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# Distributions of Tracheid Cross-Sectional Dimensions in Different Parts of Norway Spruce Stems

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Distributions of three cross-sectional dimensions: radial and tangential tracheid width, and cell wall thickness in different timber assortments of Norway spruce were investigated. Wood samples from a mature stand were measured with SilviScan. In the analysis, virtual trees were constructed from measurement data, and divided into three assortments: whole stem, top pulpwood and sawmill chips. Average values and distributions of the properties were calculated for all assortments, and distributions divided into earlywood and latewood across the whole tree assortment. There was considerable variation within latewood in all three cross-sectional dimensions, but variation in earlywood was slight in radial width and cell wall thickness. In earlywood, tangential tracheid width showed considerable internal variation, and the difference between earlywood and latewood in tangential width was small. Within-assortment variation of all three properties was larger than between assortments. We may conclude that only a moderate difference in pulp properties can be achieved by sorting raw material into sawmill chips and top pulpwood. Pulp fractionation into earlywood and latewood seems to be a more efficient method, since it gives classes with small within-class variation and distinct average properties. However, it should be kept in mind that the results are valid only in mature stands, where growth rate variation and juvenile wood content are small.

**Keywords** Norway spruce, tracheid dimension, earlywood, latewood, cell wall thickness, tangential width, radial width
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# 1 Introduction

About 94 percent of the tissue volume of Norway spruce consists of longitudinal cells or *tracheids*, while the rest is mostly radial cells: parenchyma and ray tracheids (Ollinmaa 1959, Petric and Šcukanec 1973). In production of coniferous pulp and paper, the word *fibre* is used as a general term meaning tracheids. In this paper, the words fibre and tracheid are used as synonyms in different contexts. The tracheid properties of Norway spruce (*Picea abies* (L.) Karst.) are of interest since it is widely used for chemical and mechanical pulps in the Nordic countries.

Wood properties show considerable natural variation, cross-sectional tracheid dimensions being no exception. There is variation within the annual ring, because a softwood annual ring consist of wide, thin-walled earlywood tracheids and narrow, thick-walled latewood tracheids. There is also variation between annual rings, since physical tracheid dimensions depend on the maturity of the cambium, which changes with accumulation of wood tissue and cambium age (Sirviö and Kärenlampi 2001). The latewood proportion varies because of the growth rate (annual ring width) (Lindström 1997), and together with between annual ring variation, these two factors cause variation in cross-sectional tracheid dimensions from the pith to the bark and from the stump to the top.

There are a number of studies on how forest management affects cross-sectional tracheid dimensions in Norway spruce stands. For example, thinnings and fertilization (i.e., enhanced growth rate) have been found to decrease the mean cell wall thickness (e.g., Mäkinen et al. 2002, Lundgren 2004, Jaakkola et al. 2005, Jaakkola et al. 2007). There are a few studies on actual variation of dimensions (Ollinmaa 1959, Atmer & Thörnqvist 1982), and no studies about distributions of cross-sectional dimensions in raw material assortments like top pulpwood. However, since tracheid cross-sectional dimensions affect a number of paper properties, like strength and light scattering, it's essential to characterise the properties of different assortments.

Paper strength is positively correlated to fibre length, but cross-sectional fibre dimensions have been found to play a more important role in paper-making potential. According to Paavilainen (1993a), cell wall thickness accounted for over 80 percent of the variance in softwood sulphate pulp coarseness. Furthermore, coarseness alone accounted for over 80 percent of the variance in the tensile and tear strength of European and American softwoods and over 70 percent of the variance in apparent sheet density and air resistance. Adding the fibre length to the model had no significant effect on the paper properties. The bonding potential of fibres, a necessity for papermaking, is dependent on fibre conformability, i.e., flexibility and collapsibility (see Paavilainen 1993b, 1994). Jang and Seth (1998) state that thin-walled fibres collapse more easily than thick-walled fibres and bond together well, producing a positive effect on tensile strength.

Light-scattering ability has been found to correlate positively with fibre flexibility in softwood sulphate pulp (Paavilainen 1993b). Similar phenomena have also been observed with mechanical pulp. According to Braaten (2000), decreased fibre wall thickness and increased fibrillation had a positive effect on light-scattering ability and surface smoothness. Middleton and Scallan (1992) found that the light-scattering coefficient is related to the cross-sectional dimensions of fibres, which vary between tree species.

The natural variation in cross-sectional dimensions raises two issues: the extent of variation in raw material, and how it can be controlled. When the extent of variation is known, the paper-making potential of different raw material assortments can be evaluated. Further, the production of papers with enhanced properties needs methods for controlling variation.

In principle, wood material for paper-making can be controlled by sorting wood before pulping. In Finland, pulpwood is commonly divided into two assortments, round pulpwood and sawmill chips, which are treated separately. There are proposals for more efficient control, for example, by sorting logs into butt, middle and top logs (Duchesne et al. 1997), but at the moment this kind of sorting is not done in Finnish wood procurement. Another method of controlling pulp properties is fractionation of fibres after pulping. In pulp fractionation, hydrocyclones have turned out to be most efficient in separating thin- and thick-walled fibres (Paavilainen 1992), while pressure screening seems to be the best method of fractionating fibres into length classes (Corson 2002).

The pulp classes obtained by a control method should have distinct properties and small internal variation. If the average properties between classes are too similar, or if variation within a class is large, the pulp properties cannot be controlled efficiently. The evaluation of control methods or papermaking potential of different pulpwood assortments cannot be based simply on average properties. The reason is that the same average value can be obtained with very different distributions. Detailed information on variation of cross-sectional dimensions is therefore needed, the best way to describe this variation being to present both distributions and average values.

This paper aims to characterise the distributions of cross-sectional tracheid properties – cell wall thickness and tracheid width – of wood raw material obtained from a mature stand. The raw material is considered as whole stems, and divided further into sections of sawmill chips and top pulpwood according to current Finnish bucking rules. The detailed definitions of the rules to be applied appear in Section 2.2. The purpose is to establish basic knowledge of dimension distributions which can later be utilised in the evaluation and development of control methods, as well as in the evaluation of the papermaking potential of various assortments.

# 2 Material and Methods

## 2.1 Data Collection and Measurements

The study material was based on sample trees chosen from one sample plot situated in a mixed old-grown Norway spruce and Scots pine (*Pinus sylvestris* L.) stand (42 and 58 percent of stem numbers respectively). This even-aged stand was located in Southern Finland (61°49´N, 24°18´E, 170 m a.s.l) near the Hyytiälä Forestry Station (University of Helsinki) and represented the *Vaccinium myrtillus* site type according to Cajander (1926) classification. The stand density was 310 stems $ha^{-1}$.

First, a circular sample plot of 1000 $m^2$ (radius = 17.84 m) was determined. The diameters at breast height (dbh) of all spruces in the sample plot were measured. A diameter distribution was then calculated, and divided into five classes at equal intervals. One tree was randomly selected for felling from each size class. The dbh of the sample trees ranged from 282 mm to 474 mm.

Sample discs were taken at the following relative tree heights after felling: 0 (stump height), 11, 22, 33, 44, 55, 66, 77, and 88 percent. Furthermore, a disc at a height of 1.3 m was taken, making a total number of sample discs of 50. The sample discs were stored in a freezer, sawn into bars from pith to bark, and dried under weight to prevent cracking. The bars were measured by a SilviScan device in STFI-Packforsk (Stockholm, Sweden). Detailed description of this device can be found in Evans (1994). Before measurement, the surfaces of the bars were polished and the bars sawn to a thickness of 2 mm. During the measurement, the samples were illuminated from the sides, so that the light was conveyed through the tracheids to the surface of the bar. Images of the surface were taken at 50 μm intervals, and tracheid dimensions were measured from the images by means of image analysis. Radial and tangential tracheid width and an average of tangential and radial cell wall thicknesses were obtained from each measuring point.

## 2.2 Data Analysis

The first part of the analysis concentrated on constructing virtual trees from the measurement data, while in the latter part the virtual trees were divided into assortments, and mass distributions were calculated. Analysis was done with mass distributions, because in paper-making it is customary to use the mass or basis weight as a measure of pulp quantity.

The measurement data was analysed using a program written with the *Mathematica* programming language (Wolfram Research Inc., Champaing, IL, USA). The analysis started by determining annual ring boundaries, which was done by the increase in radial lumen diameter between two measurement points. The boundary was defined as between those measuring points

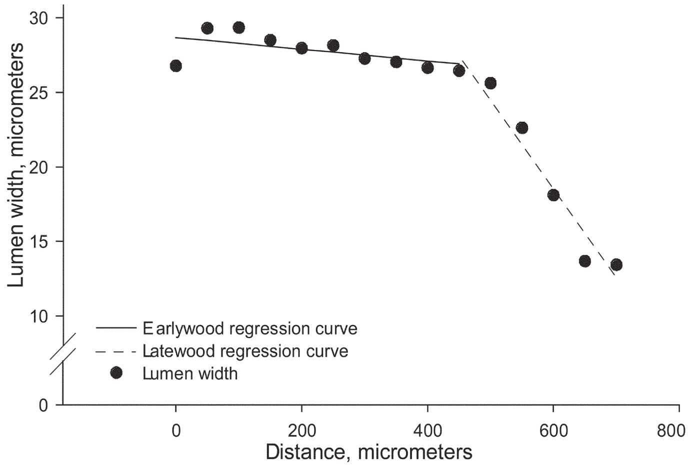


**Fig. 1.** Method for determining earlywood and latewood. The intersection of regression curves determines the border between earlywood and latewood. The horizontal axis is the distance from the beginning of the annual ring. The vertical axis is the lumen width in the radial direction.

where the lumen diameter increased 3 μm or more. Fig. 1 shows the radial lumen diameter of one annual ring.

Earlywood and latewood were determined by radial lumen diameter. The part of the annual ring where the radial diameter was constant was defined as earlywood, while the latewood was defined as the part where the radial diameter gradually decreased. These definitions were implemented by fitting pairs of linear regression curves onto the radial diameters of the annual rings (Fig. 1) and finding the curve pair which best matched the definitions above. The intersection of this curve pair was the boundary between earlywood and latewood.

Partitioning of earlywood and latewood started by dividing annual ring measuring points into two groups. The second group contained the three outermost measuring points, and the first group the rest of the measuring points. Regression curves were fitted onto both groups, and one point was moved from the first group to the second and new curves were fitted onto both groups. This procedure was repeated until the first group contained the three innermost measuring points. This method produced curve pairs like the ones in Fig. 1. At the second stage, those curve pairs where the slope of first curve was more than 0.2 were discarded. The pair from those accepted cases where the slope of the curve of the second group was steepest was chosen.

Once the annual ring and earlywood/latewood boundaries were determined, the virtual trees were reconstructed from the measurement data. The reconstruction started by determining the dimensions of tracheids on a line which spanned from pith to bark, and had a width of one tracheid. Determination of tracheid dimensions was done by analysing one earlywood or latewood annual ring at a time. Fitting regression curves to the measurement points of the earlywood/latewood annual ring produced linear regression functions for all three dimensions. In the regression functions, distance from the beginning of the earlywood/latewood ring was an independent variable, and dimension a dependent variable. Three dimension functions altogether were obtained for each earlywood/latewood ring:

$$y_i = a_i x + b_i$$

where

$y_i$ = dimension i, (cell wall thickness, radial or tangential diameter)

$x$ = distance from the beginning of the earlywood/latewood annual ring

$a_i$, $b_i$ = coefficients.

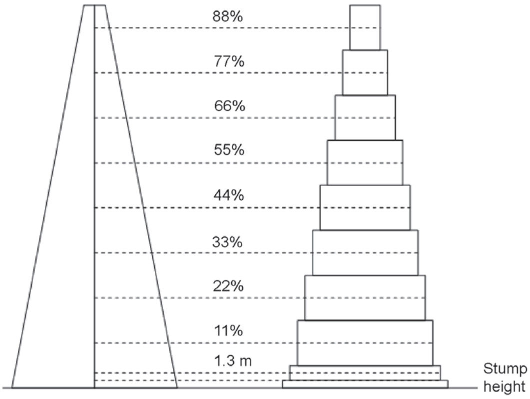


**Fig. 2.** Sampling and reconstruction of the trees. Information derived from the sample discs of the original stems (left) was utilized in reconstruction of virtual trees for further calculations.

The dimensions of the first tracheid were obtained from the regression equations by using a zero distance, the dimensions of the second tracheid by using the radial diameter of the first tracheid, the dimensions of the third tracheid by adding the radial diameters of the first and second tracheids, and so forth, until the end of the earlywood/latewood ring was reached.

A disc was constructed from individual tracheids after obtaining the dimensions of tracheids on a line from pith to bark. The number of tracheids on the disc was calculated by taking one tracheid on the measuring line at a time and dividing arc of a circle whose radius was the tracheid's distance from the pith by its tangential diameter. The number of tracheids in the stand was obtained from the diameter distribution of stems by multiplying number of tracheids on the arc of the circle by the number of stems of the dbh size class.

The virtual disc was further extended to a bolt whose length was the distance between two measuring lines (see Fig. 2). This procedure assumes that the properties on the measurement line represent the whole bolt; i.e., no influence of tapering is allowed for. At the next step, the tracheid mass was calculated from the dimensions and cell wall density (1500 kg/m$^3$, Kellogg and Wangaard 1969). The cross-sectional cell wall area was calculated from the measurement data. Since the data does not include tracheid length, this was assumed to be same as the length of the bolts, an assumption which considers tracheids as rectangular pipes without end caps. The following equation was used:

$$m = (ab - (a - 2t)(b - 2t))l\rho$$

where
$m$ = mass of tracheid, kg
$a$ = radial tracheid diameter, m
$b$ = tangential tracheid diameter, m
$t$ = cell wall thickness, m
$l$ = length of bolt, m
$\rho$ = cell wall density, kg/m$^3$.

When the construction of virtual trees was finished, the trunks were divided into assortments including all dbh classes in the stand. The top diameter of saw logs and top pulpwood were 15 cm and 6 cm respectively in the analysis. The length of the saw logs varied from 3.3 m to 6 m in 0.3 m modules. The posting of saw logs was done by the simple method of fitting the largest possible square inside the circle formed by the top end of the log. The part of the circle which was inside the square was regarded as sawn timber, and the part outside the square as sawmill chips.

The distributions were formed from the virtual tracheids in the final stage of the analysis. At this point, five characteristics for each tracheid were available: mass, cross-sectional dimension, position in the trunk, amount in the stand and the information on whether it was formed by earlywood or latewood. Knowing the position of the tracheid, made it possible to calculate whether it belonged to sawmill chips or pulpwood. The tracheids were divided to 50 classes for presenting the distributions,. The width of one class was calculated by the equation:

$$w_i = \frac{\max_i - \min_i}{50}$$

$w_i$ = width of a class in dimension i (cell wall thickness, radial or tangential diameter)
$\max_i$ = maximum value of property i among all tracheids in the assortment
$\min_i$ = minimum value of property i among all tracheids in the assortment

To obtain mass proportions, the mass of tracheids in a class was divided by total mass of all classes in the assortment. This was calculated as follows:

$$p = \frac{m_i}{\sum_{i=1}^{n} m_i}$$

where
$p$ = mass proportion of tracheid class $i$
$n$ = number of tracheids in the assortment
$m$ = mass of class $i$, kg.

The distributions representing properties within earlywood/latewood were calculated as shares of total mass of the assortment.

# 3 Results

Since the earlywood and latewood distribution pattern was similar in all assortments, its effect is shown only in the whole tree assortment. In all timber assortments, cell wall thickness and tracheid radial diameter distributions had similar shapes, which exhibit two distinct peaks (Figs. 3 and 4). The first peak was narrow for the cell wall thickness, and was mainly formed by earlywood tracheids, although it also included some latewood tracheids. The second peak, including only latewood tracheids, was much wider. The first radial diameter peak was wide, and the second narrow.

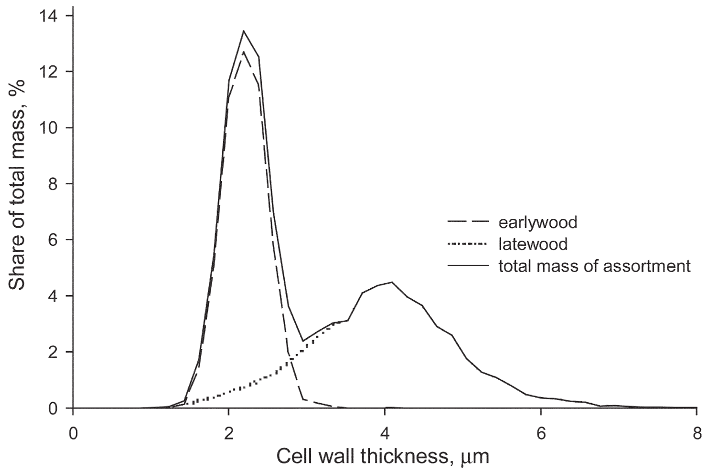


**Fig. 3.** Cell wall thickness distribution across the whole stem assortment. Earlywood and latewood mass proportion is their share of total mass of the assortment.

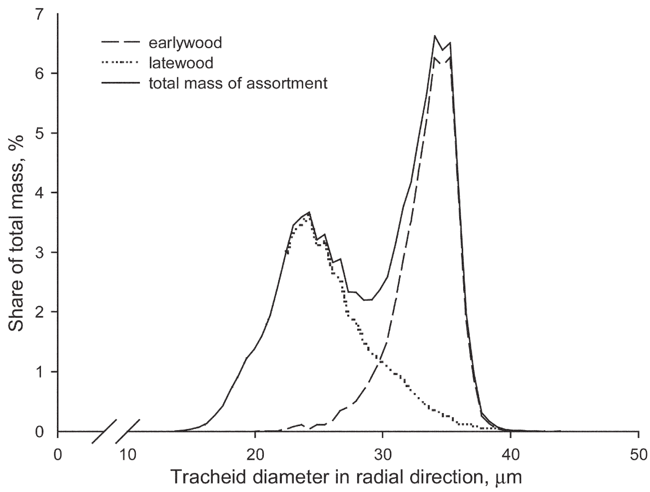


**Fig. 4.** Radial tracheid diameter distribution across the whole stem assortment. Earlywood and latewood mass proportion is their share of total mass of the assortment.

**Table 1.** Mass-weighted average values for the characteristics measured.

| Characteristics | | Whole stem | Top pulpwood | Sawmill chips |
|---|---|---|---|---|
| Cell wall thickness, µm | Earlywood | 2.12 | 2.13 | 2.2 |
| | Latewood | 3.88 | 3.88 | 4.04 |
| | Total annual ring | 2.99 | 3.04 | 3.10 |
| Tracheid diameter, µm | | | | |
| Radial | Earlywood | 33.06 | 31.75 | 34.23 |
| | Latewood | 24.73 | 23.90 | 25.3 |
| | Total annual ring | 28.92 | 27.69 | 29.87 |
| Tangential | Earlywood | 31.17 | 30.74 | 32.55 |
| | Latewood | 30.33 | 30.05 | 31.57 |
| | Total annual ring | 30.75 | 30.38 | 32.07 |

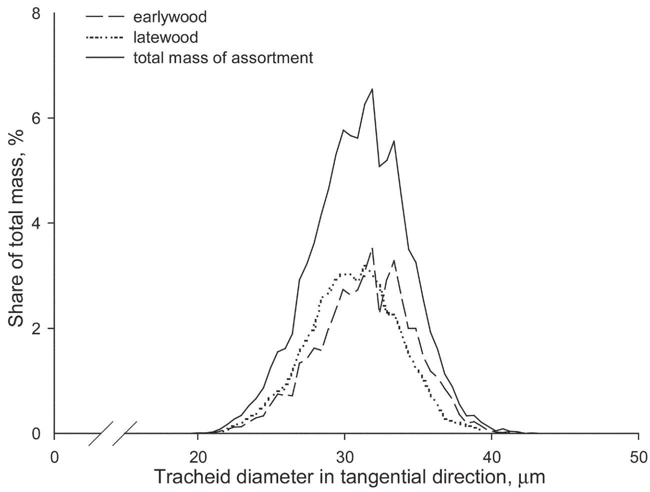


**Fig. 5.** Tangential tracheid diameter distribution across the whole stem assortment. Earlywood and latewood mass proportion is their share of total mass of the assortment.

The distribution of tracheid tangential diameter differed considerably from the distributions of cell wall thickness and tracheid radial diameter (Fig. 5). Both earlywood and latewood classes had similar, nearly normal distributions, which were centred on averages of 32 µm in earlywood and 31 µm in latewood across the whole tree assortment.

The distributions were quite similar between assortments: cell wall thickness and tracheid radial diameter distributions were skewed, with two distinct peaks (Figs. 6 and 7), while the distribution of tracheid tangential diameter was normal (Fig. 8). The reason for skewed distributions in radial diameter and cell wall thickness was the difference between earlywood and latewood. In latewood, both dimensions changed gradually, whereas in earlywood they were nearly constant. The radial lumen diameter of the single annual ring in Fig. 1 represents this situation.

Table 1 shows the averages for the various assortments. Top pulp wood tracheids were narrowest in the radial direction, whereas tracheids were widest in sawmill chips. The differences between whole stem and top pulp wood assortments in tangential direction were small, but in the sawmill chip assortment tracheids were somewhat wider. The cell wall thickness was largest in the sawmill chip assortment and smallest in the whole stem assortment, although differences between whole stem and top pulp wood were minor.

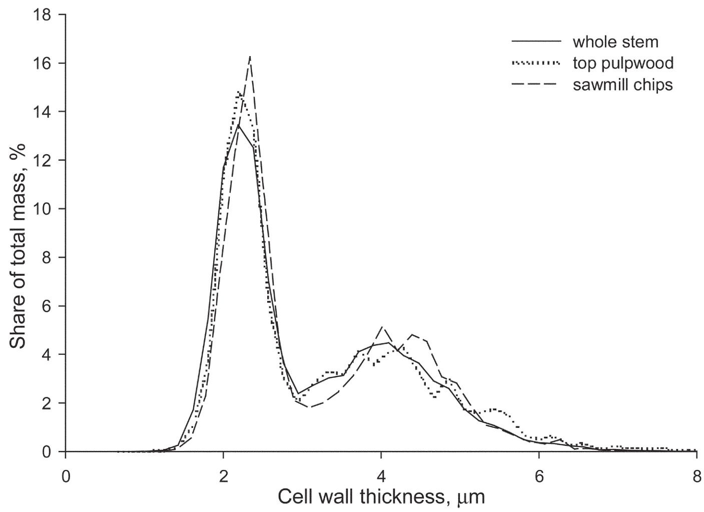


**Fig. 6.** Cell wall thickness distributions in all assortments.

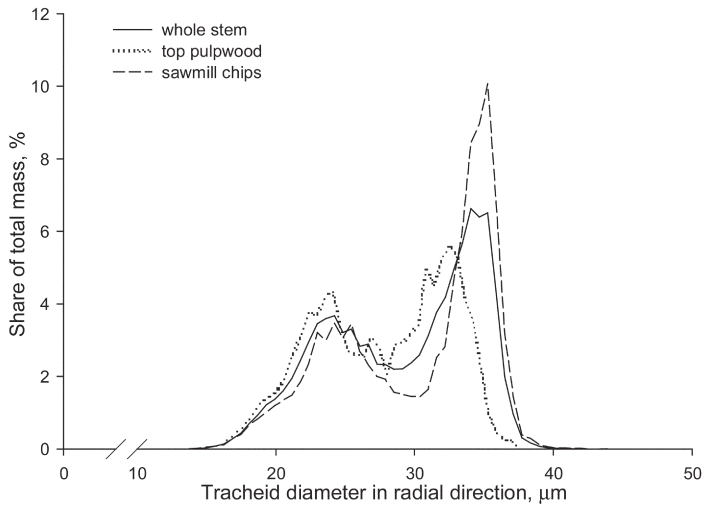


**Fig. 7.** Radial tracheid diameter distributions in all assortments.

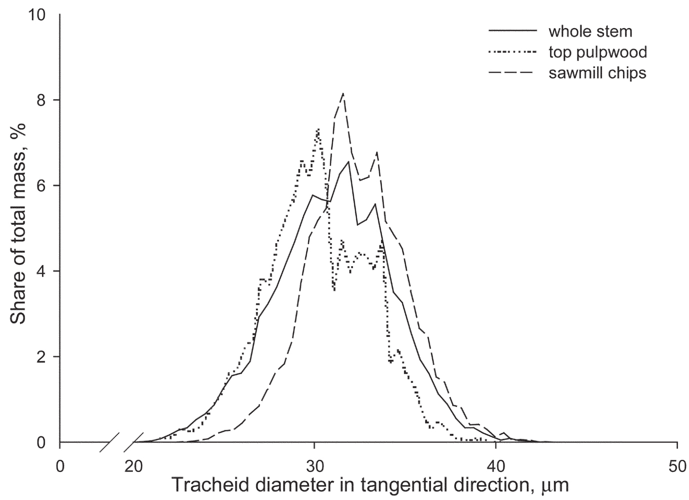


**Fig. 8.** Tangential tracheid diameter distributions in all assortments.

# 4 Discussion

The distributions of cell wall thickness and radial diameter had two different peaks because of earlywood and latewood tracheids. The peaks skewed the distributions, but when in all cases the assortment distributions were divided into earlywood and latewood classes, these classes resemble normal distribution (Figs. 3 and 4). The distribution of cell wall thickness had a shape similar to that Reme and Helle (2002) reported for Scots pine. In the study by Liukkonen et al. (2007), the cell wall thickness distribution was also similar to our findings in their slow grown tree class, but the wall thickness distribution was skewed to left in their fast grown tree class. Further, the latewood did not show as a distinct pattern in cell wall thickness as it shows in the trees measured here. The reason for these differences is probably the small amount of latewood in the fast grown spruces.

The distributions shown here reveal large variation within assortments, which is due to the difference between earlywood and latewood. Cell wall thickness and radial tracheid diameter distributions were narrow in earlywood but wide in latewood. This difference has an impact on tracheid separation; if one can separate earlywood and latewood tracheids, for example, by the means of a hydrocyclone, one would get two classes which not only differ in their averages, but also in variation. The earlywood class would be homogenous, including wide thin-walled tracheids. The latewood class is more heterogeneous consisting mainly of thick-walled, narrow tracheids. However, it should be noted that the difference is only in radial diameter, since tangential diameters are nearly the same in both classes.

The variation between assortments is moderate, and far smaller than within assortments. In Finnish pulp mills, sawmill chips and round pulpwood are often treated separately. With respect to cross-sectional dimensions this sorting gives two moderately different pulps; sawmill chip pulp, in which tracheids are wide with thick cell walls, and top pulpwood pulp, in which tracheids are narrow with thin cell walls. Since the distributions are narrower in sawmill chips (Figs. 6, 7 and 8) than in top pulpwood, sawmill chip tracheids have less variation in cross-sectional dimensions than top pulpwood tracheids.

The reason for different distributions between assortments is probably the amount of juvenile wood. In sawmill chips, the juvenile wood content is nil, and small in the whole tree assortment, while its content can be considerable in small diameter top pulpwood (Duchesne et al. 1997, Wilhelmsson et al. 2002). By definition, the wood properties within juvenile wood change rapidly from ring to ring, while in mature wood they remain quite constant.

The moderate variation between assortments means that fractionation in pulp mills is an adequate method for controlling cross-sectional tracheid properties. Sorting into sawmill chips and top pulpwood does not have a major affect on the cross-sectional properties of pulp tracheids. At least this is the case in mature stands, where the juvenile wood content of stems is small, and variation in growth rate minor. On the other hand, this finding gives some freedom in sorting. If there are some other tracheid properties which promote sorting into assortments, this sorting will not have a large harmful effect on cross-sectional properties.

These distributions represent wood obtained from a mature stand in Southern Finland. The results can be generalised to top pulpwood and sawmill chips from sites where stand characteristics are similar or nearly so. The reliability of measurements is good, since the data consists of five size classes, ten heights on a stem, and measurements on very fine resolution from pith to bark. However, the distributions of a third important assortment, pulpwood from first thinnings, should be measured in future. This would complete the characterization of cross-sectional tracheid properties in Norway spruce.

# 5 Conclusions

The analysis of distributions of tracheid cross-sectional dimensions leads to the following conclusions:

1) The distributions of cell wall thicknesses and radial diameters are skewed, and have large internal variation because of earlywood and latewood. Within the earlywood class, the variation in dimensions is small and resembles normal distribution. The variation within the latewood class is large, but the distribution is similarly normal.
2) The distributions of tangential diameters are similar in both earlywood and latewood. Both distributions are normal, and the average values are close to each other.
3) Differences between the properties of sawmill chips and top pulpwood are only moderate in a mature stand. The results suggest that fractionation of tracheids after pulping is a far more efficient method of controlling cross-sectional tracheid dimensions than sorting into sawmill chips and top pulpwood.

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