

Dissertationes Forestales 108

**Variation in tracheid cross-sectional dimensions and
wood viscoelasticity – extent and control methods**

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Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in the Walter Auditorium of the EE-building (Agnes Sjöbergin katu 2) on October 1, 2010, at 12 o'clock noon.

Title of dissertation: Variation in tracheid cross-sectional dimensions and wood viscoelasticity – extent and control methods

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Dissertationales Forestales 108

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ISSN 1795-7389

ISBN 978-951-651-305-1 (PDF)

Publishers:

The Finnish Society of Forest Science

Finnish Forest Research Institute

Faculty of Agriculture and Forestry of the University of Helsinki

School of Forest Sciences of the University of Eastern Finland

Editorial office:

The Finnish Society of Forest Science

P.O. Box 18, FI-01301 Vantaa, Finland

<http://www.metla.fi/dissertationes>

Havimo, M. 2010. Variation in tracheid cross-sectional dimensions and wood viscoelasticity – extent and control methods. *Dissertationales Forestales* 108. 40 p. Available at <http://www.metla.fi/dissertationes/df108.htm>

Printing papers have been the main product of the Finnish paper industry. To improve properties and economy of printing papers, controlling of tracheid cross-sectional dimensions and wood viscoelasticity are examined in this study. Controlling is understood as any procedure which yields raw material classes with distinct properties and small internal variation.

Tracheid cross-sectional dimensions, i.e., cell wall thickness and radial and tangential diameters can be controlled with methods such as sorting wood into pulpwood and sawmill chips, sorting of logs according to tree social status and fractionation of fibres. These control methods were analysed in this study with simulations, which were based on measured tracheid cross-sectional dimensions. A SilviScan device was used to measure the data set from five Norway spruce (*Picea abies*) and five Scots pine (*Pinus sylvestris*) trunks.

The simulation results indicate that the sawmill chips and top pulpwood assortments have quite similar cross-sectional dimensions. Norway spruce and Scots pine are on average also relatively similar in their cross-sectional dimensions. The distributions of these species are somewhat different, but from a practical point of view, the differences are probably of minor importance. The controlling of tracheid cross-sectional dimensions can be done most efficiently with methods that can separate fibres into earlywood and latewood. Sorting of logs or partitioning of logs into juvenile and mature wood were markedly less efficient control methods than fractionation of fibres.

Wood viscoelasticity affects energy consumption in mechanical pulping, and is thus an interesting control target when improving energy efficiency of the process. A literature study was made to evaluate the possibility of using viscoelasticity in controlling. The study indicates that there is considerable variation in viscoelastic properties within tree species, but unfortunately, the viscoelastic properties of important raw material lots such as top pulpwood or sawmill chips are not known. Viscoelastic properties of wood depend mainly on lignin, but also on microfibrillar angle, width of cellulose crystals and tracheid cross-sectional dimensions.

Keywords: wood utilisation, control, tracheid cross-sectional dimensions, viscoelasticity, variation

LIST OF ORIGINAL ARTICLES

The dissertation at hand consist of a summary and the following studies, referred to in the text by the Roman numerals **I-IV**.

The articles **I-II** and **IV** are reprinted with the kind permission of the publishers while the study **III** is the author version of the submitted manuscript.

- I** Havimo, M., Rikala, J., Sirviö J. & Sipi, M. 2008. Distributions of tracheid cross-sectional dimensions in different parts of Norway spruce stems. *Silva Fennica* 42(1): 89–99. <http://www.metla.fi/silvafennica/full/sf42/sf421089.pdf>
- II** Havimo, M., Rikala, J., Sirviö J. & Sipi, M. 2009. Tracheid cross-sectional dimensions in Scots pine (*Pinus sylvestris*) – Distributions and comparison with Norway spruce (*Picea abies*). *Silva Fennica* 43(4): 681-688. Available at <http://www.metla.fi/silvafennica/full/sf43/sf434681.pdf>
- III** Havimo M. Control of tracheid cross-sectional dimensions in Norway spruce and Scots pine wood raw material. Manuscript
- IV** Havimo, M. 2009. A literature-based study on the loss tangent of wood in connection with mechanical pulping. *Wood Science and Technology* 43:627-642. DOI 10.1007/s00226-009-0271-4

The planning of measurements was carried out by the authors of papers I and II. Havimo planned and implemented the data analysis for both papers. Rikala wrote the Introduction chapter of paper I, whereas Havimo wrote the rest of the paper. Other writers commented the manuscript. Havimo wrote the first draft of the paper II, which was then commented by the other authors.

ACKNOWLEDGEMENTS

The process where man creates new knowledge is often a long and only rarely a straight road. When a young researcher takes a journey on this road, the outcome is called a thesis. The work at hand is a result of such journey.

Numerous people have helped me in the research process. I am grateful to Professor Marketta Sipi for supervising my thesis and letting me work in her group. Dr. Jari Sirviö has also been a valuable supervisor. He and Dr. Juha Rikala have rigorously inspected my manuscripts. Juha has also provided help in many practical problems. Discussions with Dr. Lauri Salminen have deepened my understanding of mechanical pulping.

M.Sc. Ilkka Väliäho and M.Sc. Petri Ratia helped with the sample collection, preparation and measurements. Staff of Innventia Ab (previously STFI-Packforsk) made SilviScan measurements. I thank them all for their valuable help.

Methodology is a tool for researcher, and if the research process is a journey, then methodology is like a bicycle for making the journey. I got many parts to my methodological bicycle from Pepe Hari. These parts have been invaluable to my research. Hannu Rita has tuned the bike in many seminars, courses and discussions. I owe them warmest thanks.

Taking a research journey is many times like driving a bike on a hilly road. There are lot of long and steep uphill roads, but when you reach the top of the hill, you find a nice and fast downhill. Unfortunately the descent is always a short one, and after the descent there is another uphill. The terrain in the realm of research is never flat.

Other post-graduate students and the younger staff at the Department of Forest Sciences, and at its predecessors, have formed a lively working group, in which discussions have ranged widely from work to leisure. I am grateful to them, and to my family and friends, for helping me with the uphill of my journey. The biggest push has come from my Terhi, and I am grateful to her for all the help and companionship on this route.

Viikki, August 2010

Mikko Havimo

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INTRODUCTION

In Finland, spruce and pine are the most important raw materials for the forest industry: the use of both exceeded 57 million m³ in 2007, which constituted almost 80 % of the total wood consumption (Peltola 2008). Of this softwood raw material flow, 50 % was pulpwood used in mechanical or chemical pulping. The pulps were further processed to various paper and paperboard grades, including printing papers.

Printing and writing papers have been the main products of the Finnish paper industry for decades and their production grew steadily from the 1960s onwards (Diesen 1998). The production reached an all-time record of 10 million tonnes in 2004 (Peltola 2008), but only a few years later, the industry faced serious problems, which led to large cutbacks in paper production. These cutbacks concerned mainly mills producing printing papers. In 2008, the worst year, the shutdowns of printing paper mills permanently eliminated capacity of one million tonnes (Peltola 2008).

In 2008 and 2009 the world economy encountered the worst crisis since the Great Depression in the 1930s (Gylfason et al. 2010). The recent economic recession was not the main reason for the mill shutdowns; it did, however, accelerate the already planned structural changes (Valtonen 2009). These changes result from an overcapacity on the European markets, which is the main market area for the Finnish paper industry (Virta 2008), as well as from slow or negligible growth in number of paper grades (Hetemäki 2005, Suhonen 2006, Soirinsuo & Hetemäki 2008). This slow growth is a result of the rapid replacement of printed media with new information and communication technology (ICT) (Hetemäki 2005).

Yet, although ICT is replacing printing papers as a communication and advertising media, printing papers are expected to remain a powerful communication media also in the future (Suhonen 2006). The recent mill shutdowns have decreased capacity, but it is still above the level of the mid '90s (Peltola 2008). Therefore, printing papers will continue to be a significant product, but their competitiveness has to be maintained. This requires better products at lower prices, but in such a mature industry as papermaking, improving paper properties and reducing production costs can be a challenging task.

In the case of printing papers the maintaining of competitiveness means, for example, improved optical and mechanical properties with a reduced amount of fibres and energy. One alternative to improve printing papers is the careful control of wood raw material properties. Wood has large variation in various properties, including density (e.g. Hakkila 1966, Uusvaara 1974, Jyske et al. 2008), fibre length (e.g. Saranpää 1994, Molteberg & Høibø 2006, Rautiainen & Alén 2009) and cross-sectional dimensions (e.g. Lundgren 2004, Molteberg & Høibø 2006, Jaakkola et al. 2007). At the moment this variation is not controlled in most pulp and paper mills, although at least two pulp mills in Sweden have segregated Norway spruce pulpwood according to its properties (Spångberg 1999), and in Finland some mills pulp sawmill chips and round pulpwood separately.

In practice the variation can be utilised most conveniently by classifying the wood material into separate classes, and either processing these classes separately or blending them in a controlled manner. The benefits are enhanced properties of the end product (e.g. Tyrväinen 1995, Braaten 1997, Rautiainen & Alén 2007a), or savings in the production process (e.g. Spångberg 1998, Bradley et al. 2005). The control of wood variation is understood in this study as a method to create raw material classes with distinct properties.

The method can be any technological procedure, such as sorting of logs or fractionation of fibres.

The efficiency and functioning of control methods has been previously studied experimentally (e.g. Duchesne et al. 1997, Spångberg 1998, El-Sharkawy et al. 2008), but the experimental studies include large sorting operations in a forest or log yard, or special devices for separating fibres after pulping. Both are expensive and time consuming operations.

An alternative for experimental methods are simulations. They are an inexpensive method to study theoretically different control methods, and are therefore utilised in this study for evaluating controlling of tracheid cross-sectional dimensions. Detailed measurements of wood properties are needed when simulations are developed; therefore, high resolution measurements combined with property distributions are utilised here. Simulations can be used to screen the most potential control methods for further studies, but experimental methods are still needed to confirm the results found with simulations.

Mechanical and optical properties of printing papers depend, among with other things, on tracheid cross-sectional dimensions, that is, on the cell wall thickness and radial and tangential diameters (Middleton & Scallan 1992, Paavilainen 1992, Braaten & Molteberg 2004). By controlling the amount of tracheids with different cell wall thicknesses and diameters, the properties of paper can be tailored to meet certain end product requirements. If the controlling is efficient, the amount of tracheids needed to reach the requirements can be minimized.

Another field of printing paper production in which the control of raw material properties can yield significant improvements is mechanical pulping. It is an energy-intensive pulping method, which is used to produce pulp, for example, for magazine and newspaper mills. The classification of raw materials according to their energy consumption and the processing of raw materials lots separately are one alternative for saving energy and improving the economy of the process. Studies with Radiata pine (*Pinus radiata*) show considerable decrease in the energy consumption of mechanical pulping when the pulped logs are segregated according to their acoustic properties (Bradley 2005). Also, classification based on annual ring width and harvest type resulted in energy savings at a given freeness level (Spångberg 1998), but classification based on wood origin (thinnings, clearcuts or sawmill chips) has not been a successful way to reduce energy consumption (Tyrväinen 1995).

Energy consumption in mechanical pulping is a complex phenomenon, which is a result of interaction between the machinery and wood material. Since wood viscoelasticity plays a large role in this interaction (Salmén et al. 1999), classification of pulpwood according to its viscoelastic properties could result in energy savings.

This thesis deals with two subjects: tracheid cross-sectional dimensions and wood viscoelasticity, which are both discussed in the context of controlling wood properties. The application area is printing papers, but the results can be partly applied to other paper grades or products made from wood. Tracheid cross-sectional dimensions, their variation in Scots pine and Norway spruce and control of variation are discussed in three articles (I, II and III). The relationship between wood viscoelasticity and mechanical pulping is covered in the last article (IV).

Tracheid dimensions

Different control methods can be used to sort wood raw material, but the improvement of printing paper properties by classification requires a detailed knowledge of variation of tracheid dimensions in different classes, such as in different parts of trunks, between trunks or in pulpwood and sawmill chips. The relationship between given paper property and cross-sectional dimensions is also of concern, as it determines how fibres affect light scattering, tear strength or other properties. This section examines previous literature on these issues, and includes brief summaries on the measurement methods used to determine cross-sectional dimensions and biological explanations of the origin of variation.

In the pulp and papermaking discipline the term fibre is used to describe all cell types used in the paper raw material. In wood anatomy fibre refers to cell type found in angiosperms, which give mechanical support to the trunk (see e.g. Mauseth 2003). This study deals only with gymnosperm tracheids, and in those sections in which papermaking is discussed, the term fibre is used synonymously with tracheid.

Measurement methods

Tracheid cross-sectional dimensions can be determined with a light microscope, but the problem is the vast manual work needed to prepare and measure samples. The amount of work grows rapidly when the dimensions in different parts of the stem or in a whole stand are characterised. For example, the number of measurements needed to cover the variation in a stand can be illustrated with a strategy that takes into account the variation on four levels: between trees, between heights, from pith to bark and between earlywood and latewood. If we assume that five samples should be taken from tree, height and pith to bark levels, and we measure five tracheids from earlywood and latewood separately, we get $5 \times 5 \times 2 \times 5 = 1250$ measurements. This is not an exceptionally high figure: recent wood anatomical studies have included the measurement of 2000 - 22 000 xylem cells (see e.g. McCulloh et al. 2004, Weitz et al. 2006).

The preparation of samples for light microscope measurements includes multiple steps. Together they form the most time consuming phase of the work (see Schweingruber 2007 for sample preparation). The actual measurement of tracheids with a light microscope is also laborious and prone to human errors.

In recent decades, the development of digital imaging and image analysis with computers has resulted in major improvements in the measurement of tracheid dimensions. Several different measurement devices utilising these new techniques have been built. In semi-automated devices measurement from a digital image is automated, but image taking and movement of samples are manual (e.g. Sarén et al. 2001). In the most advanced devices these phases are also automated. Devices such as kajaaniFiberLab (Metso automation, Helsinki, Finland) and SilviScan (Evans 1994) belong to this group. Their operating principles and application areas differ, but the basic principles are similar. The automation of measurements has made the measurement of large numbers of tracheids fast, reliable and moderately inexpensive.

Within tree variation of cross-sectional dimensions

The observed variation in tracheid dimensions depends heavily on the observation scale. For example, the perimeter of *Pinus radiata* tracheids ranges from 50 to 240 microns if the

perimeter is measured from 50 to 100 individual tracheids (Downes et al. 2004). At the whole tree level the average perimeter shows smaller variation, ranging from 116 to 141 microns, although the whole tree sample includes more than one million tracheids. The example illustrates the effect of calculating averages from tracheid dimension data: the extreme dimension values tend to cancel each other out, reducing variation between average values. This is one reason for determining distributions for tracheid dimensions, as the distributions contain more information on variation than mere average values.

One of the earliest rules developed for predicting the tracheid dimensions in conifers are the five Sanio's laws, determined by German scientist Karl Sanio in 1872, after observing tracheid dimensions of Scots pine (Sanio 1872). The laws, according to the translation from German by Bailey & Shepard (1915), are as follows:

1. In the stem and branches the tracheids everywhere increase in size from within outward, throughout a number of annual rings, until they have attained a definite size, which then remains constant for the following annual rings.
2. The constant final size changes in the stem in such a manner that it constantly increases from below upward, reaches its maximum at a definite height, and then diminishes toward the summit.
3. The final size of tracheids in the branches is less than in the stem, but is dependent on the latter, inasmuch as those branches which arise from the stem at a level where the tracheids are larger themselves have larger tracheids than those which arise at a level where the constant size is less.
4. In the gnarled branches of the summit the constant size in the outer rings increases toward the apex, and then falls again, but here irregularities occur which may be absent in regularly grown branches.
5. In the root the width of the elements first increases, then falls, and next rises to a constant figure. An increase in length also takes place, but could not be exactly determined.

According to Mencuccini et al. (2007), the applicability of these laws to other coniferous species was debated in the early 20th century. Some initial tests supported the laws, but further investigations showed several discrepancies between measurements and the proposed laws (e.g. Gerry 1915). Some of Sanio's laws were tested recently with a large dataset collected from 24 independent studies (Mencuccini et al. 2007). The study confirmed that Sanio's second law is generally applicable to gymnosperms, but it also clarified that its applicability depended on the size of the tree. This chapter reviews measurements made from tracheid cross-sectional dimensions, and although there are some deviations from Sanio's laws, the literature mostly supports these laws.

Measurements on Norway spruce (*Picea abies* (L.) Karst.) show that the average tracheid diameter increases from pith to bark (Lindström 1997, Sarén et al. 2001, Mäkinen et al. 2002, Lundgren 2004, Molteberg 2006). The earlywood radial diameter was approximately 24 μm near the pith, and increased to 35 μm in the outermost annual rings (Sarén et al. 2001). The average tangential diameter is circa 23 μm near the pith, and can reach 30 μm in the outer annual rings (Lundgren 2004). On average the tracheid width varies in the trunk from 23 to 42 μm in Scots pine (*Pinus sylvestris* L.), and from 21 to 42 μm in Norway spruce (Atmer & Thörnqvist 1982).

The radial diameter increase shows typical juvenile – mature wood pattern: the increase is rapid in the juvenile wood zone, but steadies in the mature wood to a slower level (Lindström 1997, Lundgren 2004). Tangential diameter pattern from pith to bark is slightly

different from the radial diameter pattern. Tangential diameter can even decrease in the second and third annual rings, but after that it increases steadily towards the pith (Lundgren 2004).

In contrast to other studies, Molteberg & Høibø (2006) found decreasing tracheid width in mature wood of young Norway spruce stems. They reported average tracheid width of an annual ring, which included both earlywood and latewood tracheids. In their study material the annual ring width dropped in the outer growth rings, resulting in greater amounts of narrow latewood tracheids in the annual ring, and thus a decreasing trend in the tracheid width.

In Norway spruce stems, the tracheid width increases from stump to top until it reaches a maximum at 7-8 m height (Molteberg 2006). After this, the width decreases towards the tree top. According to another study, the width decreases continuously towards the tree top (Molteberg & Høibø 2006), but later this was argued to be due to the young age of the trees and poor resolution of measurements (Molteberg 2006). The growth rate of the tree also has an effect on the tracheid width: suppressed trees have narrower tracheids than dominant ones (Lindström 1997, Molteberg & Høibø 2006a).

In Scots pine, the cell wall thickness is on average 3.4 μm in earlywood and 5.7 μm in latewood (Ollinmaa 1959). In Norway spruce earlywood the average cell wall thickness is 3.3 μm and in latewood 5.5 μm , indicating that average thicknesses are quite similar in both tree species (Ollinmaa 1959). The cell wall thickness increases from pith to bark in Norway spruce (Mäkinen et al. 2002, Molteberg & Høibø 2006). However, some studies indicate that cell wall thickness can decrease after the first annual rings and then again increase in the outer annual rings, but they report cell wall thickness as an average of both earlywood and latewood tracheids (Lundgren 2004, Molteberg 2006). Sarén et al. (2001) measured cell wall thickness of 2.9 μm in the second annual ring from pith, and 3.4 μm in the 42nd annual ring, indicating that there is only a small difference in the cell wall thicknesses of inner and outer annual rings. At the same time the radial diameter increased from 24 μm to 35 μm , and tracheid length more than doubled from 1.4 mm to 3.6 mm.

In the vertical direction the cell wall thickness increases steadily from stump to top, but the increase is only of the order of 0.1 μm (Molteberg & Høibø 2006). Their results also show small differences between suppressed and dominant trees; in dominant trees the cell walls are thinner.

The biological origin of variation: concepts and models

Understanding the source of variation in tracheid dimensions forms the basis for forestry practices and control of variation. Several concepts and models have been developed for explaining the relationship between tracheid dimensions and such factors as growth rate or tree size. Some are based on the idea of cyclophysics, and others on functionalism.

The concept of cyclophysics is built around the hypothesis that the maturation of cambium determines the dimensions of tracheids. According to the definition of Olesen (1978), cyclophysics is "the process of maturation of the apical meristems". Maturation is then defined as the "stable juvenile-to-adult phase change and ageing". Since the cambial meristem originates from the apical meristem, the maturation of apical meristem during the height growth of the tree also results in the maturation of the cambium (Olesen 1977). The maturation in turn determines the tracheid dimensions produced by cambium.

The concept of cyclophysics has been utilised in several studies concerning wood properties (e.g. Mäkinen et al. 2002, Mäkinen et al. 2007, Jyske 2008). It has also been

developed further in a study by Sirviö (2000), who showed that maturity and growth rate control the properties of tracheids, and the maturity in turn is controlled by the amount of cambium and apical meristem produced. These, along with growth rate, depend on external factors such as climate or the position of the tree in the stand.

Other concepts explaining the determination of tracheid dimensions are based on functionalism, which assumes that all plant parts have certain functions (Mahner & Bunge 2001). The properties of the cells thus depend on how they fulfil these functions. The xylem has three main functions: to transport water to the needles, to provide mechanical support, and to store energy (Mencuccini et al. 1997). The tracheids carry out the transport and mechanical support functions; therefore their dimensions should reflect these two tasks.

Probably the most referred to model at the moment, which takes into consideration the transport and support hypothesis, is the so-called West, Brown and Enquist model (WBE) (West et al. 1999). The model is based on the allometric scaling laws, but it also utilises the hypothesis that the branches in different positions in the crown should experience the same hydraulic resistance. If this is not the case, the branches in the lower canopy get more water than the branches in the upper parts. The model can explain the tapering of water transporting conduits, that is, the width of earlywood tracheids, but assumes constant cell wall thickness. The validity of the model has been tested in several studies, but there seems to be no wide understanding of its soundness. Some experimental studies support the model (e.g. Anfodillo et al. 2005) or give partial support (Meinzer et al. 2005), but other studies which the whole model (Reich et al. 2006, Fan et al. 2009). There also exist other theories, based on hypotheses derived from the water transport function, such as the model proposing that the conduit diameter can be derived from Murray's law (McCulloh et al. 2004).

The WBE model and Murray's law do not explain the thickness of the cell wall, but there exist other theories, based also on functionalism, which give insight into the determination of cell wall thickness. The function of the cell wall is clearly to give mechanical support, but interestingly, the stress due to the above growing biomass may not be the greatest load. Water is transported to needles under negative pressure. The pressure in the water column loads the cell wall, and this stress can be larger than the stresses created by wind or snow loads. Hacke et al. (2001) have developed a model based on the implosion hypothesis, on the assumption that the water pressure may cause the cell wall to collapse into the lumen. The measurements also support the model (Hacke et al. 2001). The implosion hypothesis gives a partial explanation for the tracheid cell wall thickness, but it cannot explain the thickness in latewood cells, whose main function is not water transport.

The above-mentioned concepts and models give significant insight into the relationship between various external and internal factors and tracheid cross-sectional dimensions, but they also demonstrate that the picture is not complete. The discipline has fragmented into several theories, and there seems to be no single theory, or set of theories, which could give theoretical explanations for all tracheid cross-sectional dimensions.

The biological origin of variation: experiments

Although the theoretical studies give useful insight into the issue, they are difficult to utilise in applied problems such as control or forest management. In applied research, experimental studies are often the main research method. Experimental studies concerning the effect of growth conditions on tracheid dimensions are performed in long-term field experiments, where different silvicultural measures are applied to stands.

Thinning intensity experiments with Norway spruce show that enhanced growth rate decreases cell wall thickness and increases lumen diameter. However, the changes in these dimensions were only minor, although the growth rate increased 31-37% (Jaakkola et al. 2005). Combined thinning and fertilisation treatments also gave similar results (Jaakkola et al. 2007). On the other hand, in an experiment in which the water and nutrient supply of Norway spruce was optimised, the effect on tracheid dimensions was statistically significant (Lundgren 2004). The cell wall thickness decreased and radial diameter increased, whereas the treatments had no effect on tangential diameter. However, this experiment was carried out in stands which were constantly fertilised and irrigated to obtain very high annual growth, ranging from $14 \text{ m}^3\text{a}^{-1}$ to $29 \text{ m}^3\text{a}^{-1}$ (Bergh et al. 1999). Such extreme growth is rarely found in natural or managed forests in Finland.

Empirical models provide tools for predicting cross-sectional dimensions in various circumstances. They can also be used in situations where the mechanistic models presented above fail, but are restricted to cases which are similar to the data used in the construction of the model. This may in some cases limit their usefulness.

Mäkinen et al. (2002) developed regression models for predicting the fibre length, fibre diameter, cell wall thickness and lumen diameter in Norway spruce. The models use either distance from the pith or the number of annual rings as an independent variable. Later improved models, based on a larger data set, were developed (Mäkinen et al. 2007). Annual ring width, ring number and site quality were independent variables in these models. Since site quality was included in the models, they can be used to predict cross-sectional dimensions in different stands. Also, Molteberg (2006) developed regression models for predicting the cross-sectional dimensions of Norway spruce, with sample material from Norway.

Paper properties and tracheid cross-sectional dimensions

The literature reviewed in the previous chapters showed how tracheid cross-sectional dimensions depend on the biology of trees and growth conditions. The next question is how dimensions and their variation affect to printing paper properties: which properties depend on cross-sectional dimensions and to what degree. Paper properties also depend on the treatments done in the pulp and paper mills, but if the quality of fibres is low, it cannot be overcome with treatments (Paavilainen 1994). Most of the articles reviewed in this chapter consider paper made from sulphate pulp fibres, but the discussion is also broadly applicable to papers made from mechanical pulps. However, one has to bear in mind that in mechanical pulps the amount of fines is considerable, and they strongly influence the structure and properties of the fibre network (Retulainen et al. 1999, Braaten 2000).

Density is one fundamental property of paper. The density of paper made from pure latewood kraft pulp is approximately 440 kg/m^3 , while the density of paper made from pure earlywood kraft is circa 590 kg/m^3 (Retulainen 1991). The earlywood tracheids give denser paper, because their thin cell walls collapse easily in refining. The result is a flat fibre, in which the tracheid lumens have almost completely disappeared. In contrast, the lumens of thick-walled latewood tracheids remain almost intact in mechanical treatments, increasing the volume of voids in the paper.

During manufacturing, and in end-use applications, paper is seldom loaded near ultimate failure stress (Niskanen & Kärenlampi 1998). In many practical cases the elastic modulus of paper is therefore interesting, as it determines the behaviour in loading conditions below failure stress. The density of paper has a great effect on the modulus of

elasticity: high density paper also has high stiffness (Niskanen & Kärenlampi 1998). Because density depends on cell wall thickness, paper made from earlywood tracheids has a notably larger modulus of elasticity than paper from latewood tracheids (Retulainen 1991).

Flexibility of tracheids is an important property for the mechanical strength of paper, because the area of fibre-fibre bonds depends on it (Paavilainen 1994). When the paper web consolidates from the water-pulp suspension, flexible fibres get easily close to each other. This, together with the collapse of the lumens, increases the bonded area between the fibres. The bonded area depends mainly on the cell wall thickness (Paavilainen 1994). Theoretical studies on paper strength show that high relative bonded area (RBA) in paper gives good tensile strength (Niskanen & Kärenlampi 1998). Since flexible fibres have high RBA, fibres with thin cell walls should give high tensile strength. Several experimental studies support this view: the tensile index decreases as cell wall thickness increases (Retulainen 1991, Paavilainen 1993, Braaten & Molteberg 2004).

Thin cell walls are preferable for high density, good stiffness and high tensile index, but there is one mechanical property of paper which benefits from thick cell walls. The tear index of paper increases with increasing cell wall thickness (Paavilainen 1993, Braaten & Molteberg 2004). The tear index nearly doubles as the cell wall thickness increases from 2.0 μm to 2.8 μm (Braaten & Molteberg 2004).

The light scattering coefficient is the only optical property which depends on the tracheid cross-sectional dimensions. The scattering of light from paper is a complex physical phenomenon, which depends on such parameters as fibre size, geometry and material properties (Leskelä 1998). However, suitable modelling work can provide a good insight into the relationship between cross-sectional dimensions and paper optical properties. Middleton & Scallan (1992) developed a mechanistic model of light scattering for papers made from bleached kraft pulp. They assumed that in the sheet all lumens have collapsed, there are no interfibre bonds, the fibres are hollow cylinders and their chemical properties are similar. The light scattering depends only on the cell wall thickness, since at a given basis weight, lower cell wall thickness results in a larger fibre surface area. According to the theory, the light scattering increases as the cell wall thickness decreases.

The model systematically underestimates light scattering when compared to the measured light scattering coefficients, but it still gives satisfactory results. Other experimental studies also indicate that the light scattering coefficient decreases as the cell wall thickness increases (Paavilainen 1993, Braaten & Molteberg 2004).

Cell wall thickness is by far the most important cross-sectional dimension from the point of view of both mechanical and optical properties. The radial and tangential diameters seem to have little effect on these properties, although they should to some extent contribute to the fibre collapsibility. According to Braaten & Molteberg (2004), the cell wall thickness alone explained 77% of the variance of tensile index, and no other fibre property, including fibre width, significantly improved the variance. A similar observation was made for the tear index.

Viscoelastic properties of wood

Control of wood properties for reduced energy consumption in mechanical pulping

Tracheid cross-sectional dimensions markedly affect the properties of printing papers, as was seen in the previous chapter. These properties are important in the end-uses of printing

papers. Another field in which classification of wood raw material can be used to enhance the competitiveness of printing papers is mechanical pulping. Mechanical pulps are used in various printing paper grades, and they have several good aspects, such as high pulping yield and good optical properties (Sundholm 1999). However, the downside of mechanical pulping is low energy efficiency and the subsequent need for large amounts of electrical energy (Sundholm 1999). The low energy efficiency of the process has even been called “the Achilles’ heel of mechanical pulping” (Salmén et al. 1999).

The classification of pulpwood is an interesting possibility for gaining energy savings in mechanical pulping. It has been previously studied on a mill scale. In a study by Tyrväinen (1995) wood raw material was sorted into three classes: regeneration cutting pulpwood, first thinning pulpwood and sawmill chips. In the subsequent thermomechanical pulping (TMP) there was no major difference in energy consumption on a given freeness level. On the other hand, sorting of pulpwood according to harvest type and annual ring width resulted in a 22 % difference in average energy consumption between the best and worst classes, but the variation within classes was still large, and the effect of sorting was not statistically significant (Spångberg 1998).

In another mill trial, sorted Radiata pine pulpwood showed 20 % reduction in energy consumption at a given freeness level between the best and worst classes (Bradley et al. 2005). The sorting was based on the speed of sound in the logs, and high and low speed logs formed different classes. Speed of sound c in viscoelastic material depends on density ρ , dynamic modulus E^* and loss angle δ (Lakes 1999).

$$c = \sqrt{\frac{|E^*|}{\rho}} \sec \frac{\delta}{2} \quad (1)$$

The loss angle is a measure of viscoelasticity. Wood viscoelasticity, on the other hand, is closely related to energy consumption in mechanical pulping (Salmén et al. 1999). After all, viscoelasticity is a material property that converts mechanical energy into heat (Lakes 1999).

The experiments of Bradley et al. (2005) provide a link between wood viscoelasticity, wood classification and energy consumption in mechanical pulping. Therefore, log sorting based on acoustic measurements seems to be an interesting method for gaining energy savings. The experiments made with Radiata pine could be duplicated with Norway spruce, which is the common raw material in mechanical pulping in Finland. However, mill trials, or even trials made on the pilot plant scale, are extremely expensive. Before one starts such experiments, the subject should be known very well. In this study therefore, the literature on the viscoelasticity of wood and its effect on the energy consumption in mechanical pulping is reviewed. The aim is to prepare the ground for further experimental studies on the sorting of wood according to its dynamic properties.

One of the main questions relating to wood viscoelasticity and mechanical pulping is the variation of viscoelasticity between tree species, between trees and within trunks. Similarly to the case with tracheid dimensions, a basic knowledge of variation provides a basis for the development of control methods. Another question is how viscoelasticity is related to other wood properties such as tracheid dimensions or wood density. The variation in these properties may also explain the variation in viscoelasticity. Finally, the interaction between the machine and wood in mechanical pulping has to be understood, since the measured relationship between wood acoustic properties and energy consumption can be a result of a third, more fundamental property.

Viscoelasticity and mechanical pulping

As a background to viscoelasticity and mechanical pulping, the fundamental aspects of both are discussed in this chapter.

Viscoelastic materials can be defined as being between fully elastic solids and viscous fluids (Christensen 1982). Elastic materials have an ability to store mechanical energy with no dissipation. On the other hand, Newtonian viscous fluid can dissipate energy, but not store it. Viscoelastic materials fall between these two extremes: they can both dissipate and store energy. All real materials show some degree of viscoelastic behaviour, but in some materials, such as wood or polymers, the behaviour can have great practical significance.

Basic research conducted on viscoelasticity has yielded an extensive mathematical theory, which can be used for gaining more insight into viscoelastic behaviour (Christensen 1982). However, measurements are still the main tool to gain knowledge on the viscoelastic response of material (Lakes 1999).

The relationship between wood viscoelasticity and mechanical pulping is most easily understood through the current grinding theory. The theory, summarized by Enström et al. (1990), divides grinding into three parts:

1. Heating and softening of the wood matrix caused by periodically compressing and releasing forces.
2. Fibre release caused by shearing forces. The fibres are peeled off from the wood matrix.
3. Transport of fibres out of the grinding zone. During this stage the fibres undergo some regrinding.

Viscoelastic properties of wood are particularly important in part 1. Periodic compression and release of wood causes stress waves, which propagate through wood. Viscoelasticity converts the mechanical energy of stress waves into heat, causing a temperature rise in the wood. When temperature rises enough, lignin shows glass transition behaviour, in which several material properties change rapidly (Salmén 1984, Olsson & Salmén 1997). One property that changes in the glass transition region is the storage modulus. The temperature raise yields lower storage modulus, or in other words, wood softens. This softening is necessary for the gentle release of fibres from the wood matrix: too stiff fibres tend to break, which results low quality pulp. On the other hand, at the glass transition region the viscoelastic properties of wood also change rapidly, causing an increase in heat losses. Thus there is a trade-off between the quality of the pulp and energy consumption.

Some of the concepts presented in the theory of grinding are also applicable to refining, but the major difference between grinding and refining is the large heat and mass transport processes in the latter. According to Illikainen et al. (2008), the current refining theory assumes pulp pad refining. In the inner refining zone the amount of fibres is high enough to allow a compressed bed to form between rotor and stator plates. The refining occurs inside this pulp bed. As in grinding, the softening of fibres is essential for gentle refining (Salmén et al. 1999). On the other hand, the heat generation in refining does not solely depend on damping of the dynamic loading. Viscous heating due to fluid flow is another mechanism converting mechanical energy into heat. It is important in processes where large velocity gradients occur (Bird et al. 2007), as in the refiner plate gap, where large amounts of pulp-water suspension flow through the narrow gap.

Control of wood variation

Control methods

Previous chapters showed the relationship between tracheid cross-sectional dimensions and paper properties, and the link between wood viscoelasticity and mechanical pulping. These properties can be controlled by dividing the wood raw material into different classes.

The current practice in Finnish chemical pulp mills is to debark, store and cook hardwoods and softwoods separately. Norway spruce and Scots pine are instead often mixed during the storage and cooking process. In Sweden, pulpwood is generally processed in three different categories: spruce, spruce mixed with pine and hardwood (Duchesne 1997). It is therefore of interest to know how much tracheid cross-sectional dimensions differ between Scots pine and Norway spruce.

The easiest method of controlling wood properties in the pulp mill is by handling and cooking sawmill chips and round pulpwood separately. The main benefit of this separation is the longer fibre length in the pulp made from sawmill chips, as the fibre length is higher in the outer parts of the stem than in the inner parts (Saranpää 1994, Lindström 1997, Rautiainen & Alén 2009). Sawmill chips and round pulpwood arrive in separate loads to the mill, and thus there is no extra cost for sorting them, although the separate handling systems and storages for both assortments cause some additional costs.

If sawmill chips are not available, or more efficient control of wood properties is needed, there are four main techniques to create wood classes for pulp and papermaking: 1) sorting logs in the forest, 2) sorting logs or truckloads at the mill, 3) sawing logs into different parts at the mill or 4) fractionating fibres after pulping. Each control technique has its own advantages and disadvantages. The choice between techniques depends on several aspects, such as costs, available technology and efficiency.

Sorting of roundwood can be done either by grouping individual logs or entire truckloads. When logs or truckloads are sorted, different groups are distinguished from each other by using suitable sorting criteria. Several different sorting criteria have been employed, including log type, tree class or harvest type (Tyrväinen 1995, Duchesne et al. 1997, Spångberg 1999). Spångberg (1998) studied extensively different sorting methods, and found that sorting between stands or between logs is more precise if the annual growth ring pattern is used as a sorting criterion. Utilising harvest type or log type as a sorting criterion is not as efficient as utilising growth ring pattern.

Log sorting can already be done in the forest by the harvester operator; the sorted classes are then handled separately during the forest and road transports (Rissanen & Sirviö 2000). Another place to sort logs is at the mill's log yard. If the sorting is done at the mill, there is no need for handling separate log assortments during transport, which lessens planning and logistics. However, log type or tree class information is available only at the forest sorting, which means that sorting at the log yard has to rely on sorting criteria that can be measured from logs.

Sorting logs according to the position of the bolt in the stem (top log or middle/butt log) and social status of the tree in the stand (dominant or suppressed) resulted in only minor changes in the mechanical properties of paper (Duchesne et al. 1997). Compared to the average paper properties, the tensile index could be raised 4% and tear index 7% with sorting. When mean growth ring width and the age of the log was used as sorting criteria, log sorting gave more pronounced differences between groups (Wang & Braaten 1997). The tensile index was 25% higher in the paper made of young logs with wide rings

compared to paper from old logs with narrow rings. On the other hand, the tear index of paper from young logs was then only 64% of the tear index of paper from old logs.

Spångberg (1999) compared the classification of pulpwood as truckloads or individual logs. He used mean growth ring width or harvest type as a control variable for truckloads, and log diameter, annual growth ring width or number of growth rings as a control variable for individual logs. The experiment did not include the preparation of hand sheets, but wood properties such as basic density and ISO brightness were compared. The results showed that sorting truckloads was a more effective way than sorting individual logs for creating classes with distinctive average properties. However, the standard deviations were nearly the same in the sorted truckload classes as in the unsorted pulpwood.

Wood variation is commonly larger within trunks than between trunks (Spångberg 1998, Jyske 2008, Rautiainen & Alén 2009). Splitting the trunk into different parts and processing these parts separately is therefore a promising method to create classes with distinct properties. The separation of juvenile and mature wood into their own classes can be especially efficient, since these parts of the trunk differ greatly in several properties. Juvenile wood is generally characterised by low density, thin cell walls and short tracheids with large lumens, high grain angle and high microfibrillar angle (Saranpää 1994, Lindström 1997, Lichtenegger et al. 1999, Macdonald & Hubert 2002, Mansfield et al. 2009). Juvenile wood properties are considered inferior in most applications, and papers made from juvenile wood have low strength properties, porosity and surface roughness (Brolin et al. 1995, Tyrväinen 1995). On the other hand, these papers have fairly good optical properties, and therefore juvenile wood may find use in paper grades where optical properties are important (Rautiainen & Alén 2007b).

Separating juvenile wood and mature wood by sawing the logs has been studied by Rautiainen & Alén (2007a). They sawed trunks of first-thinning Scots pine into inner and outer parts, and cooked kraft pulp from these separate classes. The inner part was a slab of 5*5 cm from the centre of the log, while the outer part was the rest of the trunk. The partition of the log resulted in only minor differences in paper optical and mechanical properties when compared to the whole tree pulp. The light scattering coefficient was higher in the paper made of inner part pulp, but on the other hand, the tear index was lower. Compared to a commercial reference pulp, the outer part pulp had a 6% smaller tear index, and the inner part pulp had 14% better light scattering. The outer part fraction was found to be a suitable substitute for pine kraft pulp in fine paper furnishes (Rautiainen & Alén 2007b).

Separation of pulp suspension into two or more streams is called fractionation. It can be done with devices which divide pulp suspension by mechanical barriers or hydrodynamical effects into accept and reject fractions (Karnis 1997). In practice, pressure screens and hydrocyclones are used to fractionate pulp suspensions according to their dimensions. The latter utilises hydrodynamic effects, and the former uses mechanical barriers for separating fibres. Hydrocyclones separate fibres according to their cross-sectional properties (Karnis 1997, Paavilainen 1992), whereas pressure screens separate fibres according to their length (El-Sharkawy et al. 2008).

The cell wall thickness correlates well with many mechanical and optical properties of paper. Hydrocyclones, Johnston fractionators and the the Jacquelin apparatus can be used to separate fibres according to cell wall thickness (Paavilainen 1992). Of these devices, the hydrocyclone proved to be the most efficient method to fractionate fibres. The fractionation produced pulps with low latewood content, good printing properties and high tensile

strength (Paavilainen 1992). The drawback of hydrocyclone fractionation is the high energy consumption, which is due to the pumping of large volumes of dilute pulp suspension.

Management and economics

Studies of controlling variation in wood seem to concentrate on technological solutions, although the issue includes also resource use strategies and economics of control processes. This section discusses about the requirements for suitable control method and economics of wood variation control.

The aim of control is to create classes with distinctive average properties. However, distinctive averages are not enough, since the same average value can be achieved with a narrow or wide variation within the classes (Figure 1). At best, the control method gives classes with small internal variation and distinctive average properties (Spångberg 1998). The effect of control methods can be illustrated by distributions, which, as Figure 1 shows, give comprehensive picture of the situation. A control method should divide the whole distribution into several narrow and distinct distributions.

Classes with different properties can be blended for obtaining a desired property combination. For example, good tensile strength can be obtained with thin walled fibres and tear strength by adding a suitable amount of thick walled fibres (see the chapter *Paper properties and tracheid cross-sectional dimensions*). The classification and subsequent blending provides a tool to optimise the paper properties and raw material consumption.

The classification of raw materials incurs costs, which have to be covered by improving the paper properties, or by using less raw material for the same amount of paper. Both cases seem to be possible in the light of literature reviewed in the chapter *Control methods*. The question is, is the improvement in paper properties large enough for covering the expenses? For example, the fractionation of fibres in the mill requires investments in the machinery, and also increases energy consumption and other operating costs. Therefore, significant improvements are needed to compensate for the costs of classification.

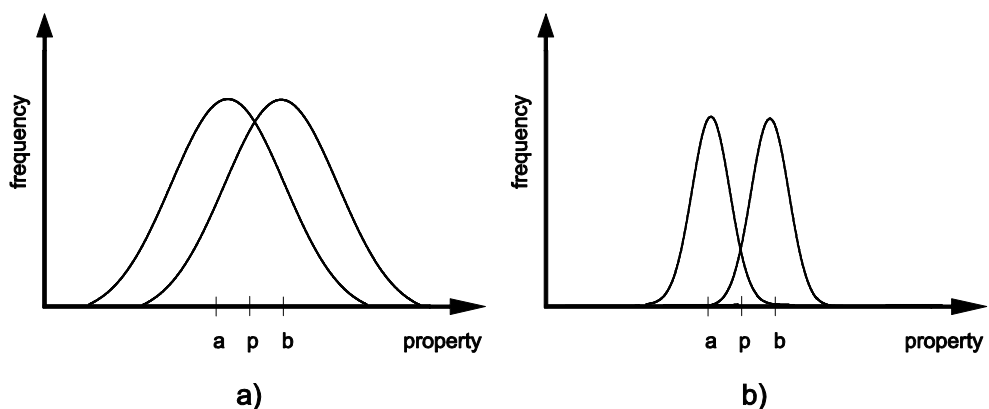


Figure 1. Schematic presentation of a property distribution. Subgroup averages a and b are similar in both figures, and yield the same population average p , although the distributions differ significantly

AIM OF THE THESIS

This study aims to develop methods for controlling tracheid cross-sectional dimensions and wood viscoelasticity. The application area is printing papers. Norway spruce and Scots pine chemical pulps are used in printing papers to give the paper suitable strength. In addition, mechanical pulp made from Norway spruce forms the major fibre component in such printing papers as high quality magazine paper or newspaper.

The aim of the study can be further refined into a set of research questions:

- How can large data masses, produced by new measurement devices such as SilviScan, be efficiently used to evaluate the variation in the tracheid cross-sectional dimensions?
- How large is the difference between cross-sectional dimensions in top pulpwood and saw mill chips?
- How effective are different control methods, such as sorting of logs according to their size or separation of juvenile and mature wood, for controlling the tracheid cross-sectional dimensions?
- How large is the difference in cross-sectional dimensions between Norway spruce and Scots pine, when these tree species grow in similar growth conditions?
- What is the variation of viscoelasticity between tree species, between trunks and within trunks?
- How does viscoelasticity depend on other wood properties, such as tracheid cross-sectional dimensions?

MATERIAL AND METHODS

Measurements

The material for studying tracheid cross-sectional properties was obtained from a mature pine-spruce stand near the Hyytiälä Forestry Field Station (61°49'N, 24°18'E, 170 m a.s.l). The trees were relatively large: in Norway spruce the diameter at breast height (dbh) ranged from 28 to 47 cm and in Scots pine from 39 to 59 cm. The stand was growing on a *Myrtillus*-type site (Cajander 1926).

We developed a systematic sampling strategy for obtaining a comprehensive picture of tracheid dimensions in the study stand. The stand level variation in cross-sectional dimensions was captured by taking sample trees from five size classes. Size classes were formed according to diameter at breast height, and one sample tree was randomly selected from each class. The sampling was done separately for Norway spruce and Scots pine. The variation from stump to top was sampled by taking discs from nine relative heights (from 0 to 88 %), and one additional disc from breast height. A total of 50 discs were collected from each species. The sample trees are described in Table 1.

Table 1. Characteristics of the sample trees. Size class 1 is the smallest and 5 the largest.

Pine			
tree class	average annual ring width, mm	tree height, m	diameter at breast height, cm
1	1.0	29	32
2	1.2	28	34
3	1.0	28	36
4	1.1	31	41
5	1.4	28	45

Spruce			
tree class	average annual ring width, mm	tree height, m	diameter at breast height, cm
1	0.9	22	25
2	1.1	26	31
3	1.1	24	32
4	1.2	27	36
5	1.7	30	41

The variation of cross-sectional dimensions in the horizontal direction was captured by taking a sample bar from pith to bark from each sample disc. The bars were dried under weight to room moisture content. Cross-sectional dimensions were measured with a SilviScan device at STFI-Packforsk (Stockholm, Sweden). A detailed description of the measurement method can be found in Evans (1994).

Data handling

The measurement of tracheid cross-sectional dimensions was tedious manual work before the advent of modern measurement devices like SilviScan. New methods provide rapid measurement of large sample sets, which is also done with a very fine resolution. The result is a large amount of raw data: the data set of this study included over 100.000 measurement points. The raw data produced by the SilviScan device from one sample disc is presented in Figure 2. The data consists of only the distance from the pith and the three cross-sectional dimensions: tangential and radial width, and the average of tangential and radial cell wall thicknesses.

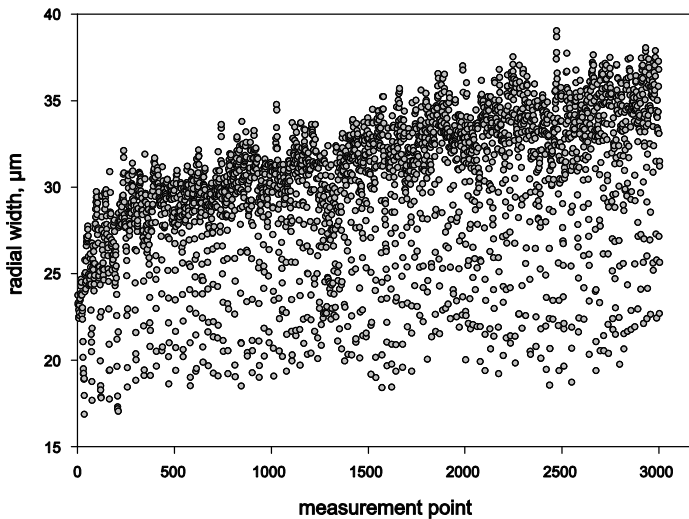


Figure 2. Radial width measurements in the SilviScan output format. The data includes only the number of measurement points and the measurement itself. The distance between measurement points is 50 µm. Norway spruce, size class 3, breast height.

Advanced measurement methods have solved problems in the laboratory, but at the same time they have created new problems in data handling. New methods have to be developed for the analysis of large data masses, or else the advantages from detailed measurements are lost. Large data masses are difficult to analyse manually or with programs like Excel. Programmatic analysis, in which specialized algorithms are developed for the problem at hand, is the most comprehensive approach.

Programmatic analysis is basically done by laying out a set of rules, which are then transferred into algorithms and implemented with programming languages. The raw data produced by the SilviScan device includes only the position information and three cross-sectional dimension measurements from each measuring point. Characters such as annual rings or latewood width have to be extracted from the data by using suitable rules.

The algorithms developed in this study were implemented with Mathematica (Wolfram Research Inc., Champaign, IL, USA) computational software. Mathematica was selected because it is easy to use in calculations and raw data handling. For example, the naming of variables and formatting of tables and functions is much simpler than with general-purpose programming languages, such as C/C++. Mathematica also includes vast graphical and statistical libraries, which make it efficient in data analysis. On the other hand, the programs written with Mathematica are not independent software; they can be run only with its kernel. In many cases the programs are also slow. However, these two complications are not decisive in this work, because the programs are used only once and the time needed for running the analysis is only 10-20 minutes.

The analyses in studies I, II and III were based on the concept of virtual tracheids and trees. Figure 3 illustrates schematically the construction of virtual trees. The program first used measurements to construct virtual tracheids, which were then extended to virtual trees. The virtual trees were implemented in the program by using multidimensional lists (called tables in Mathematica syntax). Each tracheid dimension value was stored in a list, and the position of the tracheid in the virtual tree was tracked from its index in the list. In practice the data structure was such that the tree class was the highest level on the list, height the second level, annual ring the third level, and the position from the beginning of the annual ring the fourth level.

The handling and analysis of measurement data with computers requires simplifying assumptions. When the virtual tree method was developed, these assumptions concerned the structure of trees. The assumptions were: trunks are perfectly round, there is an abrupt change in the lumen width between annual rings, the ends of tracheids comprise only a small amount of their total volume of tracheids, and in earlywood the lumen width is constant or almost constant. The last assumption implicitly assumes that the part of the annual ring in which the lumen width is not constant is latewood.

The virtual trees enabled the analysis of various virtual treatments, which simulate treatments like bucking or posting. The tracheid cross-sectional dimension in groups achieved with these treatments could then be easily derived from the data.

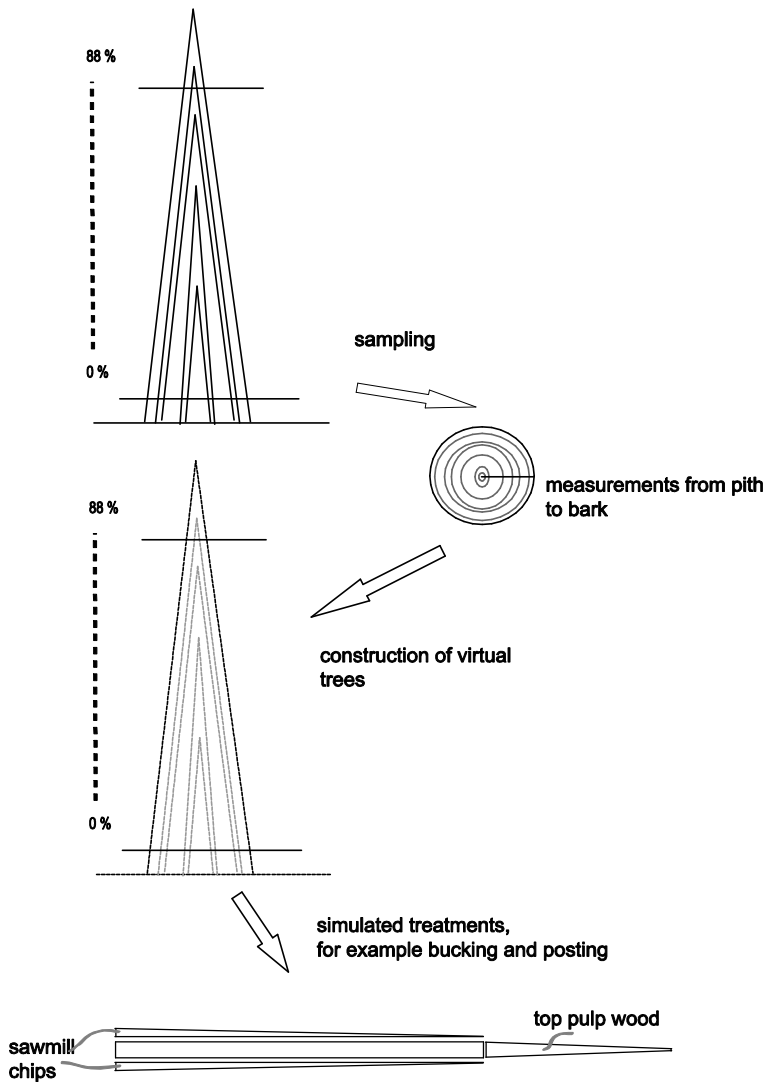


Figure 3. Sampling, measurement and virtual tree construction procedure

The data analysis

The aims of the study are operationalized by using various data analyses. For a example, in some pulp mills the pulp quality is controlled by processing saw mill chips and round pulpwood separately. This controlling method was simulated by dividing the virtual trees into saw mill chips and top pulpwood as described above (studies I and II). For comparison the dimensions and their variation are also presented for whole tree assortment. Also, mass-weighted average values for different wood assortments were calculated.

The data analysis in studies I and II gives a good insight into the variation in the tracheid dimensions, but several questions remain unanswered. First, the effects of juvenile and mature wood, or the dependency of tracheid dimensions on the size of the tree, were not included in the analysis. Second, the efficiency of different control methods was not fully explored. In study III these issues were analysed by dividing the virtual trees into earlywood and latewood, or juvenile and mature wood, or according to the size of the tree. These three treatments present existing control methods: the grouping into earlywood and latewood corresponds to the fractionation of pulp, the grouping into juvenile and mature wood corresponds to sawing of trunks into inner and outer parts, and the size class grouping corresponds to sorting of logs. At the same time they also give more insight into the origin of variation in the tracheid cross-sectional dimensions.

Study III approaches the efficiency of control methods by analysing variances and the sum of squares of the groups, which were created by dividing the population of virtual tracheids according to the above-mentioned control strategies. The sum of squares was derived from relation

$$SS_{total} = SS_{between} + SS_{within} \quad (2)$$

where SS_{total} is the total variation in a given property, $SS_{between}$ is the variation between the groups created with the control method, and SS_{within} is the variation within the groups. The efficiency of different methods can be compared by calculating the proportion of within variation of the total variation for each group:

$$\frac{SS_{within}}{SS_{total}} \quad (3)$$

The sum of squares gives an estimate of the theoretical efficiency of a given control strategy compared to other strategies, whereas the variance of a group gives variation in the raw material. A good control method has a small within variation compared to the total variation. This also leads to a small variance in one or more of the raw material groups. The theoretical efficiency is important in the development of a control method, since it gives an upper limit for the efficiency of the method. The real efficiency of the control method depends on the available technology, and can be determined experimentally.

For a better understanding of the variation of tracheid cross-sectional dimensions, and to statistically test the differences between different assortments, the χ^2 -test was utilised (Snedecor & Cochran 1967, Ranta et al. 1999). The test belongs to the family of goodness of fit tests, and in literature it is occasionally referred to as Pearson's chi-square. The test is suitable for testing data which is in the form of distributions. It compares expected and observed distributions, and gives a probability on whether the observed distribution is similar to the expected one. A distribution is formed from cells, the total number of which is n . Let o stand for set including all observed cells and e for set including all expected cells. For each cell the expected frequency is e_i and the observed frequency o_i .

The null-hypothesis of the test is:

$$H_0: \text{The distributions are similar, i.e., } o_i = e_i \text{ for all elements in sets } o \text{ and } e.$$

The test statistics are then calculated with the equation

$$X^2 = \sum_{i=1}^n \frac{(o_i - e_i)^2}{e_i} \quad (4)$$

After the test value χ^2 is calculated, it can be compared to the χ^2 distribution. The degrees of freedom df of the χ^2 distribution are $df = n - 1$.

The testing was done by using whole tree assortment as an expected distribution and top pulpwood and sawmill chip assortments as observed distributions. In addition, top pulpwood was compared to sawmill chips by using pulpwood as an observed distribution and sawmill chips as an expected distribution. The masses of the distributions were equalised in order to compare the shapes of the distributions. Two tests were made with different masses. In the first test the mass is equal to the total mass of tracheids in the stand (ca. 45 – 100 tonnes). The second test used the mass of a single A4 sheet (4 grammes). The reason for using two different masses is the sensitivity of χ^2 -test. The test finds differences between distributions more easily when the size of the sample is large. Therefore, two different size masses were compared.

RESULTS AND DISCUSSION

Tracheid dimensions

Three studies of the thesis are based on measurements made with the SilviScan, which is a fully automated device for measuring tree properties at a resolution of 50 micrometres. Due to this high resolution, the device produces vast amounts of raw data. The utilisation of large data masses requires new analysing methods, or otherwise the benefits of such vast measurements are mostly lost. One of the aims of this study was to develop new analysing techniques for tracheid cross-sectional data. Methods that can be connected to the control of wood variation were central to this development task.

Virtual trees form the basis of the analysing system developed here. They are generated from the measured tracheid cross-sectional dimensions by using a set of rules, which determine, for example, the border between the annual rings or earlywood and latewood. The virtual trees can be used to simulate the effect of various operations such as bucking or sawmilling.

Two analysis methods were developed in studies I and III to analyse the SilviScan data. Both methods utilised virtual trees for creating pulpwood, sawmill chips and whole tree assortments. In study I, property distributions for Norway spruce tracheid cross-sectional dimensions were generated. In the continuation study similar distributions were generated for Scots pine (study II). Distribution figures and average values can be utilised in the analysis of control methods. The controlling of tracheid cross-sectional dimensions by dividing wood into pulpwood and sawmill chips or earlywood and latewood were discussed in studies I and II.

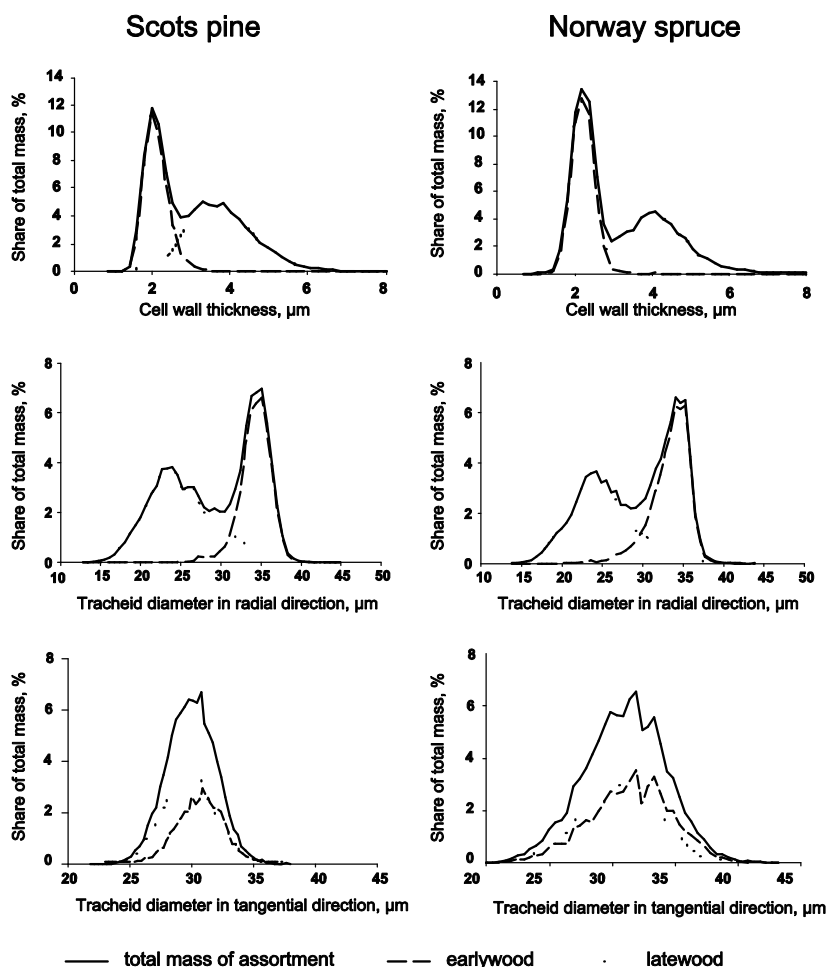


Figure 4. Cell wall thickness, radial diameter and tangential diameter distributions in Scots pine and Norway spruce. The distributions are calculated from the whole tree assortment, i.e., the distributions include all tracheids in the stand for each species. The original figures are published in studies I and II.

The distribution figures are a good method to visualise the effect of a control method, but when there are several control methods that have to be compared, this approach becomes awkward. Therefore, another method which could produce more simply interpretable results was developed in study III. The method is developed from the analysis of variances, and describes the efficiency of the control method.

The cross-sectional dimension distributions were calculated for Norway spruce in study I and for Scots pine in study II. The distribution figures presented here are obtained from these studies. There are major differences between earlywood and latewood in cell wall thickness and radial diameter: with respect to these dimensions, the earlywood has narrow and high distributions, whereas latewood distributions are flatter and wider (Figure 4). The forms of the earlywood and latewood distributions depend on how tracheids are separated

into these two classes. In this study, the separation is made with an algorithm which fits two linear regression curves to the annual ring data. The intersection of these curves is defined as the border between earlywood and latewood (Figure 5). There are other definitions for the determination of the earlywood/latewood boundary, such as Mork's definition (Mork 1928, Denne 1982). The method used here gives somewhat wider latewood widths than Mork's definition, because the regression curves locate the boundary at the position where the lumen widths start to decline. Mork's definition, instead, places the boundary at the position where the lumen widths have already declined and the cell walls widened.

The distribution which includes both earlywood and latewood tracheids is bimodal, but within the separate earlywood and latewood groups the distributions are approximately normal distributions. The cell wall thickness distributions are similar to that measured by Reme & Helle (2002) for 84-years-old Scots pine. The tangential diameter distributions are completely different from the cell wall thickness and radial diameter. The tangential diameter shows only a small variation between earlywood and latewood, and the total distribution is nearly a normal distribution.

Average tracheid cross-sectional dimensions in different wood assortments are presented in Table 4. The largest differences are between earlywood and latewood. The average cell wall thicknesses were 2.0 - 2.1 μm in the Scots pine earlywood and 3.5 - 3.8 μm in the latewood. In Norway spruce the thicknesses were of similar magnitude. The average cell wall thicknesses reported here are somewhat larger than in the previous study, where the average in Scots pine earlywood was 1.6 μm and in latewood 2.85 (Ollinmaa 1959). The average radial diameter was in all Scots pine tracheids ca. 29 μm , which corresponds to 30 μm measured by Ollinmaa (1959). The average tangential diameter varies only slightly between earlywood and latewood. Also, the differences between wood assortments are small, and the average tangential diameter is ca. 30 μm .

To statistically test the differences between assortments, a χ^2 -test setup was developed. The comparisons were made between top pulpwood and whole tree assortments, sawmill chip and whole tree assortments, and top pulpwood and sawmill chip assortments. Table 3 shows the test value and the p-value for both Scots pine and Norway spruce, when the distributions of mass of all fibres in the whole stand are compared. The p-values are in all cases below 0.000, which supports the conclusions that the assortments are different for all three tracheid cross-sectional dimensions. The practical conclusion is that large raw material lots, such as all pulpwood and sawmill chips from a single stand, have statistically different tracheid cross-sectional dimensions.

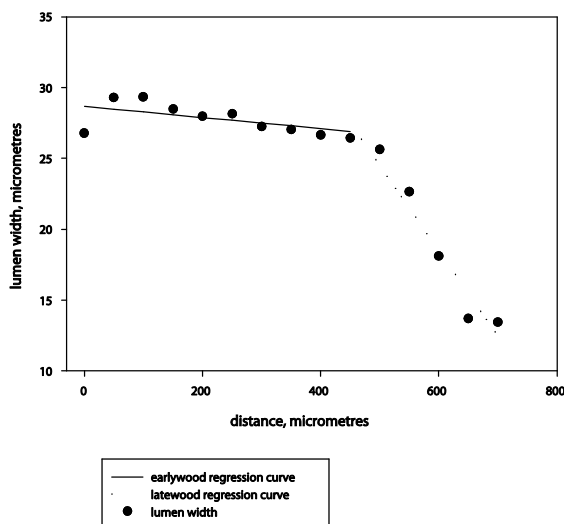


Figure 5. The division of tracheids into earlywood and latewood. The border between earlywood and latewood is defined as the intersection of the regression lines. The original figure is published in study I.

However, the conclusion is valid only in case where very large fibre masses are compared. If the total mass of the fibres is smaller, the test may yield different results (Ranta et al. 1999). To explore this, a comparison was made with a fibre amount that equalled the mass of a single A4 sheet. The results are presented in Table 4. In this case, some of the comparisons give significant support to the null-hypothesis. The cell wall thickness and the radial diameter were similar in all assortments of Scots pine. This was also the case with most assortments of Norway spruce, although the top pulpwood distribution differed significantly from the sawmill chip distribution.

The reason for the differences between the results of these two tests is the size of the sample. In the first case, the sample equals the mass of all tracheids in the stand (ca. 45 – 100 tonnes), whereas in the latter it equals the mass of one A4 sheet (4 grams). The downside of the χ^2 –test is that it finds differences more easily in large than in small samples, as was the case with the first test. The interpretation is in the hands of the scientist: which is more important sample size, the size of the end-product, or the size of one logging unit? Obviously there is no definite answer, and the interpretation of the test result depends on the problem at hand. Another problem is that after the null-hypothesis has been discarded in a test of goodness of fit, nothing precise can be said about the situation (Ranta et al. 1999). The test merely supports to further studies seeking the reasons for the differences between distributions.

Table 2. Comparison of property distributions in different assortments, when the amount of tracheids equals the mass of all tracheids in the stand. X^2 is the test statistics calculated with equation 4.

	Spruce					
	pulpwood compared to whole tree		sawmill chips compared to whole tree		top pulpwood compared to sawmill chips	
	X^2	p-value	X^2	p-value	X^2	p-value
radial width	125 174	<0.000	447 832	<0.000	73 073	<0.000
tangential width	362 212	<0.000	396 417	<0.000	165 101	<0.000
wall thickness	219 511	<0.000	243 194	<0.000	53 814	<0.000

	Pine					
	pulpwood compared to whole tree		sawmill chips compared to whole tree		top pulpwood compared to sawmill chips	
	X^2	p-value	X^2	p-value	X^2	p-value
radial width	12 472	<0.000	208 046	<0.000	5 503	<0.000
tangential width	12 533	<0.000	2 636 980	<0.000	484 695	<0.000
wall thickness	7 407	<0.000	380 072	<0.000	330 372	<0.000

Table 3. Comparison of property distributions in different assortments, when the amount of tracheids equals the mass of one A4 sheet (4 grams). X^2 is the test statistics calculated with equation 4.

	Spruce					
	pulpwood compared to whole tree		sawmill chips compared to whole tree		top pulpwood compared to sawmill chips	
	X^2	p-value	X^2	p-value	X^2	p-value
radial width	33.8	> 0.1	99	<0.000	189	<0.000
tangential width	80.2	>0.001	88	<0.000	427	<0.000
wall thickness	48.5	>0.1	53.8	>0.1	139	<0.000

	Pine					
	pulpwood compared to whole tree		sawmill chips compared to whole tree		top pulpwood compared to sawmill chips	
	X^2	p-value	X^2	p-value	X^2	p-value
radial width	1.1	>0.1	19	>0.1	14	>0.1
tangential width	1.1	>0.1	232	<0.000	444	<0.000
wall thickness	0.7	>0.1	35	>0.1	30	>0.1

The mixed pine-spruce stand was selected as the experimental stand for studying the differences between the tree species in similar conditions. The soil and climate are similar for all trees in the stand, so their effect can be excluded. On average the cross-sectional dimensions are quite similar in both species (Table 4). The differences in cell wall thicknesses between the tree species are 0-0.2 μm and in tracheid width 0-2 μm . The distribution figures (Fig. 6) show somewhat larger differences between the species than the average values suggest. The largest difference is in cell wall thickness distributions, where the proportion of earlywood tracheids is lower in Scots pine than in Norway spruce. Scots pine pulp therefore contains more thick-walled latewood fibres.

Studies I and II discussed how cross-sectional dimensions of wood raw material can be controlled if the raw material is divided into pulpwood or sawmill chips. Pulpwood and sawmill chips are processed separately in some Finnish pulp mills, and this separation can be seen as a control method. Distributions of tracheid cross-sectional dimensions are presented for Scots pine sawmill chips and top pulpwood in Figure 6. From a practical point of view, the differences between the assortments are small, and particularly cell wall thickness distributions are similar between sawmill chips and top pulpwood. The greatest difference is in the tracheid radial diameter. The radial diameter is wider in sawmill chips earlywood than in top pulpwood earlywood. Similar conclusions are also applicable to Norway spruce: cell wall thickness is fairly similar in both assortments, whereas the radial diameter of earlywood is larger in sawmill chips than in top pulpwood.

Because dividing wood raw material into top pulpwood and sawmill chips has only a minor effect on the cross-sectional dimensions, and especially on cell wall thickness, other control methods have to be developed. However, pulpwood and sawmill chips may differ in other fibre dimensions, such as fibre length.

Table 4. Cross-sectional dimensions in different assortments of Norway spruce and Scots pine

	whole stem		top pulp wood		saw mill chips	
	Scots pine	Norway spruce	Scots pine	Norway spruce	Scots pine	Norway spruce
cell wall thickness						
earlywood	2.0	2.1	2.0	2.1	2.1	2.2
latewood	3.7	3.9	3.5	3.9	3.8	4.0
all tracheids	3.0	3.0	2.9	3.0	3.1	3.1
radial width						
earlywood	34	33	33	32	34	34
latewood	25	25	24	24	25	25
all tracheids	29	29	28	28	29	30
tangential width						
earlywood	30	31	31	31	31	33
latewood	29	30	29	30	30	32
all tracheids	30	31	30	30	30	32

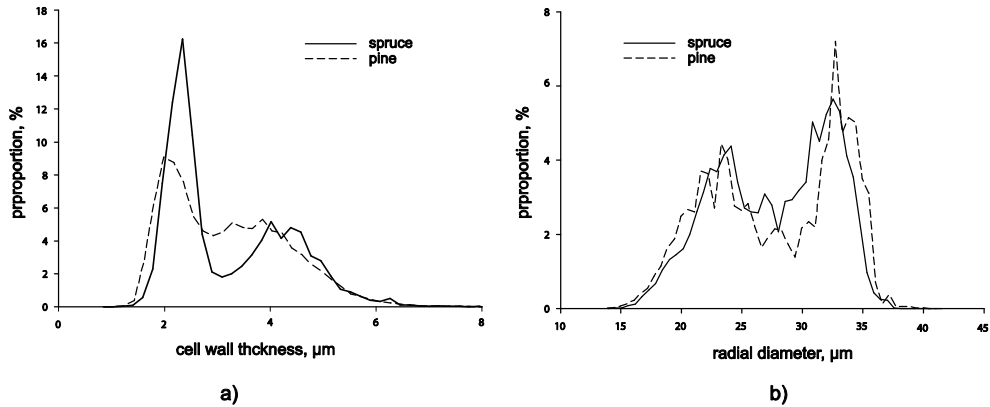


Figure 6. Differences in tracheid cross-sectional dimensions between Norway spruce and Scots pine. a) cell wall thickness in sawmill chips of both species, b) radial diameter in top pulpwood of both species.

The efficiency of three control methods were studied in study III: grouping of tracheids into earlywood and latewood, grouping into mature and juvenile wood and grouping according to size of the trees. In Figure 7 the efficiency of these control methods is compared by examining the proportion of within variation of the total variation. The radial diameter and cell wall thickness can be efficiently controlled by grouping tracheids into earlywood and latewood groups, but the tangential diameter cannot be altered with this method. Grouping into juvenile and mature wood is the second most efficient method, but it is far behind grouping into earlywood and latewood when the aim is to control cell wall thickness and radial diameter. However, the tangential diameter can be more efficiently controlled by grouping into juvenile and mature wood than into earlywood and latewood.

The low efficiency of grouping to juvenile and mature wood may partly stem from the small proportion of juvenile wood in the sample trees. The low juvenile wood proportion is the result of the low growth rate of the stand (Table 1). Another reason is that variation within the tree rings is much larger than between rings, and therefore the within ring variation obscures the between ring variation. Similar results have been obtained for wood density in Norway spruce: variation within annual rings was the major source of total variation within a trunk (Jyske et al. 2008).

Published experimental studies give an opportunity to compare how different control methods affect paper properties, but since the experimental setups differ between studies, it is somewhat difficult to find a suitable paper property for the comparison. However, at least in three studies a tensile index was measured from papers made of grouped raw material (Paavilainen 1992, Wang & Braaten 1997, Duchesne et al. 1997). In hydrocyclone fractionated pulp the difference in tensile index between the lowest and best class was 41 % (Paavilainen 1992), whereas the difference was only 5.5 % when the logs were sorted into dominant and suppressed classes (Duchesne et al. 1997). The sorting of logs from suppressed and dominant trees probably resulted in a poor performance because the within tree variation is larger than between tree variation (Spångberg 1998, Jyske 2008, Rautianen & Alén 2009).

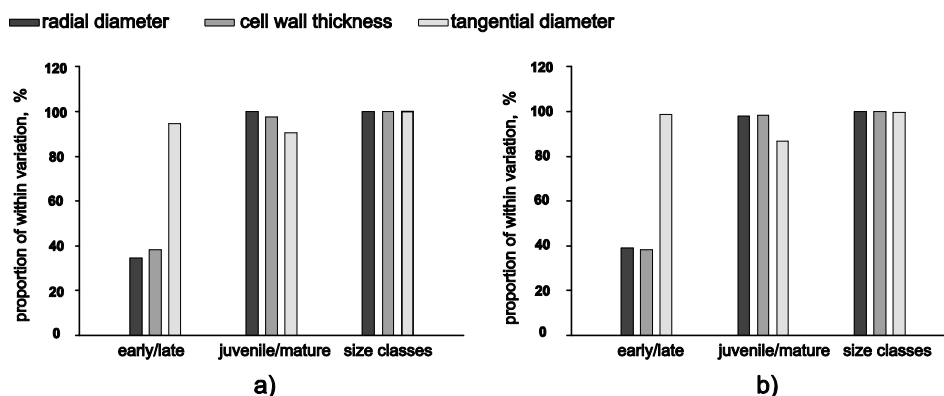


Figure 7. Proportion of within variation of the total variation in a) Scots pine and b) Norway spruce.

The sorting of logs according to age and growth ring width gave a higher difference in the tensile index between the lowest and best classes (21 %, Wang & Braaten 1997). These differences between the lowest and best classes concur with simulation estimates, which indicate that the hydrocyclone is a more efficient method than log sorting to create differences between classes.

In conclusion, hydrocyclone fractionation is the most efficient method to control the tracheid cross-sectional dimensions. Although this is not surprising, it is noteworthy that other methods lag far beyond hydrocyclone, and have very limited practical efficiency. Further studies on controlling wood properties should therefore focus on developing more feasible hydrocyclones for fractionation of fibres. Hydrocyclones are already widely used in the pulp and paper industry, but they are generally utilised in applications other than control of pulp properties. For example, one important application for hydrocyclones is the cleaning pulps from sand and other impurities. Hydrocyclones may find more use in the control of pulp properties if the energy efficiency of the device is improved. Pulp has to be diluted to a low consistency, for example 0.1 %, which results in the pumping of large volumes of dilute pulp suspension (Paavilainen 1992). This, in turn, incurs large energy costs, and is one obstacle in the introduction of hydrocyclone-based pulp property control.

Further studies should also concentrate on incorporating the fibre length distributions into the cross-sectional dimension distributions. Tracheid cross-sectional dimensions can be easily measured with the SilviScan or similar device, but they do not measure fibre length. On the other hand, devices like kajaaniFiberLab, which measure pulped or macerated fibres, measure accurately fibre length, but they often give only an index of cell wall thickness, not the real value. A solution for this problem could be X-ray microtomography, which is capable of producing 3D images from cellular solids. Microtomography has already been utilised in the study of wood structure (Trtik et al. 2007), but there is still room for new studies using this advanced device.

Wood viscoelasticity

A review of the literature of wood properties shows that a number of measurements have been made of wood viscoelasticity in different species. For example, viscoelastic properties

have been measured for ten species and for both softwoods and hardwoods (IV). Norway spruce is the most studied species, but there some measurements have been made with Scots pine and birch (*Betula sp.*).

The variation of viscoelastic properties within a species, or in other words, between trunks and within trunks is important in the control of this wood property. A comparison of different studies using Norway spruce as sample material, gives some insight into this issue. The lowest value of loss tangent, which is the common measure of viscoelasticity, found in Norway spruce is 0.047 (Salmén 1984), whereas the highest value is 0.3 (Becker et al. 1977). Although the measurement methods and loading conditions are different between studies, the large difference in the loss tangents indicates a notable within-species variation.

The evaluation of variation of wood viscoelastic properties is difficult due to several reasons. One problem is that taking of wood samples from the trunks is reported poorly (e.g. Salmén 1984), or as in most cases, omitted completely from the articles (e.g. Becker et al. 1977, Backman & Lindberg 2001). Another complication is the diversity of measurement methods and loading conditions, which prevents the comparison of different studies (IV). Each study utilises a slightly different test type, loading frequency or loading direction. Owing to these reasons, the extent of variation within a species is difficult to evaluate, and the viscoelastic properties of top pulpwood, pulpwood from first thinning or sawmill chips are not known.

Although the within-tree variation of viscoelastic properties is not well known, the factors behind the viscoelastic properties have been studied in several papers. Wood viscoelasticity is a combination of factors on the molecular, cell wall and cell levels. Of all these factors, the molecular structure of lignin has the greatest impact on wood viscoelastic properties, because properties of lignin determine the glass transition behaviour of wood (Atack 1981, Salmén 1984, Olsson & Salmén 1997). On the cell wall level, the width of cellulose crystals and microfibril angle affect viscoelastic properties (Hori et al. 2002). On the cell level, the tracheid cross-sectional dimensions may have a significant effect on viscoelastic behaviour. This is because of hydraulic damping, which is caused by fluid flow in porous materials during dynamic loading (IV). Hydraulic damping has not been studied with wood, but the general theory of hydraulic damping in porous materials (Biot 1955 a, b, 1961) suggests that this phenomenon can also have significance in wood.

Energy consumption in mill and pilot plant trials can be predicted, at least qualitatively, with the general theory of viscoelasticity and laboratory measurements made with wood (IV). For example, treating the cell wall with chemicals before mechanical pulping changed the energy consumption in a way (Atack 1978), which could be predicted with the basis of the theory of wood viscoelasticity (IV). However, at the moment viscoelasticity can only be used to make qualitative interpretations of behaviour of wood in mechanical pulping. There are no quantitative models on mechanical pulping which would incorporate wood viscoelasticity.

The apparent relationship between wood viscoelasticity and energy consumption suggests that the controlling of viscoelastic properties of wood raw material results in more energy-efficient production. In practice, controlling could be done by measuring the acoustical properties of logs, and grouping the logs according to the speed of sound, as was done in the study of Bradley et al. (2005).

In subsequent studies, the viscoelastic properties within a trunk and also within raw material assortments should be characterised. Viscoelastic behaviour of wood depends on the loading conditions, and in the characterisation of wood raw material measurements should be made in conditions which are relevant from the mechanical pulping point of

view. A study of the literature (IV) shows that the measurement conditions should be following:

- Temperature scan at least in the range 40-150 °C, but preferably in a wider range.
- Water saturated conditions
- Loading in radial or tangential direction

Viscoelastic measurements should be done in water saturated conditions, but because temperatures range above the water boiling point, the measurement chamber has to be pressurised. If this is not possible, the measurement should be done with bone dry wood; otherwise the result may exhibit peculiar viscoelastic behaviour when the wood dries during the temperature scan (IV, Sun et al. 2007).

CONCLUSIONS

- Top pulpwood and sawmill chips have on average similar cross-sectional dimensions. The average cell wall thicknesses and radial and tangential widths are slightly larger in sawmill chips than in top pulpwood, but the difference is not decisive. Also, the cross-sectional dimension distributions are close to each other in both assortments.
- Fractionation of fibres into earlywood and latewood is the most efficient method for controlling cell wall thickness and radial tracheid width. Sawing a trunk into juvenile and mature wood parts is the second most efficient method, and classification of trunks according to the tree's social status is the least efficient method, if the aim is to control the above-mentioned dimensions. The tangential dimension can be controlled most efficiently by sawing the trunk into juvenile and mature wood parts.
- The average tracheid cross-sectional dimensions approximate each other in Norway spruce and Scots pine. The distributions are quite similar in both species, but Scots pine has more thick walled latewood tracheids than Norway spruce.
- Wood viscoelasticity varies within a tree species notably, but sampling and measurement methods differ between studies, and therefore an evaluation of the literature results is awkward.
- Wood viscoelasticity depends mainly on lignin. Microfibrillar angle, width of cellulose crystals and tracheid cross-sectional dimensions also affect the viscoelastic properties of wood.

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