sawing pattern on change in crook during drying and rewetting is illustrated.

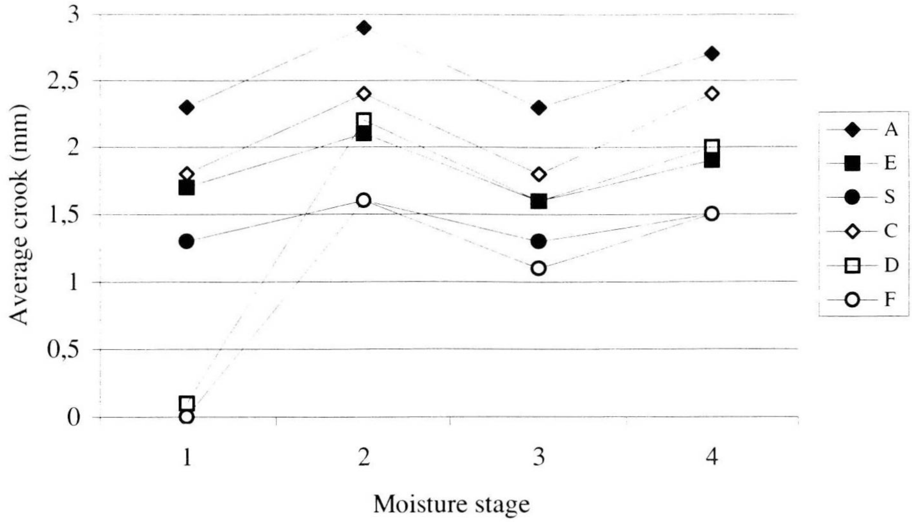


Figure 35. Average crook for different groups of studs at each of the moisture stages.

The changes in crook were reversible when moisture content reverted to its original level.

When not only the magnitude, but also the direction of crook was considered, total changes in crook were larger than average changes when only absolute values were studied. Many studs changed the direction of crook as the surrounding climate changed. This was also shown by Mishiro and Booker (1988) in their study of Radiata pine. Stud types differed significantly. Quarter-sawn studs had a significant larger total movement when the surrounding climate changed compared to flat-sawn; average values for total change in crook are shown in Table 24.

Table 24. Total changes in moisture content (MC-DIFF) and crook (CR-DIFF) between stages in the moisture cycle.

Stud group		Moisture stages					
		1 - 2		2 - 3		3 - 4	
	N	MC-DIFF	CR-DIFF	MC-DIFF	CR-DIFF	MC-DIFF	CR-DIFF
All	137	- 8.4	1.2	7.0	- 1.0	- 6.4	1.0
Flat-sawn							
- A	20	- 8.3	1.3	7.1	- 1.1	- 6.5	1.2
- E	42	- 8.5	0.7	7.0	- 0.6	- 6.4	0.6
- S	15	- 8.4	0.8	7.0	- 0.6	- 6.4	0.5
Quarter-sawn							
- C	23	- 8.5	2.2	7.0	- 1.5	- 6.4	1.7
- D	15	- 8.4	1.4	7.0	- 1.0	- 6.5	1.1
- F	22	- 8.5	1.2	7.0	- 0.8	- 6.4	0.9

Crook measured at moisture stage 1, i.e. 15.6%, correlated well with crook measured at moisture stage 2, i.e. 7.2% (R^2=0.67-0.91).

Comparison of crook in green condition with crook after first drying, (values from chapter 3), showed much lower correlation, i.e. crook in green condition could not be used as a criterion for sorting out studs prone to develop severe crook during drying. One reason could be that the direction of crook was not considered in that study. Forsberg (1997) found a significant, but weak correlation between crook in green and dry condition.

Bow

Average changes in absolute values of bow were of the same size as for crook, 0.6 and 0.5 mm increase during the first and third moisture cycle, respectively. During the second cycle bow decreased by 0.6 mm. In Table 25, average values for bow at the four moisture stages are shown.

Table 25. Average values for bow (absolute values) at the four moisture stages. Number of observations (N), arithmetic mean value and standard deviation ( ).

Stud group		Bow (mm) at moisture stage			
	N	1	2	3	4
All	137	2.4 (2.1)	3.0 (3.1)	2.5 (2.1)	2.9 (2.9)
Flat-sawn					
- A	20	3.5 (2.1)	4.4 (4.5)	3.8 (2.4)	4.3 (4.1)
- E	42	2.2 (1.9)	3.0 (3.1)	2.2 (2.0)	2.8 (3.0)
- S	15	1.0 (0.7)	1.0 (0.8)	1.2 (0.7)	1.2 (0.7)
Quarter-sawn					
- C	23	3.0 (2.6)	3.7 (2.7)	3.2 (2.6)	4.0 (2.9)
- D	15	1.6 (1.4)	2.1 (1.9)	1.7 (1.2)	2.1 (1.9)
- F	22	2.6 (2.1)	2.7 (2.7)	2.2 (2.5)	2.5 (2.6)

There was a significant difference in average values of bow among different types of studs and a radial trend within groups of studs, i.e. flat-sawn and quarter-sawn. Studs containing pith, no matter if flat-sawn or quarter-sawn, showed the largest bow of all studs. As for crook, changes in bow were reversible when moisture content reverted to its original level.

During the dry cycle (15.6% -> 7%) bow increased in studs of type E, C and D, whereas bow in most S-studs decreased. For studs of type A and F, bow increased as well as decreased to the same extent. When moisture content reverted to the higher level, studs C and E reacted in the opposite way as before. Groups D, F and S did not change.

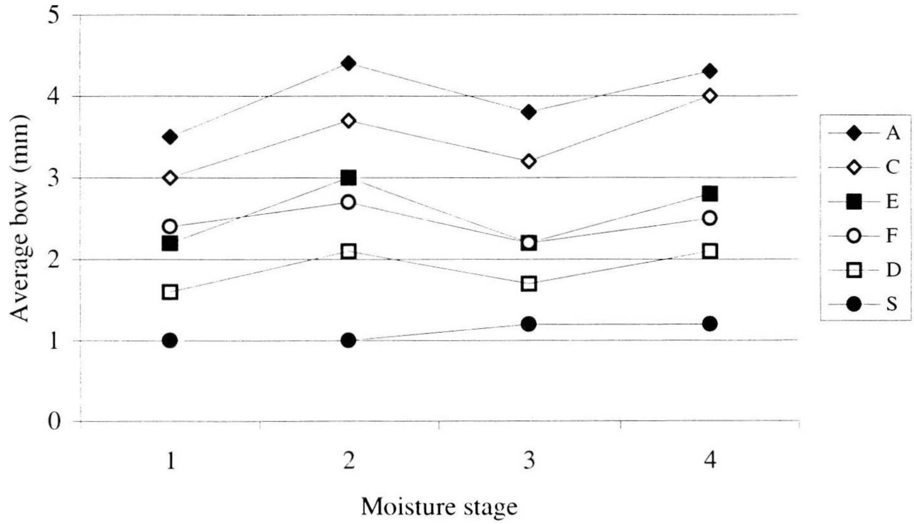


Figure 36. Average bow for different groups of studs at each moisture stage.

When not only the magnitude, but also the direction of bow were considered, total changes in bow were larger than average changes when only absolute values were studied. Thus, many studs changed the direction of bow as the surrounding climate changed. As for crook, this was also shown by Mishiro and Booker (1988) in their study of Radiata pine. Stud types differed significantly. Flat-sawn studs had a significantly larger total movement when the surrounding climate changed compared to quarter-sawn studs; average values of total change are shown in Table 26.

Table 26. Total changes in moisture content (MC-DIFF) and bow (B-DIFF) between stages in the moisture cycle.

Stud group		Moisture stages					
		1 - 2		2 - 3		3 - 4	
	N	MC-DIFF	B-DIFF	MC-DIFF	B-DIFF	MC-DIFF	B-DIFF
All	137	- 8.4	1.5	7.0	- 1.5	- 6.4	1.3
Flat-sawn							
- A	20	- 8.3	2.3	7.1	- 2.4	- 6.5	2.0
- E	42	- 8.5	1.8	7.0	- 1.9	- 6.4	1.6
- S	15	- 8.4	0.5	7.0	- 0.4	- 6.4	0.4
Quarter-sawn							
- C	23	- 8.5	1.4	7.0	- 1.2	- 6.4	1.1
- D	15	- 8.4	0.9	7.0	- 0.7	- 6.5	0.7
- F	22	- 8.5	1.3	7.0	- 1.2	- 6.4	1.0

There was a strong relationship between bow measured at the different moisture stages - R^2 for bow at moisture stage 1 and 2 varied between 0.71 and 0.86. The intervals of R^2 between moisture stage 2 and 3 and moisture stage 3 and 4 were 0.73-0.90 and 0.79-0.91, respectively. This means that the original bow had a large influence on bow in the following steps of the moisture cycles. The relationship was strongest for quarter-sawn studs.

Comparison of bow in green condition with bow after first drying, (values from chapter 3), showed much lower correlation, i.e. bow in green condition could not be used as a criterion for sorting out studs prone to develop severe bow during drying. One reason could be that the direction of bow was not considered in that study. As for crook, Forsberg (1997) found a significant, but weak correlation between bow at green and dry condition.

4.3.7 Influence of compression wood and knots on shrinkage

The presence of compression wood, classified as described in section 4.2.4, did not influence the shrinkage parameters. As the classification of compression wood used in this study was rough, it is difficult to say if it was compression wood that occurred as widened growth rings in 17% of the sticks, therefore this variable will not be considered from now.

Presence of knots was positively correlated with longitudinal shrinkage, but did not significantly influence the radial and tangential shrinkage coefficients. (Table 27). However, tangential and radial shrinkage tended to decrease if knots were present.

Table 27. Influence of knots on the shrinkage coefficients. Number of observations (N), arithmetic mean value and standard deviation ( ).

Knots		Shrinkage coefficients (% / %)			
	N	Longitudinal	N	Radial	Tangential
0	477	0.007 (0.003)	94	0.19 (0.04)	0.38 (0.05)
1	213	0.008 (0.002)	43	0.18 (0.04)	0.36 (0.05)
All	690	0.007 (0.003)	137	0.19 (0.04)	0.38 (0.05)

4.3.8 Influence of shrinkage parameters on warp

Changes in twist, crook and bow in the studs between the moisture stages were not correlated to the shrinkage parameters measured on the sticks. The reason for this was probably that shrinkage measurements on sticks from the top end of the stud were not representative of the whole stud. It was concluded by Kliger et al. (1999) that the variation in shrinkage within a single board could be very large, i.e. it is necessary to know the three-dimensional shrinkage variation to predict bow and crook accurately.

4.4 Conclusions

For material parameters measured on the sticks, the following was found:
- Longitudinal shrinkage decreased from pith to bark.
- No significant radial variation of shrinkage in the radial direction was found.
- Tangential shrinkage increased with increasing distance from pith.
- Shrinkage parameters were correlated to density; longitudinal shrinkage decreased whereas transverse shrinkage increased with increasing density.
- The rough classification of compression wood used here did not show any relationship to shrinkage parameters.
- Presence of knots led to increased shrinkage in the longitudinal direction whereas transverse shrinkage decreased.

Based on the results from this study it can be concluded that:
- Warp, especially twist, was influenced by changes in relative humidity in the air.
- Studs containing pith showed larger changes in twist and bow as moisture content changed than studs without pith.
- Larger changes in crook occurred in quarter-sawn than in flat-sawn studs.

- Crook and bow changed direction during the moisture cycles, i.e. total change in warp was larger than change in absolute values.
- There were strong relationships between twist, crook and bow measured at the different moisture stages, when both magnitude and direction were considered.
- Twist, crook and bow in green condition were not correlated to warp after drying and could therefore not be used as a criterion for sorting out warp-prone studs before drying.
- No relationships could be found between changes in warp and shrinkage parameters, probably because warp was measured on full-size studs whereas shrinkage parameters were measured on sticks from the top end of each stud.

5. Economic aspects

5.1 Introduction

5.1.1 Background

To reduce the problem with warp and improve the reputation of wood as a building material the grading systems must be modified and better adapted to the end-user requirements. However, doing *only* this would lead to a larger proportion of warped low-quality boards remaining at the sawmills. Thus, complementary measures, in the production process, must be taken. Changing the drying process, i.e. to dry sawn timber with restraint at high temperatures, could be a solution, but only in a long-term perspective as it normally would involve investments in new drying equipment. Furthermore, there are contradictory results on the long-lasting effect of high-temperature drying on warp. The method demonstrated in this thesis, to alter the sawing pattern, has shown promising results. In chapters 3 and 4, it was shown that quarter-sawn studs without or with only a minor proportion of corewood were straight after drying and also remained straight when they were exposed to different moisture climates.

5.1.2 Aim and limitations

The economic aspects of an "incorrect" sawing pattern, i.e. from larger waste at the sawmill to a totally lost market share for some products, have been little discussed in the literature. This chapter should be regarded as a brief discussion of these questions, based on the example wall studs. Costs and revenues of production of studs as it is usually done today were compared with production of studs applying the sawing pattern suggested in chapter 3.

The production process at a sawmill can be divided into four main steps: handling and preparation of logs, sawing, drying of sawn timber and finally handling of sawn timber (Grönlund 1992). Within each step, there are a number of alternative methods to choose from and no sawmill is exactly like the other. To be able to draw accurate economic conclusions it would be necessary to study the technical as well as economic situation for the specific sawmill. This would be complex and a large amount of data requiring much work, would be needed.

Therefore, calculations were made only for the steps directly involved in the production process at the sawmill, i.e. costs of raw material and production process. Overhead costs were not included as they were distributed per cubic metre measured at top end of logs ($m^3$to), and thus were equal for all diameter-classes and sawing patterns.

5.2 Material and methods

5.2.1 Basis for the calculations

This study was based on data from a sawmill producing about 200 000 cubic metres sawn timber per year. The total raw material supply consists of 80% spruce and 20% pine logs. The sawing equipment used is a reducer bandsaw and kiln-drying is done in progressive as well as compartment kilns. Sawn timber with moisture contents from 10 to 20% can be delivered depending on the customer's demands.

The calculations were based on output from an optimization computer program, TimberOpt, used at many sawmills in Sweden today. Input data, i.e. raw material prices, production costs and prices of sawn timber products refer to 1999. An overview of the individual cost items is given in Table 28.

Table 28. Classification of individual cost items used in the calculations.

Raw material Log price and transportation from forest to sawmill
Log handling Costs of measurement and transportation of logs within the sawmill
Sawing Transportation of logs, barking, sawing and sorting of green boards
Centre yield Costs of kiln drying, trimming, transportation of sawn timber, packaging and storage - Conventional sawing pattern: centre boards were dried to moisture content class 18 - Alternative sawing pattern: middle centre board dried to 15% MC, other centre boards were dried to moisture content class 18
Side yield Costs of kiln drying, trimming, transportation of sawn timber, packaging and storage All side boards were dried to moisture content class 18
Overhead costs Costs related to items not accounted for in the analysis of each item above e.g. management, sales, administration, research, costs for assets etc.
TOTAL COST

Exact values of different items included in the calculations of costs and revenues are not shown as these are specific for the company and therefore lacks general interest. Instead, results are shown as relations between the alternatives compared.

5.2.2 Raw material and sawing patterns

Logs from four diameter classes, 150, 270, 320 and 360 mm, were included. Within each diameter-class two production methods were used, *normal* and *alternative*. In Figure 37 dimensions of logs and sawing patterns used in the calculations are shown.

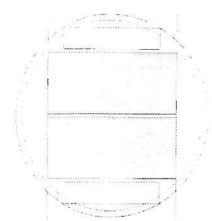
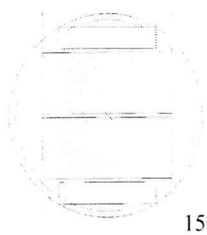
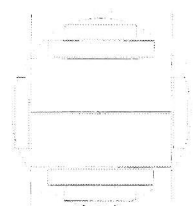
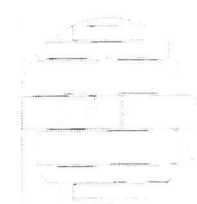
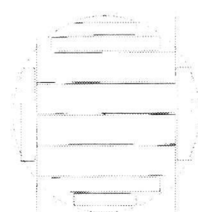
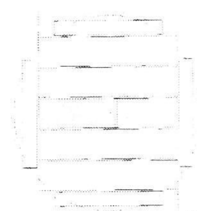
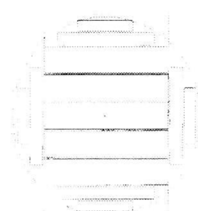
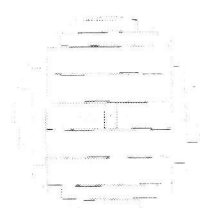
Diameter class (mm)	**Sawing pattern**	
	Normal[1]	Alternative[2]
150	 150_{NORMAL}	 150_{ALT}
270	 270_{NORMAL}	 270_{ALT}
320	 320_{NORMAL}	 320_{ALT}
360	 360_{NORMAL}	 360_{ALT}

Figure 37. Log dimensions and sawing patterns used in the calculations.

1 Normal: Sawn wood dried to moisture content class 18.

2 Alternative: Middle centre yield dried to 15% moisture content, other boards to class 18

Normally, studs are produced only from logs in diameter-class 150. A split-pith sawing pattern is used and the studs are dried to moisture class 18, i.e. 18 $\pm$ 6% moisture content (Anon. 1991).

For larger logs, the normal sawing patterns were represented by the ones commonly used for each diameter-class at the sawmill today. Centre yield from 270-mm logs were sawn into 75 x 200 mm, and from 320- and 360-mm logs into 47 x 225 mm. These planks are normally strength-graded according to the GS/SS-rules (Anon. 1988) and sold mainly to the British market. Planks and boards produced by the normal method were dried to 18 $\pm$ 6% moisture content and were graded and sold as usual.

The alternative sawing pattern used in the calculations was chosen on the basis of results from grading according to end-user requirements in chapter 3. Sawing pattern 150_{ALT} yield A-studs whereas sawing patterns 270_{ALT}, 320_{ALT} and 360_{ALT} yield D-studs (see Figures 15 and 37). The dimension of A- and D-studs was 50 x 100 mm. In diameter class 150 mm, the sawing pattern was the same as for the normal production, but A-studs were dried to 15% instead of moisture content class 18. The obvious choice of alternative sawing pattern for larger logs was the sawing pattern that produced pith-free quarter-sawn studs, type D. For these logs the middle centre boards were dried to 15% , whereas all other boards and planks were dried as usual.

To adequately compare the production methods, the final quality yield of studs must be considered. Quality yield of studs A and D are based on results from chapter 3, i.e. 70% of the A-studs and 95% of the D-studs fulfilled the requirements on warp and could be sold as wall studs. The centre-boards rejected because of warp were graded as a lower quality. The remaining centre yields and side boards were graded and sold as usual.

5.2.3 Calculations

Comparison of *costs* were made for:

- Conventional stud production compared to stud production when quality yield was considered, i.e. between production methods 150_{NORMAL} and 150_{ALT}.
- Conventional stud production and production of studs from larger logs, i.e. production method 150_{NORMAL} was compared to methods 270_{ALT} , 320_{ALT} and 360_{ALT}
- Production of studs from larger logs and the normal sawing pattern within each diameter-class, i.e. comparison of 270_{NORMAL} and 270_{ALT} , 320_{NORMAL} and 320_{ALT}, and 360_{NORMAL} and 360_{ALT}.

The basis for the calculations are studs produced by method 150_{NORMAL}. Today studs are sorted according to The Green Book or Nordic Timber. This means that almost all studs are "accepted" and the rejection is transferred to the end-user. There is a fixed market price for these studs. However, there is a also market price for rejected studs if they are separated at the sawmills and sold as a lower grade, this price is about 2/3 of the price of studs (Nyberg 1999).

According to the studies presented in previous chapters, 30% of the studs produced by method 150_{NORMAL} should be rejected at the building site. Thus, they represent a cost, today born by the end-user. In the calculations, also the cost of rejected studs is considered.

Comparison of *revenues* was made for sawing patterns within each diameter class for large diameter logs.

5.3 Results and discussion

5.3.1 Volume yield

Volume yield of sawn timber from the normal sawing patterns used for logs of 150, 270, 320 and 360 mm varied from 54 to 68%. Volume yield increased with increasing log diameter. For the alternative patterns in each diameter-class, volume yield was approximately the same, and varied from 54 to 67%. The central part of the log, removed in the alternative sawing patterns for logs of 270, 320 and 360 mm, was chipped.

5.3.2 Comparison of production costs

In Figure 38 costs of alternative production methods for logs of 150, 270, 320 and 360 mm are compared to conventional stud production. Total cost of conventional stud production was set to 100%. Costs of each item and total cost of each sawing pattern are shown as percentage of total cost of the conventional production method 150_{NORMAL}.

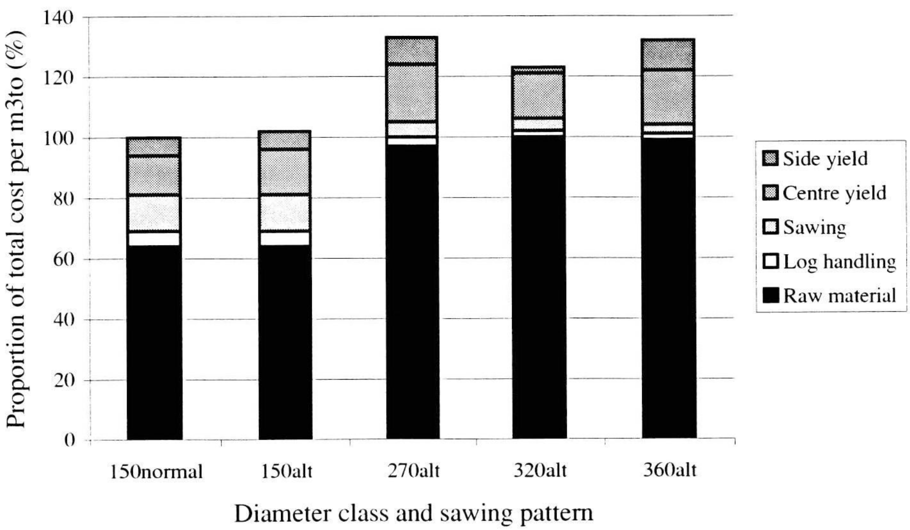


Figure 38. Comparison of costs for conventional stud production (150_{NORMAL}) with studs produced by the alternative sawing pattern from logs in all diameter classes - costs of each cost item as percentage of total costs of sawing pattern 150_{NORMAL}.

Studs from small-diameter logs

As expected, costs for production of studs dried to 15% moisture content increased because drying time increased. Total production costs per $m^3$to increased by 2% (Figure 38) which may seem small, but as 30% of the studs would be down-graded according to the end-user requirements, actual costs for production of an equal number of accepted studs would increase much more. According to this, it would be necessary to produce 1.43 m^3 sawn timber to achieve 1 m^3 straight studs. Today, the price for the down-graded boards is 2/3 of the price for straight studs (Nyberg 1999).This must be compensated for by a higher price for the straight studs. According to the calculation in Table 29, the actual cost for production of 100% straight studs will increase by 17%. Thus, the price need to be increased by 17% to reach break-even with $150_{NORMAL.}$

Table 29. Calculation of actual production costs of 100% accepted studs according to sawing pattern 150_{ALT}, 270_{ALT}, 320_{ALT} and 360_{ALT}. Production cost of 1 m^3 split-pith studs according to method 150_{NORMAL}=100%.

	Production method			
	150_{ALT}	270_{ALT}	320_{ALT}	360_{ALT}
a Production cost, for unsorted studs, relative to 150_{NORMAL}	102	132	122	132
b Quality yield (%)	70	95	95	95
c Total production cost of 100% accepted studs	146	139	128	139
d Relative sawn volume to reach 100% accepted studs	143	105	105	105
e Value of down-graded studs	29	3	3	3
f Actual production cost of accepted studs	117	136	125	136
g Cost increase compared to 150_{NORMAL} (%)	17	36	25	36
h Cost increase compared to 150_{ALT} (%)	-	16	7	16

a: from Figure 38, b: from chapter 3, c = a/b, d = 100/b, e = 2/3 * (d-100), f = c - e, g = f/100, h = f /117

Conventional studs from small diameter logs vs. studs from larger diameter logs

Total costs were higher for production of studs from logs of 270, 320 and 360 mm, compared to the standard method. Striving for a lower moisture content prolonged drying time and use of larger dimension logs increased raw material cost due to higher price per $m^3$to, whereas costs for handling of logs and sawing decreased with increased log diameter. Total costs in the alternative methods were 22 to 32% higher than the cost for the conventional production of studs when quality yield was not considered (Figure 38).

Costs per $m^3$to of log handling and sawing decrease as log dimension increases. In this case, timber prices per m^3 to increase with increasing log diameter until diameter class 320 mm, after which prices decrease with increasing diameter. Costs of centre and side yield vary with the number of pieces that are obtained from each sawing pattern and drying time to final moisture content.

However, quality yield for split-pith studs was 70% and for pith-free quarter-sawn studs it was 95%. If this fact is taken into account, differences in cost between split-pith studs and quarter-sawn studs decrease. In Table 29, calculations of total production cost of 100% accepted studs with method 150_{ALT} is compared to the production cost of 100% accepted D-studs from logs of 270, 320 and 360 mm.

When quality yield was considered, actual cost for production of 100% accepted studs from large logs were between 7 and 16% higher compared to production cost of 100% accepted studs produced from logs of 150 mm.

Stud production vs. normal production method within each diameter class

Today, the sawmill produces construction timber, graded as GS/SS from spruce logs with a diameter of 270, 320 and 360 mm. To study if it would be a realistic alternative to produce studs from these logs, a comparison of costs for today's production within each diameter-class was made. Figure 39 shows the relation between production costs of different sawing patterns within each diameter class.

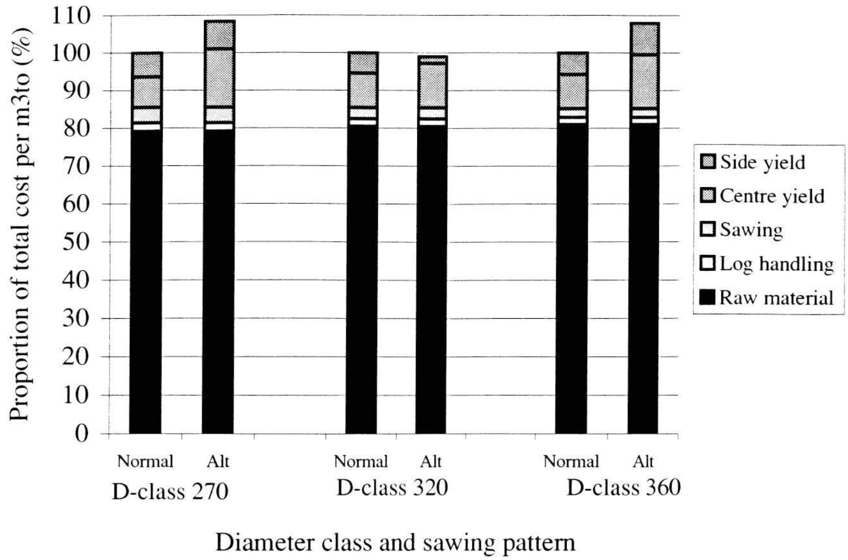


Figure 39. Relation between production costs of different sawing patterns within each diameter class.

The normally used method was either a split-pith sawing pattern (logs of 270 and 320 mm) or a boxed-pith sawing pattern (logs of 360 mm). In the alternative sawing pattern the pith was removed from the middle centre yield before drying. There were extra costs for drying to 15% moisture content and the green-splitting operation in the alternative production method.

Total cost of the alternative method within diameter-classes 270 and 360 was 8% higher than total cost of the sawing pattern normally used. Cost of the alternative production method within class 320 mm was 1% lower than the normally used method. The larger number of side boards in the normal method compared to the alternative method caused the higher costs within this diameter class.

Comparisons showed that within the same diameter class, costs of raw material, log handling and sawing were constant, whereas cost for handling of sawn yield varied. The number of pieces for centre and side yield, and drying time influenced these costs.

5.3.3 Comparison of revenues

Studying only production costs does not give a definite basis for deciding whether to change production method or not; differences in total revenue from each method must also be considered. Figure 40 shows a comparison of revenue from the different methods within each diameter class.

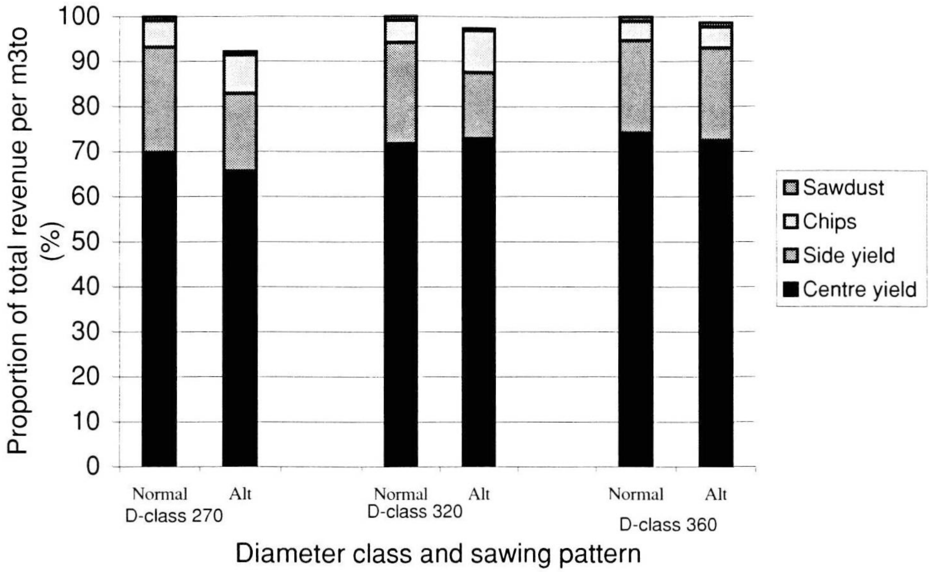


Figure 40. Comparison of revenues for different sawing patterns within each diameter class.

Revenues were 1.5 to 8% lower for the alternative method than the normal method within each diameter class. Thus, to make it attractive to produce studs or other types of structural timber products from these logs, the price for these products must increase. However, it seems reasonable to believe that it would be possible to get a higher price for quarter-sawn boards without corewood, products of higher quality when shape stability is concerned.

5.3.4 Benefit for the customer buying straight studs

To make the production of a building more cost effective through better use of the raw material, the best possible integration between market, sawmill and forest must be obtained. This means reducing waste at the sawmill as well as at the building site. According to results shown in chapters 2 and 3, a package of split-pith studs delivered today might contain up to one-third of studs that do not fulfill the requirements of the building sector. This means that the customer has to buy a larger number of studs than what is actually needed to fulfill the requirement of the builders or to use much extra time attempting to use inferior material. Thus, total cost becomes higher than necessary.

A study of production time when conventionally graded studs and studs graded for straightness were used at two building sites showed that, for the production step studied, production time could decrease by up to 30% when customer-adapted studs were used (Lindvall 1996).

As the building industry is changing more and more from being based on pure craftsmanship to a rational component industry, the cost for delivery of material with unsatisfied requirements is becoming higher and higher. As economy is one of the most important factors to the building contractor, increasing the buildability by delivering straight studs of lengths adapted to the purpose could decrease production time and thus total production cost decreases (Engström 1997). Thus, it should be interesting for the building contractor to study to what extent the higher quality leads to a lower total cost. Results of Lindvall (1996) indicate that there should be possibilities to increase market shares for timber products in construction if they were better adapted to customer requirements.

For the sawmill it would be possible to produce straight D-studs and make it profitable by regained market shares and an increase in price. By guaranteeing that at least 95% of the studs in the package fulfill the customer demands, there should be an opportunity to increase the price of the new product at the same time as waste is reduced. A building project where customer-adapted studs were used was described by Aragunde (1994). The interviewed building contractor stated that the higher price of 20%, was well justified by the fact that the studs were straight.

However, the highest possible increase in price is decided by how much money the customer could save by using a product of higher quality. Not only the actual price when buying studs decides how much more the customer would be willing to pay for a better adapted product. One alternative for the customer is to buy steel studs instead of wooden studs. It is the total cost of the complete wall that finally determines which material will be chosen. Steel studs are more expensive than wooden studs, but total cost for the wall is usually lower when straight steel studs are used instead of warped wooden studs (Johansson 1999).

5.4 Concluding remarks

For the sawmill industry to keep, increase and regain shares on the market for structural timber, it is necessary to adapt to the customers' requirements. Studies of costs in the manufacturing industry have shown that 15 to 20% of the turnover for a company appears as costs because of lack of quality, e.g. complaints, adjustments afterwards (Grönlund 1992).

The largest single cost item for sawmills is cost of raw material, on average 65% of the total production cost can be attributed to raw material (Grönlund 1992). Until now, maximum volume yield has been the major goal for most sawmills. However, the maximum volume yield is not always equal to maximized quality yield or value of the log. The goal must be to obtain as high value as possible from each log, and a high value can only be obtained when products with the right properties according to customers are produced.

Economic calculations of this type can not be generalized. Specific studies must be done at each sawmill, where the technical and economic situation as well as raw material supply must be included. All examples in this chapter indicated that production of studs from larger logs would not be profitable. High costs of raw material in combination with higher prices for the products made from these logs today resulted in low revenues. However, not only visible costs, but also costs of loosing market shares to other materials and costs of lack of quality, as mentioned above, must be considered in calculations. Such costs could be considerable, for example during the last 15 years, ever since steel studs were introduced on the Swedish market, this material has steadily increased. Today, at least 60 to 65% of the studs used for interior walls are made of steel instead of wood (Pekkari 1999). Furthermore, steel studs for exterior walls are also gaining market shares (Johansson 1999).

The important issue for the sawmill industry must be to produce timber products of the right quality, with respect to end-use. Better adapted products and reduced waste at the building site make the building process more effective, which leads to lower total costs in the building sector. By guaranteeing that at least 95% of the boards in a package fulfill the requirements on straightness, there should be an opportunity to increase the price of the "new" product and also to create a good reputation for wood as a building material and thereby regain market shares.

6 Discussion and concluding remarks

For wood to keep its traditional position as a building material and to increase market shares the negative image of sawn timber, mainly because of warp, must be improved. To adapt the timber products to the customer requirements is a necessary measure for the competitiveness of sawn timber. By increasing buildability through timber products adapted for a specific use, economy in timber construction could be improved - "time is money". As a major part of the forest owners revenue comes from sawlogs, the payability of the sawmills for the logs are of great importance to the forest owners. The profitability of the sawmill industry depends, in turn, on the economy of their customers, e.g. the building industry. Through an increased integration and products that are better adapted for the end-user, payability would increase for all parties involved in the chain from forest to end-user.

There are a number of ways to adapt the products to the customers requirements. For studs, a product specification, called S-timber (Anon 1996) was developed in co-operation between the research team behind the "Guidelines for Purchasing Building Timber" (Johansson et al. 1993), a number of sawmills and The Swedish Timber Council. The sawmills involved formed the "S-Timber Association" and were certified to use a special trade-mark for S-Timber which would guarantee that the requirements stated were fulfilled. The requirements for S-Timber were identical to those described by Johansson et al., except for the moisture content which allowed a higher moisture level in the studs at delivery. The studs were produced as before, applying the Nordic sawing practice and dried to shipping dry moisture content. Only the warp limits were sharpened compared to "The Green Book" (Anon. 1982) and "Nordic Timber" (Anon. 1994). The new grading resulted in a higher percentage of rejected studs remaining at the sawmills. However, the basic problem with warp was actually not solved by this; it was just moved from the building site to the sawmill. Unfortunately, this attempt did not succeed. One reason could be that the limit for moisture content was not low enough, which meant that the S-Timber studs that fulfilled the requirements when leaving the sawmill warped as soon as the moisture level decreased.

The grading of wall studs, described in chapter 2, showed that one-third of the kiln-dried and planed studs examined at the five sawmills were rejected because of warp when graded according to Guidelines for Purchasing Building Timber. Rejection at this late stage in the timber processing chain is expensive.

The approach applied in this thesis was to enter earlier in the production process and try to find an applicable solution that would be of benefit not only for the customer, but also the producer. The results from the studies presented in chapters 3 and 4 indicate that, technically it would be rather easy to produce sawn timber products without or with only minor warp. Removing the central part of the log greatly affected the geometrical properties of the boards.

The consequences for this adjustment of the production strategy would be a somewhat lower volume yield of sawn timber, as the central part of the log probably would be chipped. However, results of simulations presented by Ormarsson (1999) indicate that improved shape stability could be obtained by gluing together laminations or pieces of wood from different positions within the log. On the other hand, quality yield would increase markedly at the same time as the amount of downgraded or rejected boards would decrease. One limiting factor could be the supply for raw material, as larger diameter logs than those used today would be needed.

In the study of sawing patterns approximately 10 growth rings were removed from the logs sawn by sawing pattern No. 4 (Figure 15). This resulted in a significantly higher proportion of straight studs compared to quarter-sawn studs where pith was included. However, no evaluation was made of *how many* growth rings would have to be excluded to guarantee a shape-stable product after drying. Removing this area including pith was adequate to obtain studs that were straight after drying and remained straight even when exposed to different moisture cycles in this study.

According to the grading rules for spruce logs (Anon 1999a), class 3 is recommended for purposes where strength and shape stability are important properties. The limits for growth ring width within 6 cm from the pith are maximum 5 mm (minimum 12 rings in 6 cm). This means that if the inner 10 growth rings should not be included in the sawn boards, a square of 100 x 100 mm centred around the pith, would have to be removed. As a comparison, for class 1, recommended for so-called high-quality joinery products, the limit for growth ring width in the corewood area is 3 mm, i.e. these logs would yield a much lower volume of waste. To minimize the waste volume, logs with narrow growth rings in the corewood zone should be chosen for structural timber products. From the recommendation given in the grading rules for logs it is obvious that these are not very well adapted to the end-user requirements.

A third approach to this problem, which was not studied in this thesis, is to maintain the choice of logs and sawing patterns used for stud production today and change the drying process. It was concluded from the study on moisture cycling, that split-pith studs and quarter-sawn studs including pith were more sensitive to changes in the surrounding moisture climate than quarter-sawn studs without pith. Studies have shown that high-temperature drying in combination with mechanical restraint could decrease warp in these types of boards. However, there are contradictory results on the long-lasting effect on warp and the effect of high temperatures on strength properties (Koch 1971, Hillis 1984, Haslett et al. 1991, Simpson and Tschernitz 1998).

Analyses of relationships between warp and site parameters, log types, wood properties and processing methods for Norway spruce have shown that there is still a large portion of unexplained variation in twist, crook and bow. However, on the basis of findings in this thesis and other studies on Norway spruce during recent years, it can be concluded that there are in fact a number of very useful changes that could be made right now to diminish the problem with warp of structural timber (Danborg 1994, Perstorper 1994 a and b, Forsberg 1997 and 1999, Ormarsson 1999):

- First, the quality of sawn timber products should be described in a specification of requirements for each end-use. This would facilitate the communication between sawmills and their customers. Such a system for a number of structural timber products has already been developed, but is not yet introduced on the market (Johansson et al. 1993, Engström et al. 1995).

- To avoid rejection at the building site, moisture content of the timber products should be as close to the expected equilibrium moisture content of the built-in products as possible. Otherwise the boards, which were straight when leaving the sawmill, could develop warp during transportation and storage at the building site as moisture climate changes.

- The shape of a board after drying greatly depends on its position within the log, making it possible to adapt the sawing pattern so that development of warp is minimized during drying. Boards containing pith and a large proportion of corewood develop a larger twist than outer boards.

- Quarter-sawn boards free of corewood, as was shown in chapters 3 and 4, seem to be well adapted to the requirement of products with well-known, consistent properties. The boards were straight after drying and remained straight even when exposed to varying moisture climates.

- All studies on spruce agree that a high spiral grain angle negatively influences twist. However, the strength of the relationships found varied and was rather weak. Even small grain angles could cause severe twist, therefore little would be gained by grading boards by measuring the slope of grain on the surface before drying. Forsberg (1999) found that the relationship between grain angle on the log surface and twist of inner boards was strong, much stronger than when grain angle was measured only on the board surface. If the relationship proves to be as strong for logs from a wider range of log diameter classes, only logs of 213 to 233 mm were used, measurement of grain angle on the log surface could be used as a means to diminish warp of the sawn timber by adapting the sawing pattern for each log according to the warp propensity of the inner boards.

According to several articles published in professional journals for the forest and sawmill sector during the last year (Anon. 1999b), Swedish sawmills can deliver products of the right quality, as long as the price is right. Today, the Japanese market for structural timber products seem to be of high priority. For example, one sawmill manager said that " Japanese customers have very high demands on dimension and lengths and would never even imagine using warped studs, but they are willing to pay for straight studs. The increased interest for multi-storey buildings with wooden frames during the last years is a great opportunity for the forest- and sawmill industry to regain shares on the market for building products in Sweden and other European countries.

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Short glossary

Anisotropic: Not having the same properties in all directions, e.g. shrinkage of wood is different in the different directions(longitudinal, tangential and radial).

Basic density: The ratio of mass of absolutely dry wood and volume of green wood.

Bow: The distortion of sawn timber along the face of a piece from end-to-end, measured at the point of greatest deviation from a straight line.

Boxed-pith sawing pattern: A sawing pattern where pith is situated in the centre of the middle centre yield.

Breast-height: 1.3 m above ground level.

Bucking: Cross-cutting felled trees into logs or bolts.

Buildability: Alternative word for Ease of assembly.

Cambium: A thin layer of tissue between the bark and wood that repeatedly subdivides to form new wood and bark cells.

Cant: A log that has been slabbed on one or more sides by the headrig (the first machine in a sawmill to start the breakdown of logs) for subsequent breakdown into timber by other machines.

Co-dominant trees: Tree height=Between 4 and 5/6 of the height of the highest trees in the stand.

Compartment kiln: A dry kiln in which the total charge of timber is dried as a single unit.

Compression wood: Abnormal wood formed on the lower side of branches and inclined stems of softwood trees - this tissue has unusually high longitudinal shrinkage and physical properties that differ from those in normal wood.

Conifer: One of the botanical groups of trees that in the most cases have needlelike or scalelike leaves.

Corewood: The innermost layers of wood close to the pith. Certain features, such as cell structure and size, differ from those of outerwood. In this thesis defined as the ten innermost growth rings in Norway spruce. (Also called innerwood, pith wood or juvenile wood).

Crook: The distortion of sawn timber from a straight line along the edges from end-to-end of a piece, measured at the point of greatest deviation from a straight line.

Crown-formed wood: see Corewood

Cup: Deviation flatwise from a straight line across the width of the board.

Density level: The whole ring average density as a function of ring width (defined by Danborg 1994a)

D5%: The mean of the 5% lowest density records in a growth ring (kg/m^3) (defined by Danborg 1994a).

Dominant trees: Tree height = At least 5/6 of the height of the highest trees in the stand.

Earlywood: The portion of the growth ring that is formed during the early part of the growing season.

Ease of assembly: Indication simple, rational erection or assembly of a structure, connections, elements and so on.

Equilibrium moisture content: The moisture content at which wood neither gains nor looses moisture when surrounded by air at a given relative humidity and temperature.

Fibre: Here the same as tracheid. An elongated cell with bordered pits and imperforated rate ends. Constitutes the principal part of the cellular structure of conifers.

Fibre saturation point: The stage in drying or wetting of wood at which the cell walls are saturated and the cell cavities are free from water. It is usually taken as approximately 25-30% moisture content, based on oven-dry weight.

Flat-sawn: Sawn timber is considered flat-sawn when the growth rings make an angle of less than 45^0 with the wide surface of the piece.

Flitch: A portion of a low sawn on two or more sides, frequently with wane on one or both edges and intended for further conversion into sawn timber.

Geometric properties: Dimensions and warp.

Green Book: Guiding principles for Grading of Sawn timber of pine and spruce - see also Nordic Timber.

Growth ring: Ring of wood resulting from a periodic growth.

GS: Visual stress grade - General Structure (see also SS)

Heartwood: The inner part of a woody system, where the cells no longer participate in the life processes of the tree. Usually contains extractive materials that gives it a darker colour and greater decay resistance then the outer enveloping wood.

High-temperature drying:

Hygroscopic material: A material that loses and gains moisture as a result of changes in the atmospheric humidity and temperature.

Hysteresis effect: The difference in moisture content between the desorption and adsorption curves when wood is dried and rewetted at a certain relative humidity.

Inner wood: see Corewood.

Intermediate trees: Tree height=Between 3 and 4/6 of the height of the highest trees in the stand.

Juvenile wood: see Corewood

Kiln drying: Drying of wood in a dry kiln.

Latewood: The portion of the growth ring that is formed during the latter part of the growing season after the earlywood formation has ceased.

Live sawing: Sawing through and through without turning the log or by turning it only once, that is, sawing with a bandmill headrig or with a circular headrig.

Longitudinal direction: Parallel to the direction of wood fibres.

Mature wood: See Outerwood.

Microfibril: A threadlike component of the cell wall structure composed of chain molecules of cellulose.

Microfibril angle: The mean helical angle, measured from the vertical, of the microfibrils in the S2-layer of the wood cell wall.

Modulus of elasticity (MOE): A measure of the stiffness of wood.

Moisture class 18: Moisture content 18 ± 6%.

Moisture content: The amount of water contained in wood, usually expressed as a percentage of the weight of oven-dry wood.

Nordic sawing practice: see Appendix B1.

Nordic Timber: Grading rules for pine and spruce sawn timber. Commercial grading based on evaluation of the four sides of sawn timber. Replace The Green Book.

Outerwood: Wood which is characterized by relatively constant cell size, well-developed structural patterns and stable physical behaviour. Also called mature wood, adult wood or stem-formed wood.

Oven-dry: Wood dried at 102 ± 3 °C until there is no further weight is loss.

Pin knot: A knot not more than 13 mm diameter

Pith: The small core of soft primary tissue occurring near the centre of a tree stem, branch and root.

Progressive kiln: A dry kiln in which the total charge of timber is dried in several units, such as kiln truck loads, that are moved progressively through the kiln.

Quality: Should be defined with reference to the appropriateness of the wood for a particular end-use. (The definition used in this thesis).

Quarter-sawn: Sawn timber in which the growth rings form an angle of 45 to 90^0 with the wide surface of the piece.

Radial direction: Coincident with a radius from the axis of the tree or log to the circumference.

Reaction wood: see Compression wood

Relative humidity: Ratio of the amount of water vapour present in the air to the amount that the air would hold at saturation at the same temperature.

Rivet: Nail or bolt for holding pieces of metal together, with its end pressed down to form a head when in place.

S-layers: The three layers of the secondary wall, designated S1 or the outer layer, S2 the central layer, and S3 the inner layer.

Sapwood: The wood located near the outside of the tree stem containing the tissues actively involved in the transport of sap. It is generally lighter in colour than heartwood and has lower natural resistance to decay.

Sawing around: Breaking down a log by turning it on the carriage of a headsaw to obtain the best yield of lumber from the clear outer portion of the log.

Seasoning: Removing moisture from green wood to improve its serviceability and utility.

Secondary cell wall: The portion of the cell wall formed after the cell enlargement has been completed.

Shape stability: see Warp.

Shipping dry: Moisture content low enough to avoid attack by fungi during transportation and storage, usually around 20%.

Shrinkage: Contraction caused by drying wood below the fibre saturation point.

Shrinkage coefficient: Percentage of shrinkage per per cent of change in moisture content.

Site index: A measure of the timber-producing ability of the site or, in other words, the fertility of the soil.

Spiral grain: Wood in which the fibres take a spiral course about the stem of a tree. Tangential direction: Strictly, coincident with a tangent at the circumference of a tree or log, or parallel to such a tangent, however, it often means roughly coincident with a growth ring layer.

SS: Visual stress grade - Special Structure.

Stress grades: Sawn timber grades having assigned working stress and modulus of elasticity values in accordance with accepted principles of strength grading.

Suppressed trees: Tree height = less than 3/6 of the height of the highest trees in the stand.

Tangential direction: Strictly, coincident with a tangent at the circumference of a tree or log, or parallel to such a tangent. In practice, however, it often means roughly coincident with an annual layer.

Transducer: Device that receives waves or other variations from one system and conveys related ones to another.

Tree height class: see Dominant, Co-dominant, Intermediate and Suppressed trees.

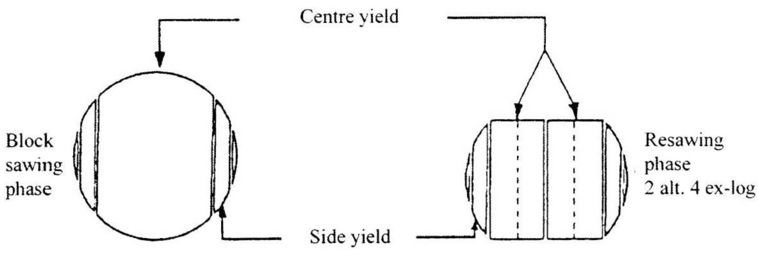
Twist a lengthwise spiral distortion.

Warp: Any variation from the true or plane surface. Warp includes bow, crook, cup and twist or any combination thereof.

Nordic Sawing Practice (Anon. 1994)

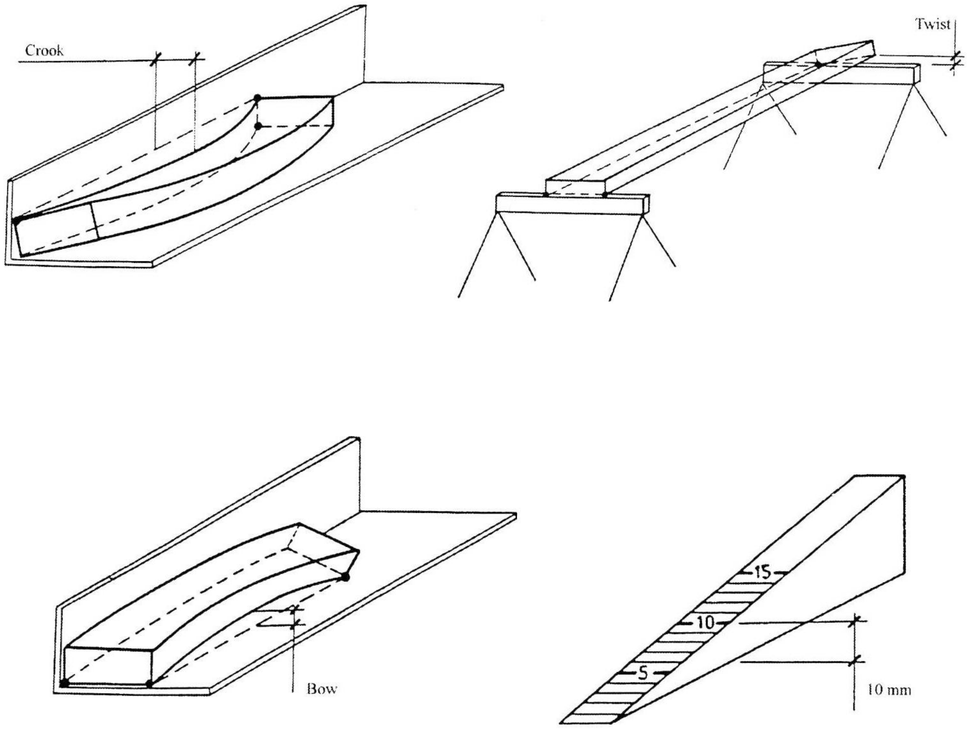
Log dividing according to Nordic sawing practice requires splitting of the log in the middle with a saw cut - heart splitting or split pith. Other cuts divide the log into *centre yield* and *side yield.*

The centre yield contains two or more pieces, which can be of the same or different thicknesses. Deviation from this sawing practice is special sawing (e.g. heart-free sawing).



(Adapted from Anon. 1994 - Nordic Timber - Grading rules).

Measurement of warp



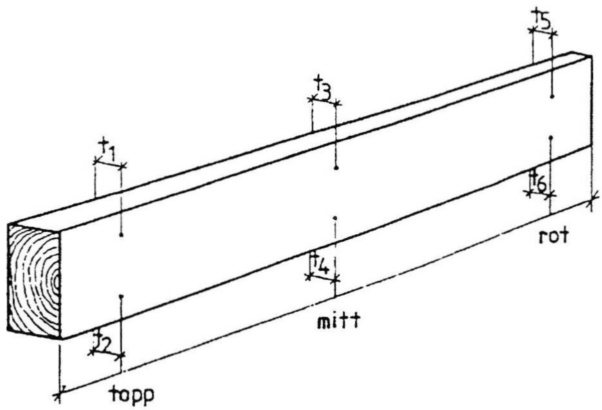
Crook and bow were measured in relation to a flat plane, represented by an L-shaped aluminium bar. Crook and bow were measured as the height of the edgewise and lengthwise deviation, respectively.

For twist measurement the studs were placed on two trestles and one end of the stud was fixed to the trestle and twist was measured as the height of deviation of the corner at the other end of the piece was raised above the flat surface.

All measurements were made with a mm-graded aluminium wedge over a span of 3 m.

(Adapted from Johansson et al. 1993).

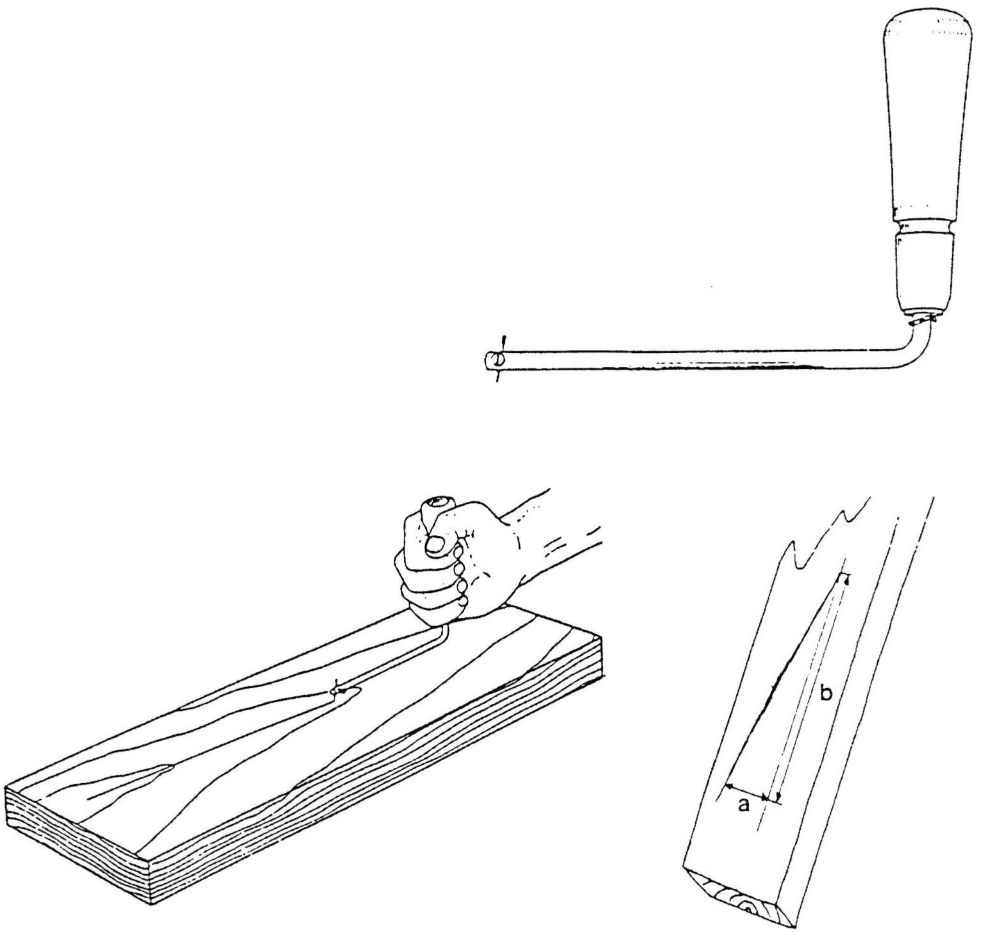
Measurement of width and thickness



Three measurements of width and thickness on every piece should be taken. The smallest of the readings for each board should be registered.

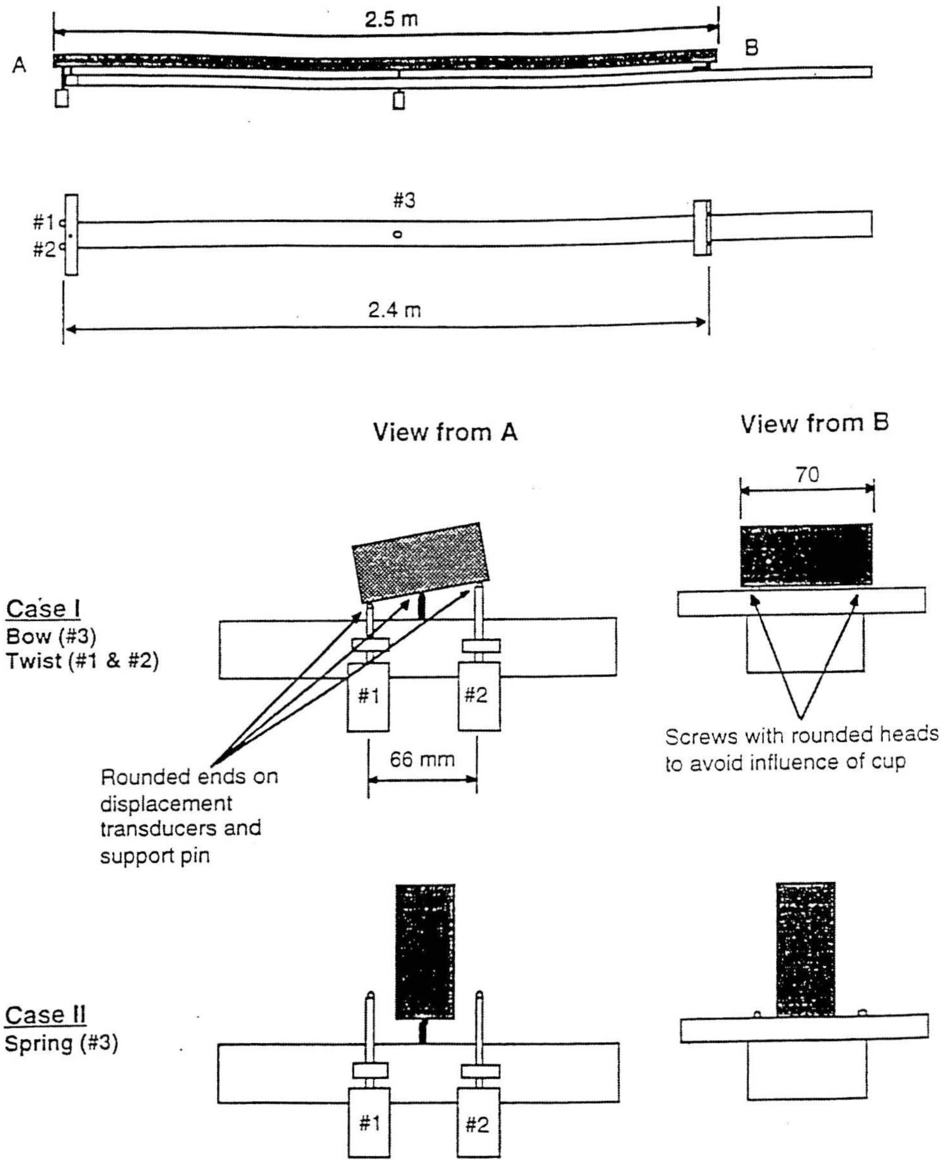
(Swedish Standard SIS 23 27 11, Anon. 1970. Sågat virke, Dimensioner.)

Grain angle measurement (Anon. 1973)



The deviation of the grain direction of the piece measured on the tangential face is the value of the slope of grain; Slope of grain = (a/b) x 100%

Warp measurement (from Perstorper et al. 1999)



Firstly, the stud was placed with the flat face downwards on the device resting on three pins with rounded heads, two at the bottom end and one at the top end. Two transducers at the top end (#1 and #2) recorded the twisting distortion and one transducer at mid-span recorded bow (#3), including the gravitation effect. The stud was then turned on its side in order to record the crook deformation with the mid-span transducer. Each stud was put onto the device in the same way at each measurement.

Conversion factors

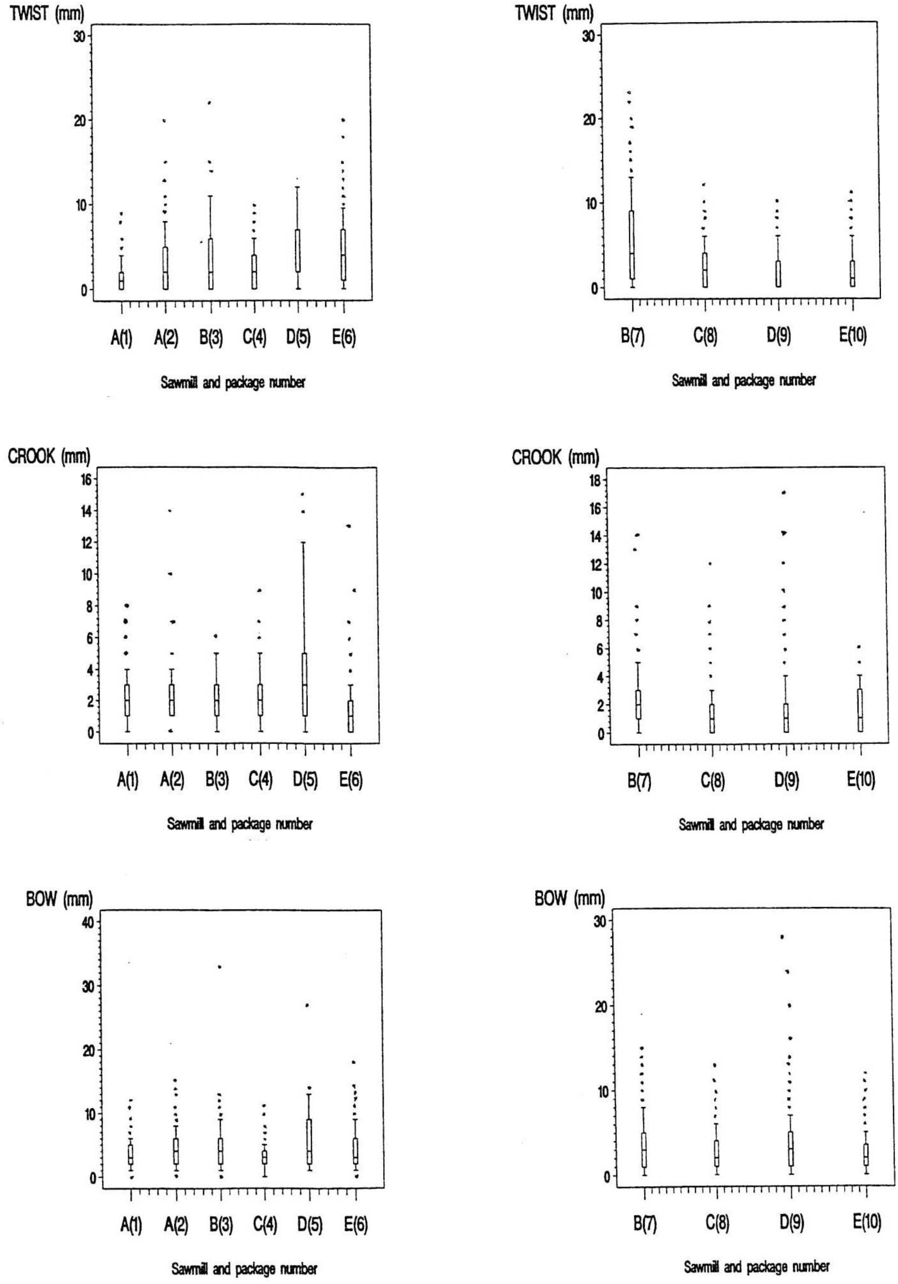
The values for twist, crook and bow in The Green Book (Anon. 1982) and Nordic Timber (Anon. 1994) were converted from 2 m to 3 m length:

Twist (3 m) = Twist (2 m) * (3/2)

Crook (3 m) = Crook (2 m) * ((3/2) ^ 2)

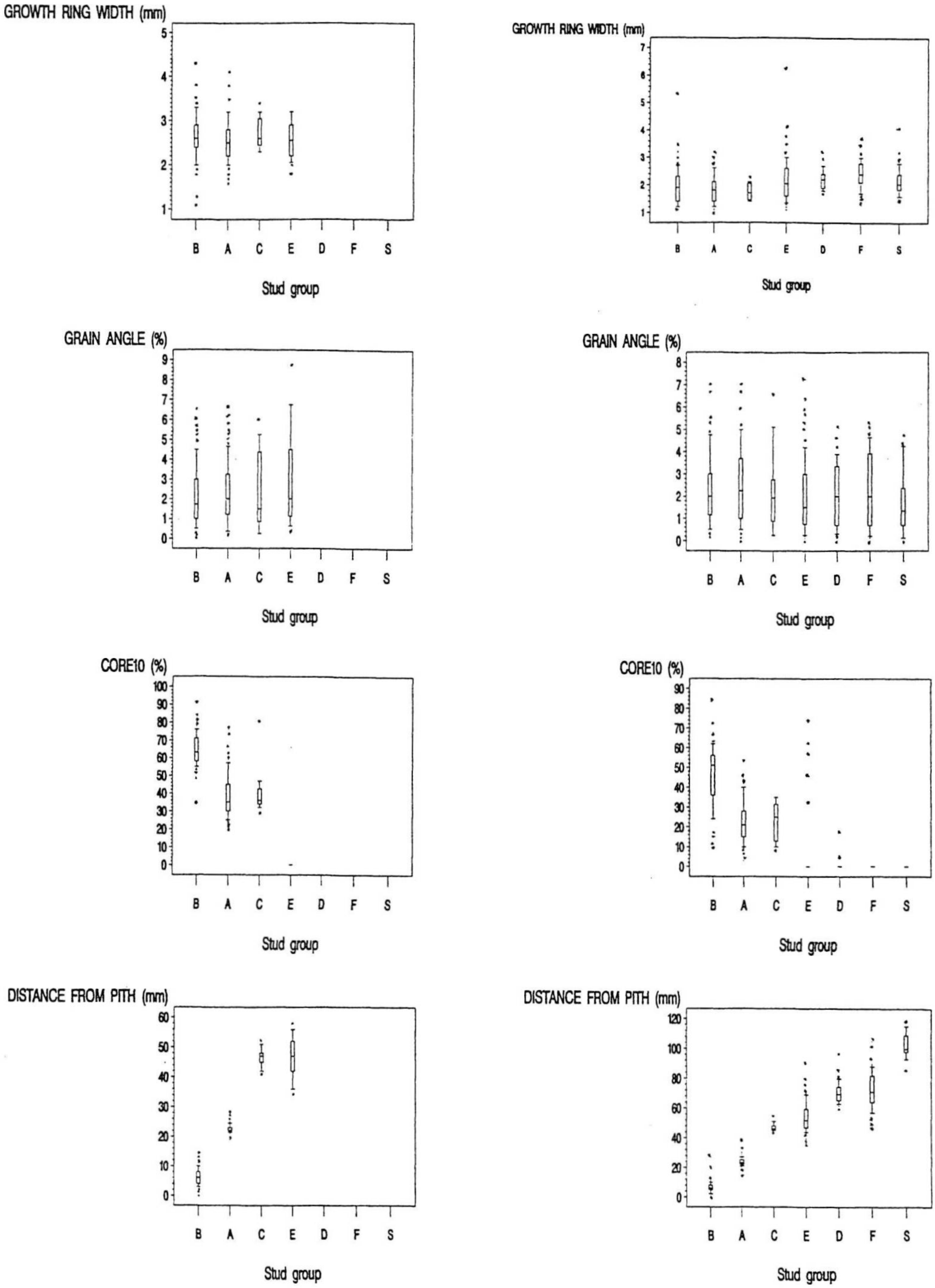
Bow (3 m) = Bow (2 m) * ((3 / 2) ^ 2)

Sample packages **Delivery packages**



Variation in twist, crook and bow for sample and delivery packages at each sawmill (Chapter 2).

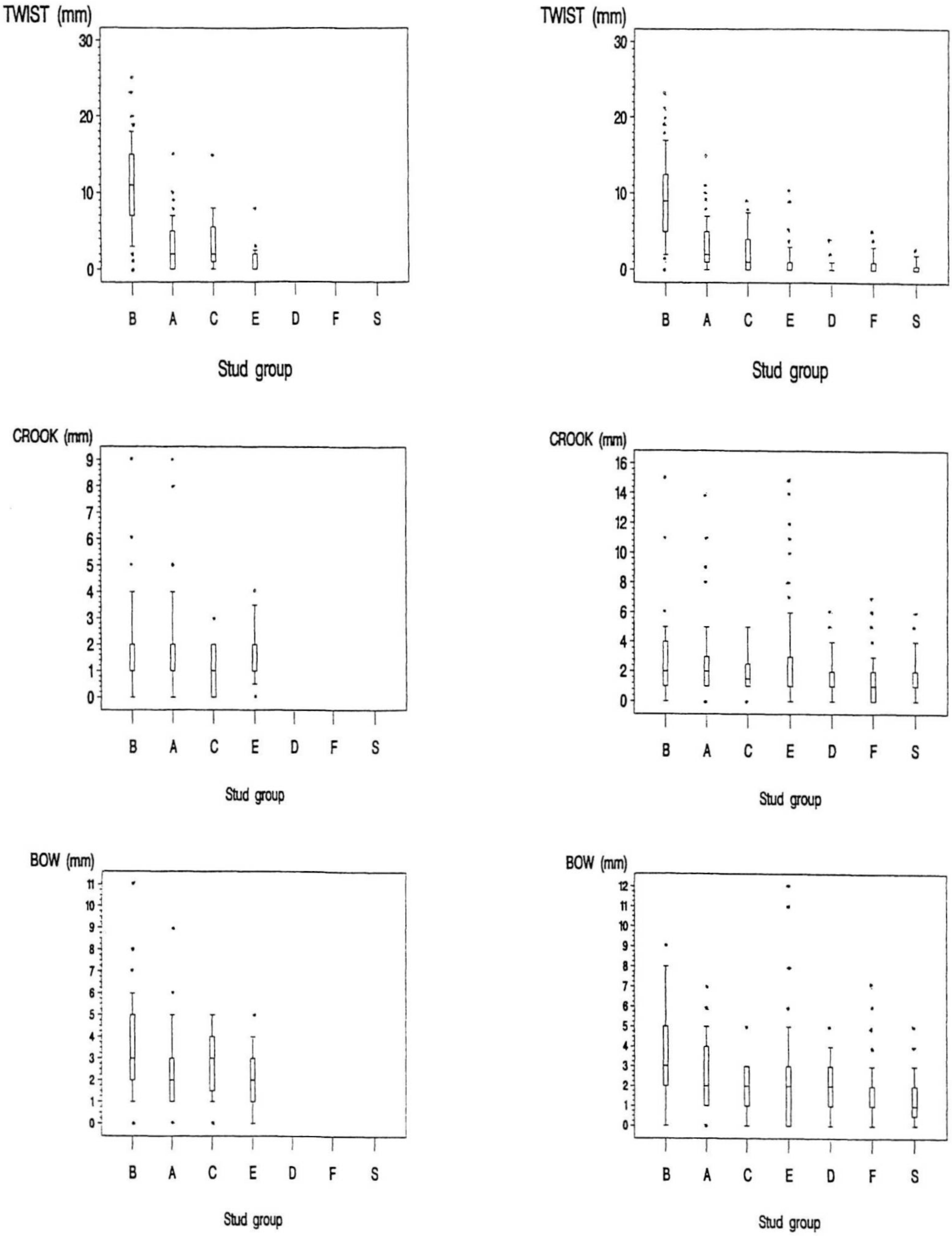
Thinning stand **Final felling stand**



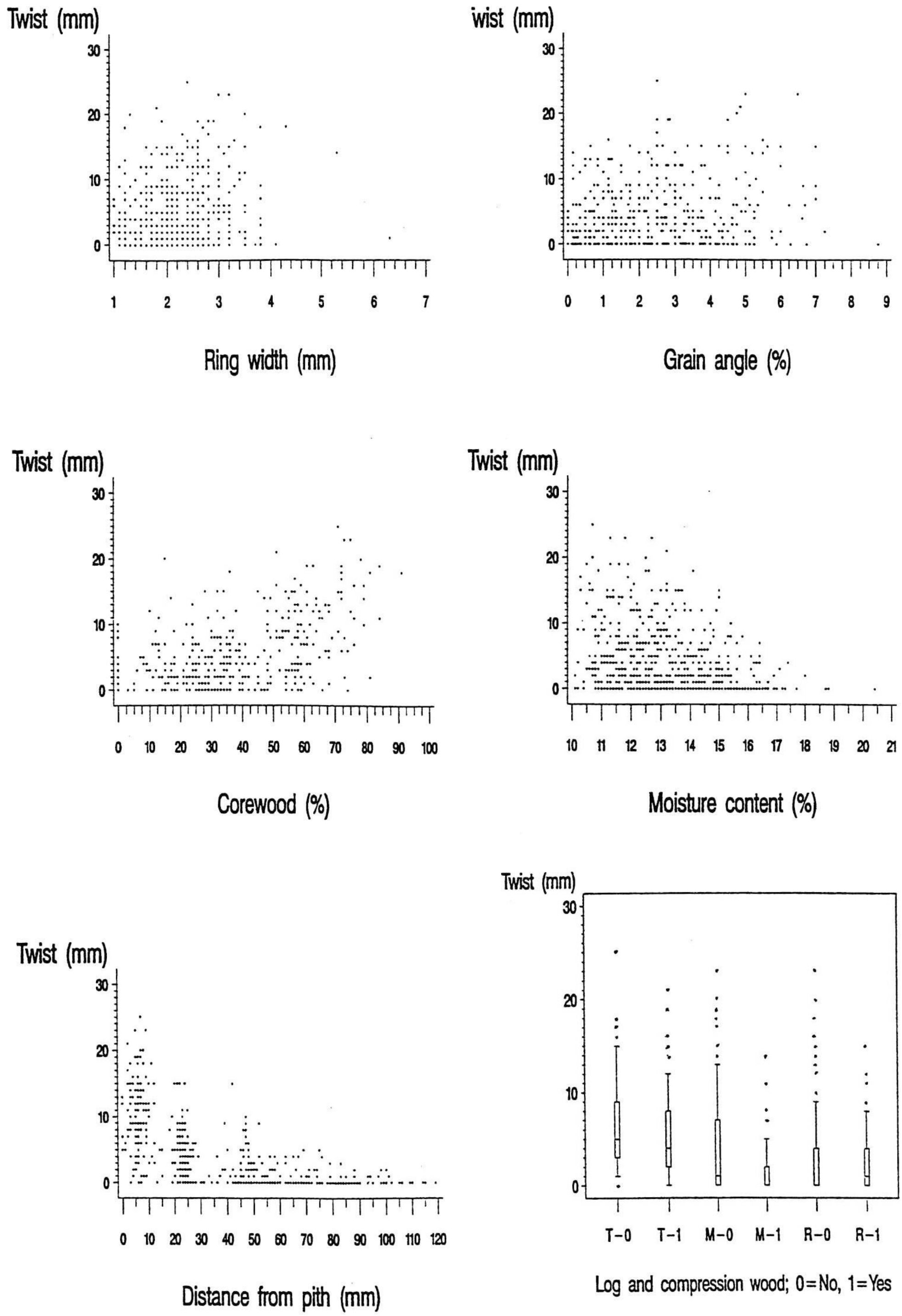
Variation in wood characteristics for studs sawn by different sawing patterns (Chapter 3).

Appendix C3

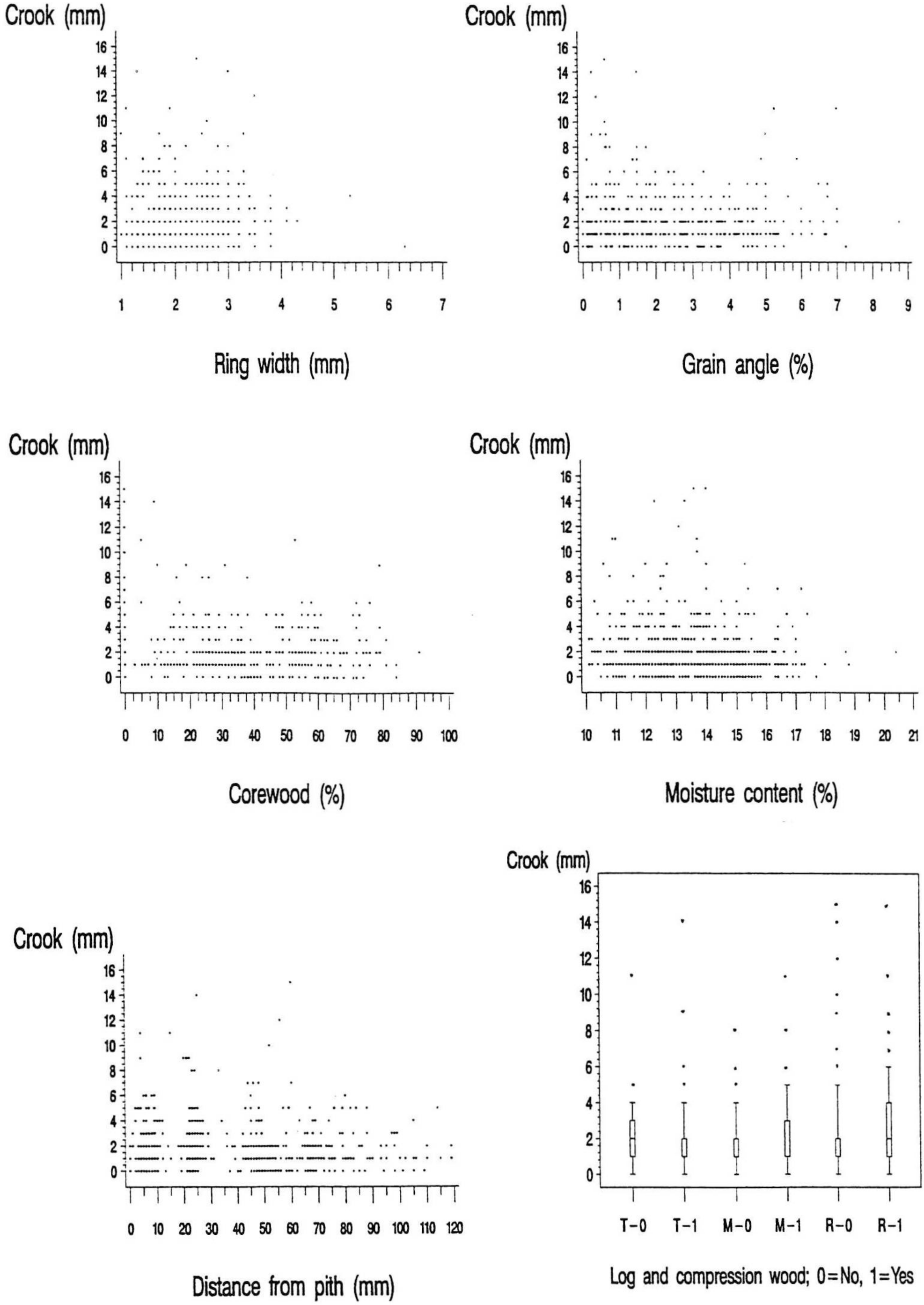
Thinning stand **Final felling stand**



Variation in twist, crook and bow for studs sawn by different sawing patterns (Chapter 3).

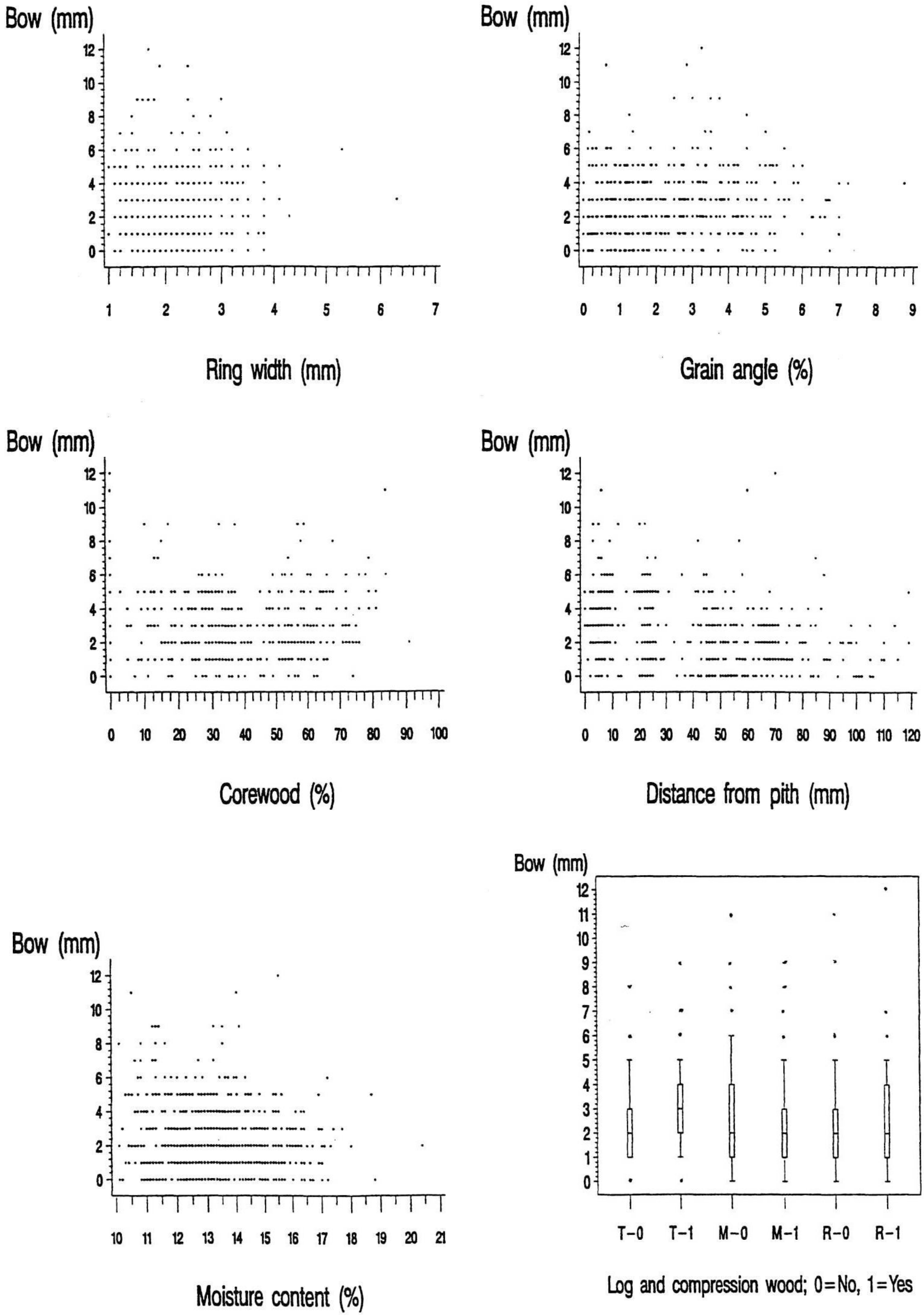


Scatter plots of relationships between wood characteristics and twist for studs (Chapter 3).



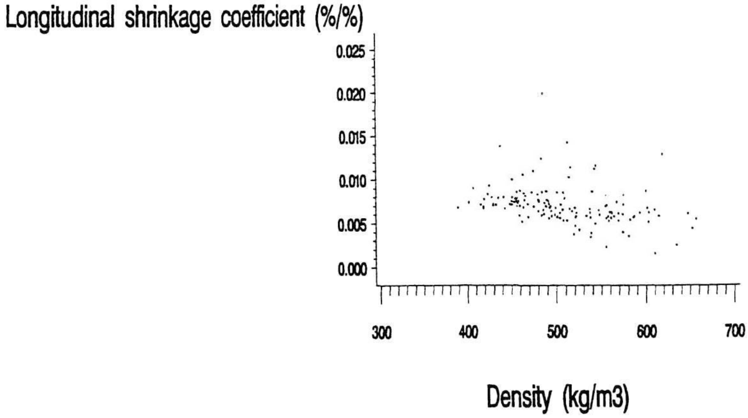
Scatter plots of relationships between wood characteristics and crook for studs (Chapter 3).

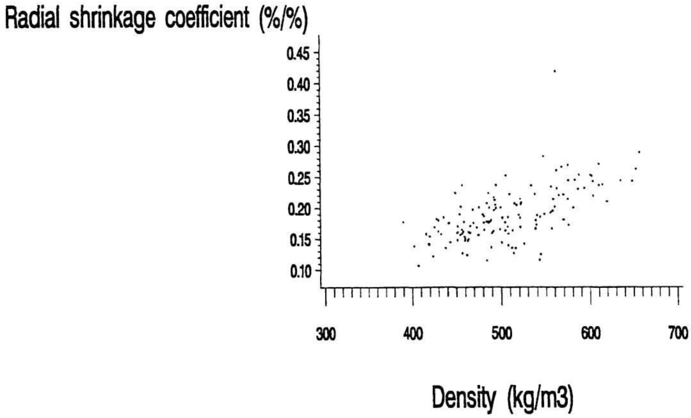
Appendix C6

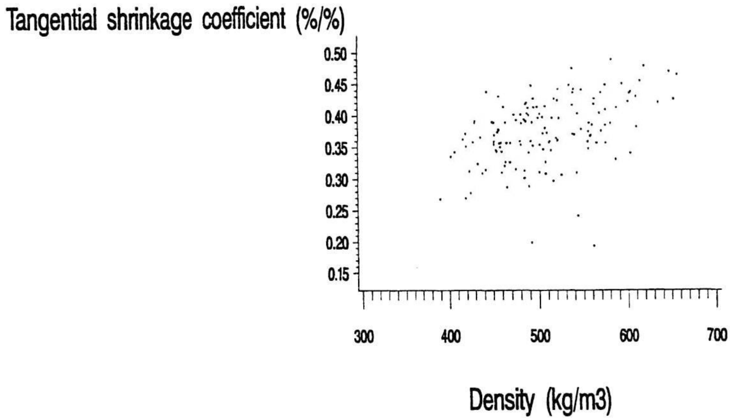


Scatter plots of relationships between wood characteristics and bow for studs in (Chapter 3).

Appendix C7

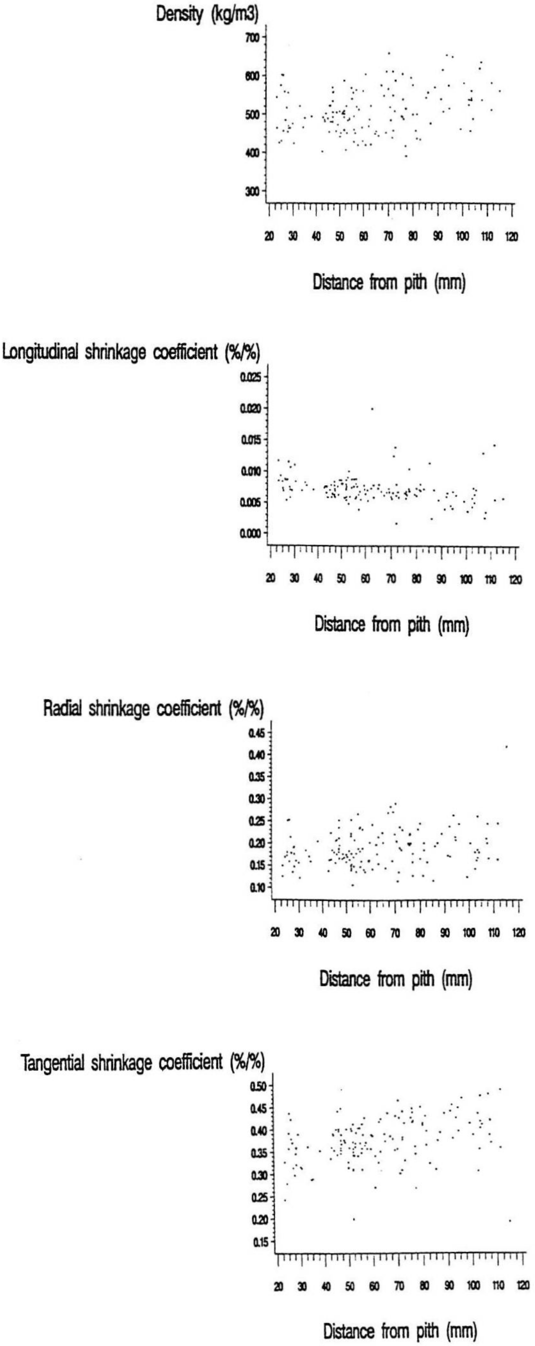






Scatter plots of relationships between density and shrinkage coefficients for sticks (Chapter 4).

Appendix C8



Scatter plots of relationships between density , shrinkage coefficients and distance from pith for sticks (Chapter 4).

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