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Relationships of the modulus of elasticity and the structure of Finnish Scots pine wood

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The paper presents preliminary results on the relationships of the longitudinal modulus of elasticity (E) in bending, based on ISO Standard 3349 tests on small, clear specimens, and some basic characteristics of Finnish Scots pine wood. A manual image analysis method – quantitative stereological counting – was introduced and applied for the investigations of wood structure.

The main results were consistent with those from the prior research. The range of E was 9.7 to 19.1 GPa. Increase in especially fiber density index ($R^2 = 0.95$), weight density and specific gravity ($R^2 = 0.90$), Runkel's ratio, coefficient of cell rigidity and number of growth rings per cross-sectional unit area, but also in latewood percentage ($R^2 = 0.58$) resulted in an increase in E. Increase in growth ring width, particularly in the width of the late wood section within a ring ($R^2 = 0.95$), coefficient of cell flexibility, and tracheid and lumen diameter ($R^2 = 0.63$ to 0.90) had a reverse effect. Cell wall thickness did not show any clear effect. Except for tracheid diameter, the relationships were stronger for the variables determined in the tangential than in the radial wood direction.

Quantitative stereological counting has been used to some degree in the Finnish wood research. The procedure is technically feasible and easy to use. A large sample of counting areas is frequently needed to obtain accurate mean results for the size and distribution of the features. Because the actual analysis points are located at a fixed distance from each other, the method is not in principle well suited for wood with a regular and simple structure, such as Scots pine. However, the good correlations between E and some characteristics obtained with stereological counting did not support this misgiving.

Tutkimus esittelee ennakkotuloksia suomalaisen mäntypuun pienistä, virheettömistä puunäytteistä ISO 3349 -standardin mukaisesti mitatun taivutuskimmomoduulin ja eräiden puuaineen perusominaisuuksien välisistä riippuvuussuhteista. Lisäksi esitellään manuaalinen kuva-analyysimenetelmä, kvantitatiivinen stereologinen laskenta.

Päätulokset olivat yhteneväisiä aikaisempien tutkimustulosten kanssa. Kimmomoduuli vaihteli välillä 9,7–19,1 GPa. Erityisesti kuitutiheysindeksin ($R^2 = 0{,}95$), puuaineen tiheyden ($R^2 = 0{,}90$), Runkel'in suhdeluvun, puusolun jäykkyyskertoimen ja poikkileikkauksen pinta-alayksikön vuosilustojen lukumäärän, mutta myös kesäpuuprosentin ($R^2 = 0{,}58$) kohoaminen johtivat kimmomoduulin kohoamiseen. Vuosiluston, erityisesti luston kesäpuun paksuuden ($R^2 = 0{,}95$), puusolun joustavuuskertoimen sekä trakeidin ja sen soluontelon läpimitan ($R^2 = 0{,}63$–0,90) kohoamisella oli päinvastainen vaikutus. Trakeidin seinämän paksuudella ei ollut selvää vaikutusta. Trakeidin läpimittaa lukuunottamatta kimmoduulin riippuvuussuhteet olivat voimakkaampia käytettäessä kimmomoduulin selittäjinä tangentin suunnassa määritettyjä muuttujia säteen suunnassa määritettyjen sijasta.

Kvantitatiivista stereologista laskentaa on käytetty jossain määrin suomalaisessa puuntutkimuksessa. Menetelmä on teknisesti kelvollinen ja helppokäyttöinen. Usein tarvitaan suuri otos analyysikohtia tarkkojen keskiarvotulosten saamiseksi mielenkiinnon kohteena olevista puuaineen piirteistä, kuten solujen koosta ja kokojakaumasta. Koska itse laskentapisteet sijaitsevat määräetäisyydellä toisistaan, menetelmä sopii periaatteessa huonosti rakenteeltaan säännöllisen ja yksinkertaisen puulajin, kuten männyn, puuaineen analysointiin. Korkeat korrelaatiot kimmomoduulin ja eräiden stereologisen laskennan avulla saatujen puuaineen rakenteellisten ominaisuuksien välillä eivät kuitenkaan tukeneet tätä käsitystä.

Keywords: Scots pine, *Pinus sylvestris,* modulus of elasticity, wood properties, wood anatomy, wood structure, stereology, tracheids.
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1 Introduction

1.1 Significance of the modulus of elasticity in wood

Bending strength and elasticity are the most usual parameters to express the effects of static strain in a wood structure (Bodig and Jayne 1982, Meyer and Kellogg 1982). Thus, they are usually the most important mechanical properties of structural lumber (Egner 1941, Vorreiter 1949, Wangaard 1950, FAO 1952, Siimes and Liiri 1952, Kärkkäinen 1985, Forest Products... 1987, Wagenführ and Scheiber 1989).

Elasticity in bending is of commercial importance as well, because it is the criterion for stress grading structural lumber. It can be conducted either visually, or by machine when it is called machine stress rating (MSR) (Riikonen 1986). In Finland, the T rules (visual grading) and MT rules (machine grading) are used for the domestic markets (Lipitsäinen 1986, Sipi 1991), and the British BS rules for these export markets (British Standards... 1988). A total of 195 000 m^3 and 130 000 m^3 softwood lumber were stress graded for the domestic and British markets in 1987, of which the proportion of MSR, performed with 19 machines, was 26 and 77 %, respectively (Current status... 1988).

The significance of elasticity lies in the fact that it determines the ability of wood to deform under a load (Bodig and Jayne 1982). If an equal load is applied on two beams with equal dimensions and unequal elasticity, the beam with a greater elasticity is able to bend more without a permanent deformation. Applied to lumber drying, the board with a greater elasticity is able to resist higher drying stresses without checking.

A spring model is applied to describe elasticity by plotting the normalized load over unit area, P/A, which is called normal stress, vs. the normalized displacement, which is called normal strain (Bodig and Jayne 1982). If the curve is linear, the material is elastic. The slope of the curve is the constant of proportionality, called modulus of elasticity (E, or MOE), or Young's modulus, after Thomas Young (1773–1829):

$$E = \rho / \gamma \qquad (1)$$

where E = modulus of elasticity, ρ = normal stress and γ = normal strain.

The units for E are identical with those for stress, thus Pa (N/m^2) in the SI system, dyne/cm^2 or kp/cm^2 in other metric systems, and psi (lb/in^2) in the British system.

Wood tends to follow Hooke's law only until a particular proportional stress-strain limit, beyond which the stress-strain relationship has a viscous (plastic) nature. Thus, it is possible to determine the E for wood only by applying relatively low stresses to a wooden member. In addition, wood is an anisotropic material. This means that it has a different structure and properties – E included – in the three main directions, longitudinal, radial and tangential.

1.2 Wood characteristics affecting the modulus of elasticity

The factors that have an effect on E in wood can be generally classified to those related to wood structure, and those related to environmental conditions, such as moisture content, temperature, chemical treatment, and time-dependent effects. In this paper, only the first factors will be discussed.

From the point of view of mechanical properties, the morphological structure of wood is often described in terms of the Reinforced Matrix Theory (Fengel and Wegener 1984, Glasser 1990, McLain 1990). Accordingly, strands of high tensile strength microfibrils (cellulose) are embedded in a plastic matrix of non-cellulosic polysaccharides (hemicelluloses) and their derivatives, and lignin (Wardrop 1971). In this structure, crystalline cellulose is the strength-creating agent, whereas non-crystalline cellulose, lignin and extractives add to the elasticity. Hemicelluloses are a presumably tangentially oriented coating of lamellae on microfibrils, compatibilizing the surface interaction with lignin and resulting in a formation of "lignin-hemicellulose gel" (Kerr and Goring 1975). Opposite observations were made on the lamellization of the gel as well (Scallan 1974). The structure is, to a great extent, comparable with reinforced concrete: the crystalline microfibrils in wood are analogous to reinforced rods and amorphous lignin, hemicelluloses and extractives are equivalent to concrete (Glasser 1990). The main differences are the discontinuity and unknown extent of the microfibrils beyond the boundaries of the particular cell wall layer, and their rare alignment with the longitudinal fiber axis.

The Reinforced Matrix Theory has been criticized, because lignin is believed to add to the ultimate strength, in addition to elasticity (Boyd 1982). It was hypothesized that strength and elasticity rather depend on the interactions of the crystalline and non-crystalline regions. Consequently, the relative alignment of cellulose, hemicelluloses and lignin would be essential to the mechanical properties.

Mark (1967) presented theoretical values of elastic parameters for crystalline native cellulose. E computed in the longitudinal direction of the cellulose chain, 132.4 GPa, exceeded that of many metals. However, E in the two other directions was only one-fifth of that in the longitudinal direction. Although the elastic characteristics of crystalline region have received a great deal of attention, the amorphous region may have a significant effect on the overall behavior. A theoretical E of 2.0 GPa was presented (Mark 1967). Hemicelluloses contribute less to the elasticity of wood than cellulose and lignin (Cousins 1976, 1978, Bodig and Jayne 1982). Extractives have less effect on the mechanical properties than on the specific gravity (Luxford 1931).

The four different cell wall layers, compound middle lamella (M+P) and three secondary cell wall layers (S_1, S_2, S_3) exhibit both different thicknesses and different proportions of chemical constituents (Fengel and Wegener 1984). A more important issue for the elasticity is the wide range of microfibrillar angles of the different layers. In particular, the microfibrillar angle of S_2 layer is crucial, because the other layers are very thin compared with that layer and because their microfibrillar orientation is unfavourable for longitudinal stiffness (Cave 1968, 1969). A decrease in a microfibrillar angle of softwoods from 35 to 10 degrees resulted to a fourfold longitudinal modulus of elasticity (Cave 1968).

The tracheids of softwoods and the fibers of hardwoods are the main cell types contributing to the strength and elasticity of wood. It was suggested that this may be due to the relatively high ratio of slenderness and the thicker walls in both types of cells (Bodig and Jayne 1982). Fengel (1969) presented results on the cross-sectional tracheid dimensions of early wood and late wood of softwoods: although the overall cross-sectional dimensions of early wood tracheids are often slightly greater than those of late wood tracheids, the cell wall of early wood is much thinner than that of late wood. Jayne (1959) observed clearly higher strength and elasticity values for late wood tracheids of cypress, compared to early wood tracheids. Suzuki (1969) found the same phenomenon for sugi.

Bodig and Jayne (1982) presumed that a knowledge of the various cell types and their distribution, the behavior of the cell, and the nature of intercellular bonding is sufficient to predict the macroscopic behavior of solid wood.

Available data suggest that interfiber bonding can be important for the elasticity as well. For example, the ray cells may contribute to the elastic properties of wood, if their proportion is large (Schniewind 1959).

As was stated before, E is different in the three main directions of wood: the ratio of longitudinal to radial E is 41 to 122 for softwoods, and 12 to 62 for hardwoods (Kollman and Cote 1968). The radial E is correspondingly one-and-a-half to six times higher than the tangential E.

Most of the mechanical properties of wood have been demonstrated to be positively correlated to density, or specific gravity (Palka 1973, Bodig and Jayne 1982, Kärkkäinen 1985). The correlation is somewhat weaker for the parameters of elasticity, such as E, than for the parameters of strength, such as modulus of rupture. Markwardt and Wilson (1935) presented the general relationships, as follows:

$$E = 2.36 \cdot \rho \text{ (for green wood)} \qquad (2)$$

$$E = 2.8 \cdot \rho \text{ (for wood at 12 \% MC)} \qquad (3)$$

where E = modulus of elasticity, 10^6 psi, and ρ = specific gravity.

Because density is negatively correlated to growth ring width and positively correlated to latewood percentage (Bodig and Jayne 1982, Kärkkäinen 1985), these wood characteristics strongly affect the strength and elasticity of wood. Ratios of the specific gravity of late wood to that of early wood ranging from 2 to 3 are frequently observed for many species (Wilson 1969). The variation of wood structure across a growth ring is of importance as well. Ifju (1969) presented a general equation to predict the effect of this variation:

$$Y = a + b \cdot \arctan\left(\frac{x+s}{10} - 10\right) \qquad (4)$$

where Y = modulus of elasticity (or tensile strength, or specific gravity), x = percentage distance across the growth ring in the radial direction, s = latewood percentage and a, b = constants.

Different growth defects tend to decrease the mechanical properties of wood. Cross grain, knots, reaction wood, and checks are among the most common of them. In addition, miscellaneous defects, such as material separation, deposits, abnormal growth, and insect and fungus injuries occur (Bodig and Jayne 1982).

Several attempts were made to model E for wood fibers, cells and cell walls (Tang 1971, Chou et al. 1972, Gillis 1972, Tang and Hsu 1973, Cave 1978a, Salmen and de Ruvo 1985). Cave (1978b) computed properties of model of wood. Koponen et al. (1987, 1988) linked the different predictors for the strength of clear wood. At first, they developed a general model for estimating elastic and shrinkage properties of the softwood cell wall. Finally, the model was enlarged for defect-free softwood, where structure of tracheid walls, cross-sectional shape of the tracheids, quantity of rays, density and moisture content were the contributing predictors.

1.3 Modulus of elasticity of Scots pine wood

In Scots pine wood, most of the reinforcing cellulose is located in the S_2 layer, as the stiffening lignin is more equally distributed into the three secondary walls (Winandy and Rowell 1984). According to Janson et al. (1981), the hemicelluloses of Scots pine wood are composed of 16 % glucomannan, 31 % glucuronoxylan, and 13 % other polysaccharides. As was stated before, hemicelluloses contribute only a little to the mechanical properties of wood. The total proportion of extractives, which also add to the stiffness, is about 3.5 % (Janson et al. 1981).

The S_2 layer has a lower proportion of the weight of the cell wall than of its volume. Instead, the true middle lamella and primary wall, and the S_1 layer have a higher weight proportion (Winandy and Rowell 1984):

Cell wall layer	Proportion of weight, %	Proportion of volume, %
M+P	10.5	2
S_1	20.3	10
S_2	60.2	78
S_3	6.0	10
Extractives	3.0	-
Total	100.0	100

An average growth ring width of 1.3 mm has been observed in Scots pine stands of natural origin in Northern Europe (Kärkkäinen 1985). Four- to fivefold averages may be obtained in plantations. Latewood percentage is normally 20 to 50 %. Compared to early wood, the late wood tracheids are somewhat longer (Dinwoodie 1961), cellulose content is higher and lignin content is lower (Fengel 1969), and cellulose molecules are longer (Wilson and Welwood 1965). Decreasing diameter growth results to increasing latewood percentage, the extreme conditions excluded (Kärkkäinen 1985). The latewood percentage is estimated to reach the maximum, when the growth rings are 1 to 1.5 mm wide (Siimes 1938).

Longitudinal tracheids are the overwhelmingly dominant cell type in Scots pine wood. Its volume is composed of 93 % of tracheids, 6.4 % of rays and 0.6 % of longitudinal resin canals (Petric and Scukanec 1973). Consequently, the tracheid properties determine the macro-level mechanical properties. The tracheid diameter is larger in the early wood than late wood, and it is larger in the radial than tangential diameter of the late wood area as well (Kärkkäinen 1985). For Finnish Scots pine, Ollinmaa (1959) measured the mean tracheid diameters of 30.6 and 24.7 mm in the radial and tangential direction, respectively. For Swedish Scots pine, Johansson (1940) obtained the mean values for early and late wood, as follows:

Growth ring section	Radial, µm	Tangential, µm
Early wood	30.2	25.3
Late wood	20.8	30.2

Sanio (1872), Ericson et al. (1973) and Atmer and Thörnqvist (1982) presented results parallel to the abovementioned.

The cell walls are normally much thicker in the late wood than early wood, particularly in relation to the lumen diameter (Kärkkäinen 1985). The following results were presented by Ollinmaa (1959):

Growth ring section	Radial, µm	Tangential, µm
Early wood	3.44	3.36
Late wood	6.21	5.06

Accordingly, late wood is a more important contributor to the mechanical properties than as could be concluded from its volumetric proportion.

Hakkila (1966) presented the average basic density of 427 kg/m³ for Finnish Scots pine logs and 417 kg/m³ for pulpwood. In England, an average basic density of 410 kg/m³ was observed (Hamilton 1975). The density decreases along with a northernmore location, decreasing soil fertility, and increasing tree age. In fact, the effect of diameter growth rate is concerned: the density reached its maximum, when the average growth ring width was 0.8 to 1,2 mm (Siimes 1938), or 0.8 mm (Saikku 1975). An increase of 1 mm in the growth ring width caused a decrease of 20 to 30 kg/m³ in the basic density (Hakkila 1966, Saikku 1975). Within a stem, the basic density increases with a decreasing rate from the pith to the shell (Kärkkäinen 1985). Tamminen (1962) observed a difference of 25 to 109 kg/m³ in the basic density between the first and the last growth ring at the breast height. The basic density also decreases from the butt to the top of the tree. The difference may be more than 100 kg/m³ (Tamminen 1962, Hakkila 1966, Uusvaara 1974). As a result of the difference in cell wall thickness, the early wood of Scots pine is much lighter than its late wood. Kollman and Cote (1968) presented the typical values of 300 to 370 kg/m³ for early wood and 810 to 920 kg/m³ for late wood.

Jalava (1945) performed an extensive study on the mechanical properties of the most important Finnish species. The longitudinal modulus of elasticity of Scots pine, 12.5 MPa, was smaller than that of Norway spruce, European birch and aspen. Siimes and Liiri (1952) obtained somewhat lower values: 12.3 MPa for Southern Finnish and 10.7 MPa for Northern Finnish Scots pine. An increase in the specific gravity did increase the E in both studies. Compared to some Northamerican species, Scots pine has a lower E than Douglas fir, but higher than Sitka spruce and yellow poplar, for example. The test results on E by Jalava (1945) were about 10 % smaller than the true values, because of the testing method.

1.4 Objectives

This paper aims to present preliminary results on the relationships of the longitudinal modulus of elasticity (E) in bending and some basic characteristics of Scots pine wood grown in Finland, measured on a subsample of small, clear specimens. The wood characteristics of the most interest are growth ring width, latewood percentage, specific gravity, tracheid diameter and cell wall thickness. The effect of some derivatives of tracheid dimensions, such as coefficients of cell rigidity and flexibility, Runkel's ratio and fiber density index, are investigated as well. A manual method of image analysis to investigate wood structure – quantitative stereological counting – is introduced and applied.

2 Materials and methods

The study material comprised five small, clear specimens of Finnish Scots pine wood. The material was considered sufficient to find potential factors contributing to modulus of elasticity. The specimens, with the approximate dimensions of 2×8×34 cm, were sampled from a large material of the Finnish Forest Research Institute and the French National Research Institute of Agriculture (Verkasalo and Leban 1990). Samples with the largest range of E were selected. The specimens were cut in June 1990 from saw timber trees, which were felled in April 1989 from two naturally regenerated, regularly tended and thinned Scots pine stands in Southern Finland (Table 1).

The specimens were conditioned in a desiccator to a 12 %MC. The length, width, height, and mass of each specimen were recorded for determining weight density. Weight density was converted to specific gravity at the actual moisture content (assumed 12 %) by the equation (Siau 1984):

$$\rho_{12} = \rho / (1 + MC / 100) \cdot \rho_W \tag{5}$$

where ρ_{12} = specific gravity at 12 %MC, ρ = weight density of the specimen, g/cm^3, ρ_w = density of pure water at 20 deg. C and 1 atm (= 1 g/cm^3) and MC = moisture content (= 12 %).

Longitudinal modulus of elasticity (E) was determinded for each specimen by the four-point bending test, in accordance with the ISO Standard 3349 (International Organization... 1975). Load was applied on the specimen in the tangential direction. After the bending test, a sample of 1 cm in the longitudinal direction was cut from the effective section of the E specimen for microscopy studies. The width of early wood and late wood section of each growth ring was measured for computing the growth ring width and latewood percentage.

Tracheid diameter and double cell wall thickness were determined by quantitative stereological counting (DeHoff and Rhines 1968, Underwood 1970, Ifju and McLain 1982, Ifju 1983). This technique attempts to numerically characterize the geometrical aspects of the features of the microstructure of materials. – Prior research in quantitative stereological counting, labelled by such terms as morphometry, quantitative microscopy, fiber microscopy, stereometric metallography and micrometric or modal analysis has been applied in the relative restricted area (eg. Ifju 1983, Clark 1985, Koponen et al. 1987). In its broadest context, stereology includes not only the quantitative study and characterization of any spatial structure, but also its qualitative interpretation, since exact representations are not possible in all cases.

Two-and-a-half cm samples were cut from the effective section of each E specimen. Eight slides were prepared from each sample. A magnification of 400:1 was used in the microscope. A 36-point grid was superimposed on the transverse cross-section of wood. The length of a test line was 12.8 mm, resulting in a grid area of 163.84 mm^2.

The quantities counted were:

1. Frequency of the points in the phase of lumens divided by the total number of points in the grid ($P_{P(Lumen)}$)
2. Frequency of the intersections of radial test lines and tracheid outlines divided by the total length of the test lines ($P_{L(R)}$)
3. Frequency of the intersections of tangential test lines and tracheid outlines ($P_{L(T)}$)
4. Total of tracheids in the grid divided by the grid area (N_A)

Table 1. Origin of the material.

Specimen nr	Stand Location	Site	Tree Age, yrs	DBH, cm	Height, m	Age of the 1st ring, yrs	Wood
1	Kuorevesi	VT	142	31.4	1.5	6	Juvenile
2	Tuusula	MT	72	29.3	6.0	3	Juvenile
3	Tuusula	MT	74	35.3	6.0	27	Sap
4	Kuorevesi	VT	142	33.2	1.5	41	Heart
5	Kuorevesi	VT	130	23.5	6.0	52	Sap + Heart

Site: VT = Vaccinium type (Arid upland soil)
MT = Myrtillus type (Moist upland soil)

Only the rayless areas were counted. Consequently, longitudinal tracheids were the only cell type considered. At first, four early wood and four late wood areas were counted from five slides of each sample to determine the number of countings needed to achieve an accuracy of ± 10 % for each quantity.

The number of countings needed was computed by equation (Ifju 1990):

$$N = \left(\frac{t \cdot \delta_x}{x}\right)^2 \cdot \left(\frac{100}{y}\right)^2 \tag{6}$$

where N = number of countings needed, t = t-value related to (N–l) degrees of freedom at the desired level of probability (here: 0.95), δ_x = estimate for the standard error of mean, x = estimate for the arithmetic mean and y = desired accuracy, ± %.

The data from the countings proved to be sufficient to achieve the accuracy of ± 10 %, except for counting $P_{P(Lumen)}$ in the late wood sections. That is why, it was decided to double these countings.

Tracheid diameter was computed for the early wood and late wood sections both in the radial and tangential direction by equation (Ifju 1990):

$$d = \frac{P_L}{2N_A} \tag{7}$$

where d = tracheid diameter in radial (or tangential) direction, mm, P_L = frequency of the intersections of radial (or tangential) test lines and tracheid outlines divided by the total length of test lines, mm^{-1} and N_A = total number of tracheids in the grid divided by the grid area, mm^{-2}.

Double cell wall thickness was computed by utilizing the fact that only rayless sections were analysed. Thus, the sum of the mean free paths of lumen and double cell wall was one (Ifju 1990):

$$\lambda_{MFP} = \frac{2 \cdot (1 - P_P)}{P_L} \tag{8}$$

where λ_{MFP} = mean free path between the features in interest, mm, P_P = number of grid points in the phase of the features in interest divided by the total number of grid points, P_L = frequency of the intersections of the test lines and feature outlines divided by the total length of test lines, mm^{-1}.

On the other hand, the mean free path of lumen equals to the double cell wall thickness, and vice versa. As a consequence, the ratio of the lumen diameter and double cell wall thickness can be determined. On the basis of the tracheid diameter, one should be able to determine both the lumen diameter and double cell wall thickness by the ratio of their mean free paths.

Averages weighed with the late wood percentage for tracheid and lumen diameter, and double cell wall thickness were computed in the radial and tangential direction for each sample. Moreover, the following parameters describing the relative cell dimensions were computed (Ifju 1990):

Coefficient of cell rigidity
= Cell wall thickness / Tracheid diameter (9)

Coefficient of cell flexibility
= Lumen diameter / Tracheid diameter (10)

Runkel's ratio
= Double cell wall thickness / Tracheid diameter (11)

Fiber density index
= $P_{P(Cell\ Wall)} / P_{P(Lumen)}$ (12)

The relationships of E and the different parameters were tested by simple linear regression analysis. Stepwise regression analysis was not attempted due to the known multicollinearity between most of the parameters.

3 Results and discussion

Results on the tracheid and lumen diameter, and double cell wall thickness for the early wood and late wood sections in the radial and tangential direction are shown in Table 2. The tracheid diameter was larger in the early wood than in the late wood in all samples. The difference was considerably larger in the radial than in the tangential direction. Compared to the prior research, both results were typical for Scots pine wood. As known, these phenomenons are due to the growth of the tracheids, their inition by cambial division and the ambient conditions.

The differences in the lumen diameter followed the same guidelines even more distinctly, especially in the radial direction. In the tangential direction the lumen diameter was strikingly constant in the late wood. The cell wall was thicker in the late wood than in the early wood, and the difference was considerably larger in the tangential than in the radial direction.

Table 2. Tracheid diameter (d_T), lumen diameter (d_L), and double cell wall thickness ($2d_{CW}$) in the early wood (E) and late wood (L) of each specimen in the radial and tangential direction.

Specimen	Radial			Tangential		
nr	d_T	d_L	$2d_{CW}$	d_T	d_L	$2d_{CW}$
		µm			µm	
1E	39.0	23.0	16.0	29.8	17.6	12.2
1L	24.7	6.3	18.4	26.5	6.8	19.7
2E	31.4	19.4	12.0	25.2	15.5	9.7
2L	19.5	3.2	16.3	24.3	4.0	20.3
3E	36.9	22.0	14.9	29.4	17.6	11.8
3L	20.6	3.3	17.3	25.4	4.1	21.3
4E	30.2	16.2	14.0	27.1	14.6	12.5
4L	20.5	4.1	16.4	21.2	4.3	16.9
5E	30.1	15.7	14.4	22.8	11.9	10.9
5L	13.5	1.6	11.9	21.2	4.1	17.1

Table 3. Longitudinal modulus of elasticity (E) and the characteristics of the wood structure for each specimen.

Variable	Specimen nr				
	1	2	3	4	5
E, GPa	9.713	12.863	14.837	18.435	19.102
Number of whole growth rings	3	7	27	41	52
Growth ring width, µm					
Early wood	4.10	1.85	0.95	0.40	0.29
Late wood	1.00	0.62	0.41	0.29	0.11
Total	5.06	2.49	1.36	0.68	0.40
Late wood percentage	20.1	25.9	29.8	41.8	28.3
Weight density, kg/m^3	398.5	449.1	460.3	630.6	598.7
Specific gravity	0.356	0.401	0.411	0.563	0.535
Tracheid diameter, µm					
Radial	36.1	28.3	32.0	26.1	25.4
Tangential	29.1	25.0	28.2	24.6	22.3
Lumen diameter, µm					
Radial	19.6	15.2	16.4	11.1	11.7
Tangential	15.4	12.6	13.6	10.2	9.6
Double cell wall thickness, µm					
Radial	16.5	13.1	15.6	15.0	13.7
Tangential	13.7	12.4	14.6	14.4	12.7
Coefficient of cell rigidity					
Radial	0.229	0.231	0.244	0.288	0.270
Tangential	0.236	0.248	0.250	0.293	0.285
Coefficient of cell flexibility					
Radial	0.543	0.537	0.513	0.425	0.460
Tangential	0.529	0.504	0.482	0.415	0.430
Runkel's ratio					
Radial	0.842	0.862	0.951	1.351	1.171
Tangential	0.890	0.984	1.074	1.411	1.323
Fiber density index	1.136	1.781	2.038	3.155	2.835

Table 4. Simple linear regression analyses to correlate the longitudinal modulus of elasticity (E), GPa, to the characteristics of wood structure.

Characteristic of wood structure	R^2	s_x	Constant	X-coefficient
Number of whole growth rings	0.801	2014.2	11.192	202.01
Growth ring width, µm				
Early wood	0.889	1506.3	18.554	–2348.2
Late wood	0.947	1039.8	20,383	–1.1147
Total	0.910	1357.5	18.930	–1972.7
Late wood percentage	0.578	2935.2	4100.0	373.21
Weight density, kg/m^3	0.904	1397.6	–3650.1	36.734
Specific gravity	0.904	1396.1	–3650.8	41.131
Tracheid diameter, µm				
Radial	0.770	2165.1	37.747	–769.34
Tangential	0.632	2738.9	43.861	–1117.3
Lumen diameter, µm				
Radial	0.898	1440.7	30.652	–1058,3
Tangential	0.894	1470.4	33.889	–1539.0
Double cell wall thickness, µm				
Radial	0.185	4076.9	32.938	–1214.4
Tangential	0.0036	4507.4	11.761	238.16
Coefficient of cell rigidity				
Radial	0.822	1904.0	–19.761	137.680
Tangential	0.894	1468.5	–23.784	147.767
Coefficient of cell flexibility				
Radial	0.831	1858.0	49.463	–69.573
Tangential	0.952	985.73	52.175	–78.782
Runkel's ratio				
Radial	0.788	2078.3	–1392.4	15.822
Tangential	0.925	1238.4	–4215.6	16.900
Fiber density index	0.954	969.19	4715.2	4693.8

Albeit the logical differences between the early wood and late wood and the radial and tangential direction, the mean free path method would have have resulted in a considerable overestimation of the tracheid diameter, if the lumen diameter and the double cell wall thickness were summed. The level of overestimation was 40 to 50 % in the early wood and 25 to 30 % in the late wood. Thus, the P_P counting appeared unreliable for Scots pine wood. This was suspected to be attributable to the regular and simple wood structure typical for this species , which results in difficulties in random sampling for stereological counting.

The results on the relationships between the longitudinal E and the basic wood characteristics are shown in Table 3. Increase in the tracheid dimensions generally resulted in a decrease in E, but the effect was not clear. The range of observations for double cell wall thickness was small. As a consequence, conclusions cannot be drawn from its effect. When testing E, the load was applied in the tangential direction. Thus, it was expected that the tracheid dimensions would have a larger effect to E in the tangential than radial direction. A clear difference was not observed, however.

The derivative parameters of the tracheid dimensions – coefficients of cell rigidity and flexibility, Runkel's ratio and fiber density index – showed a more explicit effect to E than the mere tracheid dimensions, because they indicate the relative dimensions of cell wall and lumen. The increase in most derivative parameters resulted in an increase in E. Coefficient of cell flexibility had naturally a reverse effect. All samples had a lower value for coefficient of cell rigidity and Runkel's ratio and a higher value for coefficient of cell flexibility in the radial than tangential direction.

An increase in the total growth ring width, but also in the width of the early wood and late wood section within a growth ring resulted in a

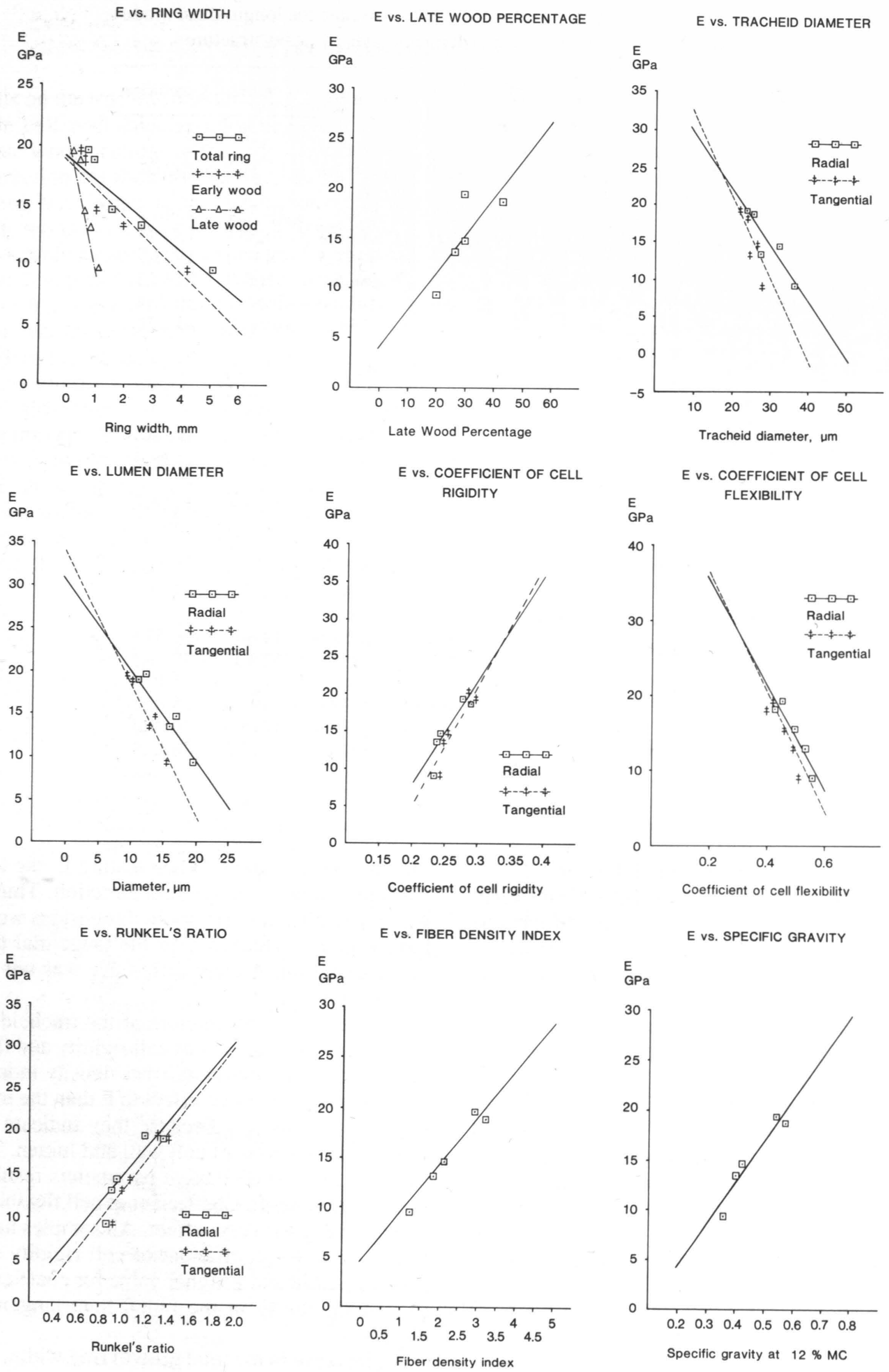

Fig. 1. Illustrations of some simple linear regression models to predict the longitudinal modulus of elasticity (E) of Scots pine by some basic wood characteristics.

decrease in E. Late wood percentage, number of rings in a sample, weight density and specific gravity, which increased by a decreasing growth ring width, had a reverse effect. All these relationships are generally acknowledged and verified by the prior research.

Only the growth ring width (or number of the rings) was able to explicitly predict E. In this light, growth ring width could be considered a good predictor for E. However, this material was too small for such a generalization. Samples 1 and 2 were from juvenile wood with wide growth rings and a low weight density and specific gravity. Analogously, their E was the lowest. Sample 5 was an interesting curiosity with the highest E – apart from the fact that its level of the basic wood characteristics (growth ring width excluded) indicated a lower E than in sample 4. The mixed composition of sapwood and heartwood in sample 5 may have had some effect on its unexpected elastic behaviour.

Results from the simple linear regression analyses on the relationships of E to the basic wood characetristics are shown in Table 4. Concluded from the coefficients of determination and standard errors of estimate, the best predictors for E were fiber density index and several parameters determined in the tangential direction, such as coefficient of cell flexibility and Runkel's ratio. Weight density, specific gravity and growth ring width were good predictors as well. Double cell wall thickness and late wood percentage appeared inefficient predictors. Moreover, the small range of observations for cell wall thickness practically made the conclusions on its effect impossible. The results indicated that the absolute tracheid dimensions do not predict well E, but the parameters that relate them to each other are quite useful.

It is possible that the presumed lack of reliablity in the stereological determination of tracheid dimensions caused a larger error in the absolute than in the relative parameters. Nevertheless, the lumen diameter appeared a rather good predictor for E.

The derivative parameters had higher coefficients of determination when determined in the tangential instead of the radial direction, This was analogous to the test technique, bending in the tangential direction.

Curves for some regression models are plotted in Fig. 1. In many models, the range of data was extremely small, which along with the small number of observations weakened the validity of the models. In this light, total growth ring width, specific gravity, weight density, runkel's ratio and fiber density index could be considered the most valuable predictors for E.

4 Conclusions

This short study showed that even with a small material it is possible to indicate rather clear relationships between the mechanical properties, such as longitudinal modulus of elasticity (E), and the characteristics of wood structure. However, the results of stereological counting may not be generalized as safely for a species like Scots pine with a regular and simple wood structure as for most hardwoods, for example.

The relationships observed were expected. Good predictors for E were fiber density index, tangential coefficient of cell rigidity and Runkel's ratio, weight density and specific gravity, whose increase resulted in an increase in E, and tangential coefficient of cell flexibility, total growth ring width, and the width of early wood and late wood section within a ring, whose increase resulted in a decrease in E. Lumen diameter had the clearest effect to E. A change by one unit in a tangential tracheid dimension had more effect to E than an equal change in a radial dimension. All tracheid dimensions had generally an inverse relationship with E.

Experiences of the stereological counting applied for Scots pine wood were of two kinds. On one hand, the actual counting was rather simple and straightforward, thanks to the simple structure of Scots pine wood. For example, detection of early wood and late wood sections was not normally problematic for the counting, even though a narrow transition zone normally occurs between them. The cells are also rather regularly arranged, and they are of few types. This fact bears a serious drawback for the stereological counting: systematic errors may occur due to the relative placement of the grid and the counting lines. In addition, a large sample is usually needed for a good accuracy. However, the results of this study did not support this misgiving.

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