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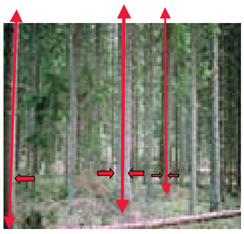



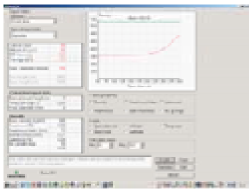
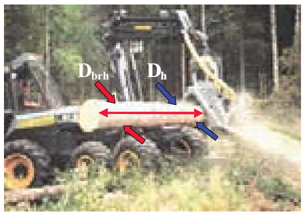

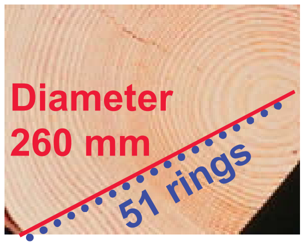

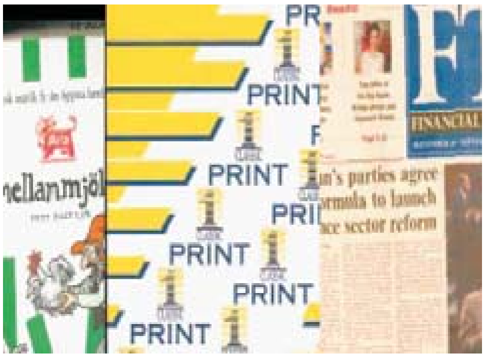

Characterisation of stem, wood and fiber properties – industrial relevance

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Contents

Abstract

All industrial production chains based on wood start physically by processing trees that have been selected and cut in the forest. The steps taken in each link of the production chain affect and sometimes amplify the results of the subsequent steps. However, the variations that inevitably occur in wood and fibre properties also affect the functional properties of the final wood and fibre-based products, the efficiency of different production processes and yields in units of final products per m^3 of raw material. Consequently, information on raw-material properties should have considerable potential economic value. However, different industrial sectors have differing requirements for their raw material, and focus on different parameters, depending on the products, processes, production strategies, logistics and market factors involved. Furthermore, the short-term scope for making supply-chain adjustments may be heavily constrained by factors such as fixed product specifications, limitations in process techniques and present market conditions. Hence, a system for characterising stem, wood and fibre properties may not offer obvious short-term benefits, even if it has a clear potential to improve products and the overall efficiency in a production chain. Thus, to realise this potential, detailed system analyses and strategic decisions to adopt such measures for each specific product and production process are needed.

This paper provides information indicating that a general system for characterising wood and fibre properties, based on cost-efficient data acquisition, will provide a profitable basis for improving production planning, product design and process development of wood-related industries, while reducing their environmental load and enhancing the marketing of final products. For example, two pieces of spruce wood with basic densities of 410 kg/m^3sw and 330 kg/m^3sw may provide sawn boards with average MOR values of around 50 MPa and 35 MPa and average MOE values of 14 GPa and 10.5 Gpa, respectively. Kraft pulping of the same pieces of wood may provide predicted tear indices of 14 and 9, and tensile indices of 106 and 118, respectively (all Kraft pulp properties also depend on process parameters). About 4.7 m^3 of the high density wood would be required to make a tonne of Kraft pulp, compared to as much as 5.8 m^3 of the low density wood.

In the wood market the most important properties of the raw material required by a certain industrial sector in a specific region could be evaluated to provide quality indices for efficient tree pricing that are directly related to the industrial needs and available forest resources. Models predicting stem, wood and fibre properties from easily acquired data comprise one of the prerequisites for a change to a more rational and widely-applicable system of quality characterisation than the assortment- and quality class- based classifications currently applied to sawlogs and pulpwood.

Retail Price Index adjusted statistics for the past 20 years from the Swedish National Board of Forestry, Statistics Sweden and Swedish Forest Industries Federation clearly show that the prices of most forest industry products, sawlogs and pulpwood have been steadily falling. The data indicate that prices for sawn goods have been declining by 1.1 % per year, while prices of pine and spruce sawlogs have decreased by 2.1% and 1.3 % per year, respectively. Corresponding declines in kraft paper, unbleached kraft pulp and sulphate softwood prices amount to about 1.1 %, 1.7 % and 3.3 % per year. In addition, the annual price losses of newsprint and spruce

pulpwood have been calculated to average about 1.6 % and 3.2 % p.a., respectively. To retain profitability in the long run all links in the production chain have to contribute to increased efficiency and the development of new products. Better characterisation of the forest resources offers a potential means to both increase the efficiency and value of industrial production chains and to help integrate forest planning, forest operations and industrial processes.

Introduction

Wood formation is affected by complex interactions between genotypic factors (which vary between and within species, and within trees as they age) and environmental conditions, which also vary continually both spatially and temporally. The major differences between tree species in terms of physical, aesthetic, mechanical and durability properties have been extensively investigated and quantified (see, for instance, Rijsdijk & Laming, 1994; Boutelje & Rydell, 1995; Ilvessalo-Pfäffli, 1994; and websites like Woodweb.com; Borealforest.org; Woodfloorsonline.com). However, due to the within-species variations the values typically presented for wood properties of any species (such as dimension, strength and quality parameters) can only be indicators of the magnitudes of the parameters. They will not always accurately describe the properties of wood from more specific sources or selected trees within the range of the species. Furthermore, most properties of the wood and fibre materials are anisotropic, that is they differ in different directions, e.g. longitudinal (root to top), radial (pith to bark) and tangential directions. An obvious example of such variation is the difference between juvenile wood (the zone spanning 10–20 rings outwards from the pith) and mature wood, which differ markedly in terms of many wood and fibre properties. At the individual tree level these differences are primarily due to interactions between the genetic code and various environmental factors, including competition and damage during the lifetime of the tree. Variations in these factors cause the observable differences in cell ultrastructure, tracheid dimensions, aggregated wood properties (earlywood/latewood, spiral grain, heartwood, basic density, moisture content, individual knot types and sizes, etc.), and macrostructures of wood (knot structures, log and stem dimensions etc.).

Considering Nordic conditions more specifically, stem, wood and fibre properties of pine and spruce are still quite variable (Table 1). But, what is the industrial relevance of this variation? What is the scope for predicting and utilising relevant properties in relation to specific processes and products, and what is the potential value of doing so?

Table 1.
Basic statistics from wood samples taken from 42 stands dominated by Norway spruce and 20 stands dominated by Scots pine within latitudes 56.6 – 65.8°. Material from the Forest –Pulp-Paper project (STFI/Skogforsk; Lundqvist et al., 2003).

	Norway spruce			Scots pine		
Property	Mean	St dev	CV %	Mean	St dev	CV %
Basic density (kg/m³)	383	37	9.7 %	398	40.1	10 %
Latewood (%)	21.8	4.7	21.6 %	23.9	4.2	18 %
Juvenile wood diam, all (mm)	73	32	43.8 %	57	22	39 %
Juvenile wood diam in discs >15 rings (mm)	78	33	42.3 %	57	22	39 %
Juvenile wood, all (%)	56	35	62.5 %	44	36	82 %
Juvenile wood in discs >15 rings (%)	39	26	66.7 %	30	25	83 %
Heartwood diam (mm)	71	65	91.5 %	54	50	93 %
Heartwood (%)	29	22	75.9 %	20	17	85 %
Bark thickness, double (mm)	9.6	4.1	42.7 %	9.3	7.4	80 %
Diameter ub, d_h (mm)	126	77	61.1 %	115	61	53 %
Annual rings (years) Height, h (m)	33	27	81.8 %	45	32	71 %
Sampling height, h (m)	9.5	7	73.7 %	7.9	5.4	68 %
Mean annual ring width (mm)	2.33	1.04	44.6 %	1.64	0.82	50 %
Tree height (m)	17.4	6.4	36.8 %	14.4	4.7	33 %
Diameter ob, bh (mm)	195	89	45.6 %	175	71	41 %
Diameter ub, bh (mm)	183	85	46.4 %	156	64	41 %
Bark thickness double, bh (mm)	11.9	5.4	45.4 %	18.8	9.8	52 %
Tree age, bh (years)	55	36	65.5 %	68	35	51 %
Distance to live crown (m)	6.2	3.3	53.2 %	7.9	3.3	42 %
Fibre length mm	2.6	0.42	16.2 %	2.3	0.37	16 %
Fibre width, µm	32.5	2.52	7.8 %	34	2.13	6 %
Fibre wall thickness, µm	2.7	0.31	11.5 %	2.7	0.37	14 %

This document has been prepared to provide brief arguments justifying the industrial relevance of models for predicting stem, wood and fibre properties. The aim is to provide background information for the introduction of such models into forest planning and forest operations. The need to acquire data on key variables as inputs for these models is also discussed.

The potential industrial relevance of stem wood and fibre properties

Efforts to improve the efficiency of sawmills have largely focused on measures to improve mainstream processes. The mean values of raw material properties and the variations in them, both between and within 'standard' log assortments, have largely been accepted as unavoidable constraints when designing new processes and products. Consequently, most current production systems are designed to neutralize effects of variation in properties. In lumber production problems associated with such variations are generally handled, to some degree, by the sorting and trimming processes following sawing and/or drying. At pulp and paper mills robust equipment for cleaning and chipping the wood and filtering processes along the production line also counter some of these problems. Thus, the industrial benefits of reducing variation and/or changing mean values of different variables (and the scope for improving the raw material in specific ways) are not always readily apparent or quantifiable.

Technical bottlenecks may be hard to widen without considerable investments. Without clear indications of sufficient profitability and acceptable economic risk such investments will not be regarded feasible. But the complexity is not the only obstacle. Generally, all the links of the production and trading chains have too little flexibility to react quickly to any but the most straightforward signals, and there is overly rigid adherence to established rules, agreements and market traditions. These features, in combination with a lack of sufficiently detailed information and knowledge, all make the industry's responses to changes sluggish. Furthermore, large numbers of people and organisations, all with differing desires and objectives, are involved in some way in forestry, the forest industry and markets for forest products. The development of common standards should help to make the interactions between these participants simpler, fairer and more cost effective. However, to avoid the standards becoming obstacles themselves, they have to be progressive, and flexible enough to facilitate the introduction of sound innovations at any point throughout the different production chains, including market communications (StanForD, 1999).

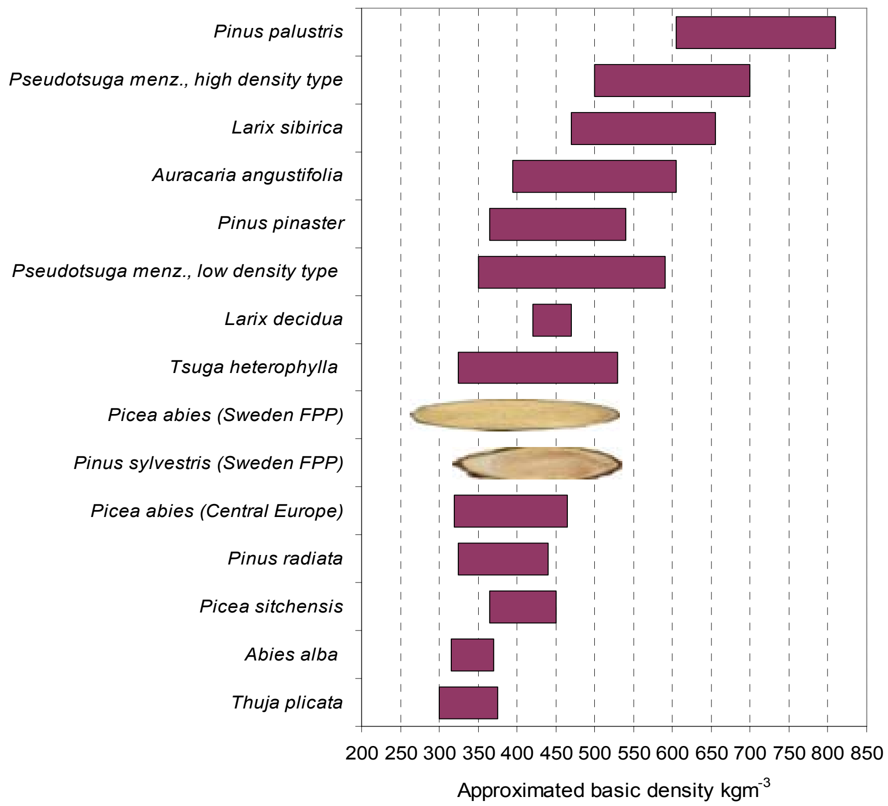

Figure 1.
Variation in approximated basic wood density of sawlog samples (origins not described in detail) from different softwood species. Derived from Rijsdijk & Laming (1994) except FPP, for which data were obtained in the Forest-Pulp-Paper project. Note: FPP samples included discs from all heights (diameter ≥5 cm) of trees sampled in Sweden (latitude 55–66°) (Wilhelmsson et al., 2002).

All industrial production chains based on wood start physically by processing trees that have been selected and cut in the forest. The steps taken in each link of the production chain affect and sometimes amplify the results of the subsequent steps. (see, for instance, Eriksson et al., 1995; Johard, 2005; Nordmark, 2005). Pre-harvesting measurements of key variables (e.g. tree diameters, ages and heights and geographic locations of the sites) allow a number of stem, wood and fibre properties to be predicted at the planning stage. At harvesting, the accuracy of such predictions can be substantially increased by considering diameter and length measurements taken by the logging machine. This kind of information can be used to characterise stem, wood and fibre properties of considerable impact on manufacturing processes and final products (Table 2). Systematic utilization of such relationships has the potential to add value to the whole Forestry-Wood-Chain and, simultaneously, to decrease the environmental load.

Operative tools for predicting log dimensions based on forest inventory data (Hansson, 1999) or stem banks adapted to local forestry conditions and bucking simulations (e.g. Ogemark & Sondell, 1998; Sondell & Mitchell, 2004) have been used in Swedish forestry for more than a decade. In addition, a system for reporting harvested log dimensions based on the measurement system in harvesters has been employed very recently by SCA Forest Products on a large scale (SDC, 2005). The next step is to integrate all of the links in a communication/information chain, retaining and enriching all potentially valuable information related to the production processes from raw wood material to the final products at the end users.

A short list of properties and their potential relevance is given in the bullet points and tables below. Figure 2 illustrates the principles involved in cost-benefit analyses of selection for improving specific properties. The larger effects of selection that should be obtained, the smaller become the available proportions of the specific wood and the higher become the costs for sorting and logistics.

Appendix 1 provides an overview of long-term trends in prices of mainstream forest products (adjusted by the Swedish Retail Price Index) and the corresponding values for sawlogs and pulpwood. Cost reductions, achieved through increases in productivity and steady increases in production capacity, have clearly been essential for maintaining profitability and competitiveness in recent decades. Consequently, for forestry in general, stumpage value has decreased much less than the prices of logs. As long as the development of new products accounts for a very limited fraction of total production volumes, this situation will probably continue. The availability of raw material with highly characterised properties could trim production costs further, by increasing the proportions of functional wood or fibres per unit produced, improving logistics or reducing the proportions of products that fail to meet specifications, for instance. The availability of highly characterised wood could also contribute to the development of new and more valuable final products, increases in the use of wood and fibre products, and the replacement of competing raw materials.

Table 2.
Potential industrial relevance of practically predictable stem, wood and fibre properties – a brief verview.

Models for predicting stem wood and fibre properties.	Industrial relevance. Impact on processes and/or products.	
Forestry planning and at harvesting	Solid wood	Pulp & paper
Log dimensions including stem taper, eccentricity	Dimensions of sawn products Optimisation of sawing yield Shape stability Yield of sawmill chips	Bark bonding strength Chip dimensions Processability Energy consumption
	Correlate with many other properties	
Bark thickness	Dimension under bark Energy, Green density	Volume under bark Energy, Green density
Green density	Affects haulage conditions, dry substance, moisture content Wood freshness important for processability, product quality and energy consumption	
Basic density	Strength e.g. modulus of elasticity (MOE) and rupture (MOR), Surface properties, hardiness, Processability, Heat-conduction, Acoustics. Bioenergy from residues	Pulp yield Correlations with fibre dimensions and paper properties (see below) Bioenergy
Juvenile wood zone	Strength (see above) Shape stability	Deviating fibre properties (see fibre dimensions)
Knot thickness	Strength properties, Processability	Deviating fibre properties, Affects chipping procedure
Knot type	Wood surface properties Workability, Aesthetic quality	Deviating fibre properties Affects chipping procedure
Heartwood diameter	Durability, Treatability, impregnation, kiln drying optimisation (energy and product quality)	Processability, extractives, chemical treatment
Fibre dimensions	See basic density (above)	All strength and surface properties (e.g. tensile, tear burst, collapsibility, porosity, gloss, brightness, opacity, bleachability) in interaction with process control and optimisation.

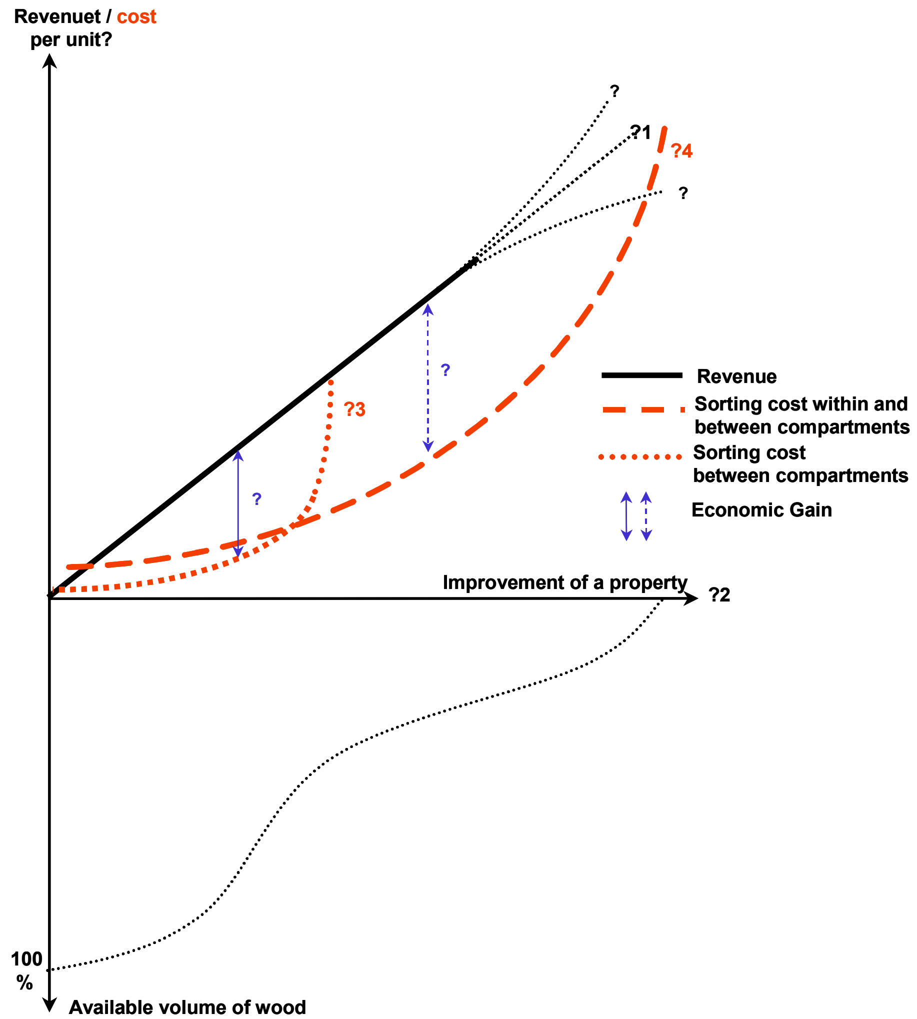

Figure 2.
To find the most economic level of sorting wood for a specific mill the following issues have to be addressed: (1) The value of a given improvement; (2) the scope to improve the property of the available wood supply by sorting; (3) the costs of sorting between and/or (4) within compartments. Sorting only between compartments results in lower cost and lower potential revenues (higher selection differential) than sorting within and between compartments. Higher selection differential results in lower available volume. (Wilhelmsson et al., 2000)

PHYSICAL AND MECHANICAL PROPERTIES OF WOOD

Wood properties are commonly divided into physical and mechanical properties. Many of these properties affect the processes or the properties of specific products (or both) depending on the processes involved.

Physical properties

- Log dimensions
- Basic density, green density, dry density and moisture content
- Moisture relations
- Radial, tangential, longitudinal and volumetric shrinkage
- Durability, decay resistance, extractives, heartwood
- Thermal properties
- Aesthetic features – grain and texture

More detailed and general considerations of physical wood properties can be found in works by various authors, e.g. Simpson & TenWolde (1999), and Fröbel (2004).

Mechanical properties

- Stiffness. Elastic properties (Modulus of Elasticity, MOE; Modulus of Rigidity, shear modulus), Poisson´s ratio (the ratio of the transverse strain to axial strain)
- Strength properties
  - Modulus of rupture (MOR)
  - Work to maximum load in bending
  - Compressive strength parallel and perpendicular to grain
  - Shear strength parallel to grain
  - Impact bending (hammer dropped until rupture occurs)
  - Tensile strength parallel and perpendicular to grain
- Working qualities
- Acoustic properties

More detailed and general considerations of mechanical properties of wood can be found in works by various authors, including Green et al. (1999) and Fröbel (2004).

Looking deeper into wood properties affecting stiffness and strength

To illustrate the relationship but also the complexity to draw straightforward conclusions between a native wood property and product properties, one can take a deeper look at wood density on one hand and lumber(timber) stiffness and strength on the other. Table 3 briefly summarises relationships between specific gravity (green wood and wood with 12 % MC) and mechanical properties of both softwoods and hardwoods presented by Green et al. (1999). The scientific background for the establishment of these relationships is not given in the publication. However, to give some indication of the scope and limitations for predicting stiffness and strength from different parameters, selected results from various studies will be briefly mentioned here. Höibö (1991) reported a number of correlations between wood density (12 % MC), annual ring width and knot area ratio in Norway spruce boards on one hand, and their stiffness (MOE) and strength (MOR) on the other. For different boards (50 × 100, 50 × 150 and 75 × 200 mm) functions predicting bending strength based on board wood density explained 29–36 % of the total variation. Functions predicting strength from annual ring width (at equal tree age) or knot area ratio gave R^2-values in the ranges 0.31 – 0.56 and 0.12 – 0.31, respectively. Correlation coefficients (R^2-values) for the wood density relationships with stiffness, annual ring width and knot area ratio were in the ranges 0.45 – 0.57, 0.20 – 0.62 and 0.09 – 0.33, respectively.

Johansson et al. (1992) stated that "Combining density and knot measures gives a fairly good prediction of strength", with R^2 values of 0.44 (bending test) and 0.59 (tension test), while density alone gave R^2 values of 0.20 and 0.38, respectively. In a review by Johansson (2003) these relationships seems to be less evident, partly depending on how it is measured (density vs. bending strength R^2= 0.16 – 0.40, density vs. tensile strength R^2= 0.29 – 0.38), even though the correlation between

MOE and MOR on one hand and density on the other is high (R^2= 0.64 and 0.66 respectively) and the effect of knots seems to be small. Johansson (2003) suggest that one explanation for this might be the variation in MOE and density over a timber cross-section, while the density used in most studies is determined as a mean value of a test piece cut across the timber. Consequently, models taking this radial variation into account might provide higher degrees of determination, than density averages. Megraw et al. (1999) developed a model for predicting the stiffness of loblolly pine specimens based on microfibril angles and specific gravity. With all rings and heights included, 93 % of the variation in MOE could be explained by these variables. For a single ring, compared across trees, R^2-values were primarily in the 0.75 to 0.85 range. At 1 metre height, the partial coefficients for individual rings tended to be larger for microfibril angle, while at 5 metres the partial coefficients tended to be larger for specific gravity. Evans and Ilic (2001) found that microfibril angle and density together accounted for 96 % of the variation in MOE of clearwood. Burdon et al., 2001 presented analyses of the relationships between basic wood density, MOE and MOR for specimens taken at five radial positions from pith to bark in radiata pines of different origins. They found fairly strong correlations between basic density and stiffness (MOE), and strong correlations between basic density and strength (MOR). Using longitudinal speed-of-stress wave transmission measurements to determine the modulus of elasticity (MOE) for logs and boards cut from the same logs Ross et al. (1997) found a strong relationship (R^2= 0.82) between the mean MOE of white spruce boards and log MOE, and a moderate relationsship (R^2 = 0.50) between individual board MOE and log MOE.

Table 3.
Mechanical properties of clear, straight-grained wood as power functions of specific gravity.
G in ton/m³ (from Green et al., 1999).

	Specific gravity–strength relationship			
	Green wood		Wood at 12% moisture content	
Property[a]	Softwoods	Hardwoods	Softwoods	Hardwoods
Static bending				
MOR (kPa)	109,600 $G^{1.01}$	118,700 $G^{1.16}$	170,700 $G^{1.01}$	171,300 $G^{1.13}$
MOE (MPa)	16,100 $G^{0.76}$	13,900 $G^{0.72}$	20,500 $G^{0.84}$	16,500 $G^{0.7}$
WML (kJ/m³)	147 $G^{1.21}$	229 $G^{1.52}$	179 $G^{1.34}$	219 $G^{1.54}$
Impact bending (N)	353 $G^{1.35}$	422 $G^{1.39}$	346 $G^{1.39}$	423 $G^{1.65}$
Compression parallel (kPa)	49,700 $G^{0.94}$	49,000 $G^{1.11}$	93,700 $G^{0.97}$	76,000 $G^{0.89}$
Compression perpendicular (kPa)	8,800 $G^{1.53}$	18,500 $G^{2.48}$	16,500 $G^{1.57}$	21,600 $G^{2.09}$
Shear parallel (kPa)	11,000 $G^{0.73}$	17,800 $G^{1.24}$	16,600 $G^{0.85}$	21,900 $G^{1.13}$
Tension perpendicular (kPa)	3,800 $G^{0.78}$	10,500 $G^{1.37}$	6,000 $G^{1.11}$	10,100 $G^{1.3}$
Side hardness (N)	6,230 $G^{1.41}$	16,550 $G^{2.31}$	85,900 $G^{1.5}$	15,300 $G^{2.09}$

[a]Compression parallel to grain is maximum crushing strength; compression perpendicular to grain is fiber stress at proportional limit. MOR is modulus of rupture; MOE, modulus of elasticity; and WML, work to maximum load. For green wood, use specific gravity based on ovendry weight and green volume; for dry wood, use specific gravity based on ovendry weight and volume at 12% moisture content.

The relationship between basic wood properties of discs taken from log ends and MOE of 40 × 90 mm structural lumber sawn from the logs of Pinus radiata were studied by Cown et al. (2004). They conclude: "Considering all boards, the results of this study suggests that density is by far the most important characteristic", when the effects of basic wood properties [Ring width, ring density, ring MFA (microfibril angle), spiral grain] on MOE were analysed.

"Defining Quality – A guide to the specification of softwood" (Anon, 2004) provides strength classes and their characteristic values, including typical class values of board density at 12 % moisture content. Figure 3 shows an example of an attempt to establish tentative models for predicting average tensile strength, in this case parallel to grain, from the average basic density of logs. Combining predicted basic density profiles with information on longitudinal and radial positions in stems, sawing patterns and knot predictions (size and structure) will probably increase the accuracy of such predictions of sawn board stiffness and strength. Models for predicting average basic density in cross-sections of stems have been published by various authors, e.g. Wilhelmsson et al. (2002), and models for predicting knot properties by authors such as Moberg (2000; 2001).

BENEFITS OF CHARACTERISING RAW MATERIAL – SOLID WOOD PRODUCTS

Knot-free window frames – case study (Bengtsson et al., 1998)

Product: Knot-free window frames constructed from finger-jointed knot-free blanks (pieces) of Scots pine. Situation: Ordinary saw-logs of specified dimensions were used to produce blanks. Problem 1: Only about 66 % of the theoretical production capacity was utilised. Problem 2: Significant proportions of the blanks produced were not knot-free and were thus unacceptable. Action: 2nd to 4th logs from relatively fast-growing trees (fertile stands) with a higher internode length (longer distance between branch whorls) than average were selected. Result: Full production capacity and higher product quality. Appropriate trees can be identified using forest inventory data and models for predicting internode length (Elfving & Kviste, 1997).

Sound-knot blanks for furniture – case study (Sondell et al., 2004)

Product: Sound-knot blanks of Scots pine for furniture production. Situation: A specific top-end diameter interval, 192–239 mm, of saw-logs was collected, with no other selection or sorting in the forest. Problem: Sound-knot blanks had to be screened from an ordinary mixture of sawn boards. The length of these boards could not be optimized to fit the optimal lengths for the furniture production. Action: By using a model based on diameter ratios (actual d/dbh; Öyen & Höibö, 1999; Sondell et al., 2004) characterising the sound-knot cylinder along the bucked stems, a log class yielding 78 % sound-knot furniture blanks was identified. Without this characterisation only 34 % of the logs yielded sound-knot boards.

Lumber grades – simulation study (Moberg & Nordmark, submitted)

Product: Ordinary Scots pine lumber graded according to Nordic Timber grading rules (Anon. 1994). Situation: Production of sawn boards is a function of delivered saw logs. Problem: Unknown proportions of saw boards sometimes fail to meet specifications. Action: Forest inventory and tree models enable volumes, sizes and proportions of boards of different quality grades to be predicted. The predictions could be further improved if similar models were used, based on production files from the harvester, thereby increasing the scope to overview and improve the fulfilment of orders and meet customers' requirements.

Sorting of strength classes (C-classes) – simulation study

Product: Structural timber of Norway spruce. Situation: A sawmill produces structural timber in C-classes, C18 or C24. The difference in price per m^3 of graded boards is 200 kr/m^3sub. By sorting sawlogs with predicted basic density >380 kg/m^3sub (aiming at C24) in one pile and sawlogs with predicted basic density 325–340 kg/m^3sub in a second pile (aiming at C18) while sawlogs within the interval 341–379 kg/m^3sub were delivered to another sawmill specialized in "ordinary spruce" logs.

Table 4 gives a brief overview of the relationships between solid wood properties and their potential relevance to product- and process-related issues at industrial sites.

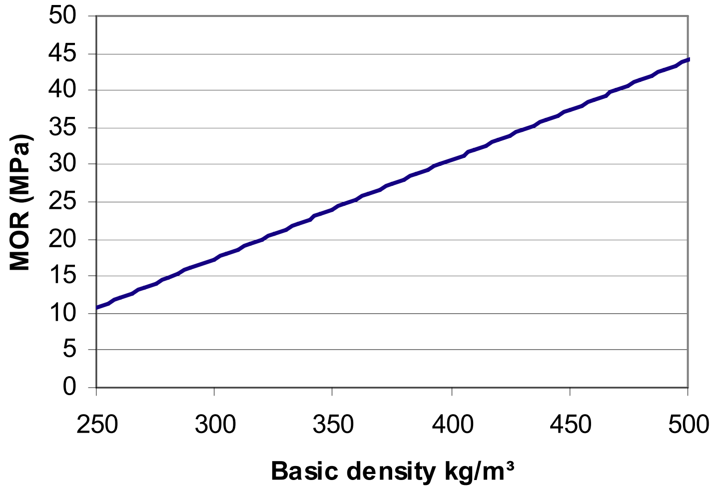

Figure 3.
Tentative model for predicting the average bending strength of boards parallel to grain from its approximated relationship with average basic density of logs. Calculated from a model developed for air dry density of boards by Höibö (1991) converted to basic density by a simple constant (Air dry density ≈ 115 % x Basic density) (OBS! Not validated).

Table 4.
Solid wood properties.

Property	Units	Industrial relevance
Log averages		
Diameter (mean of major and minor axis)	mm	Sawing pattern. Yield of primary (beams, studs, boards) and secondary products (chips, dust, shavings).
Ovality (major axis – minor axis/mean)	% of diameter	" + reaction wood
Length of log	cm	"
Long crook	% of length	" + reaction wood
Green density at felling	kg/m³fub+bark	Freshness criterion when compared with actual density at delivery to industrial site.
Green density at haulage	kg/m³fub+bark	Transportation weight and freshness criterion at delivery. To be compared with green density at felling.
Basic density (radial average)	kg/m³	Correlates with all strength properties, thermal properties e.g. Modulus of elasticity (MOE) and modulus of rupture (MOR)
Heartwood diameter	mm	Durability, water uptake, impregnability for preservatives, permeability. Emissions of extractives. Affects conditions when optimising kiln drying.
Juvenile wood diameter	mm	Shape stability, MOE, MOR correlated with spiral grain, basic density and microfibril angle.
Latewood percentage	%	Surface strength. Aesthetic
Mean annual ring width	mm	"
Internode length	cm	Length of clearwood
Maximum knot diameter at surface	mm	MOE, MOR, Probability of "critical knots". Surface properties and aesthetic quality.
Average knot diameter at surface	mm	"
Number of knots/whorl	no	"
Knot angles (average)	°	"
Sound knot length	mm	Surface properties, planeability, paintability, aesthetic quality. (Differences in load carrying capacity related to fibre distortions and stress peaks)
Pitch pockets	no./m	Spruce. Paintability, surface properties
Bark thickness	mm	Dimensions and volumes over and under bark
Debarked % of surface	%	Drying rate - freshness criterion and reduction of bark volume
Bark volume	m³	Energy
Bark dry substance	kg/m³	Energy
Bark moisture content	%	Energy
Radial profiles pith/bark		
Distance from pith	mm	Positioning at sawing
Green density at processing	kg/m³fub	Sawing conditions, kiln drying
Basic density along radius	kg/m³fub	MOE, MOR
Microfibril angle	°	MOE, MOR
Spiral grain	°	Shape stability => twist
Loose/Sound knots distances from pith	mm	Surface properties. Processability MOE, MOR, (Differences in load carrying capacity related to fibre distortions and stress peaks) planeability, paintability.
Knot diameter (largest knot)	mm	Surface properties. Processability MOE, MOR, aesthetic quality
Knot diameter (average knot)	mm	Surface properties. Processability MOE, MOR, Aesthetic quality
Knot index	%	Knot area/Total area on four board surfaces
Chip characterisation		See specifications in Table 5.
Chemical characterisation		See specifications in Table 6.Chips and solid wood products
Energy		See specifications in Table 7.

FIBRE PROPERTIES – A BRIEF OVERVIEW

Fibre length is mainly determined by the age of the cambium and its distance from the pith. Pulpwood from an old stand generally contains more long fibres than wood from a young stand. Fibres also tend to be longer when there is a large proportion of narrow growth rings in a log. Long fibres are desirable in products demanding high tear strength.

Cell-wall thickness varies considerably between earlywood and latewood. The proportion of earlywood is largely influenced by the growth rate, whereas that of latewood is mainly determined by the length of the growing season. Thus, slow-grown wood contains a high proportion of latewood, particularly in southern Sweden. The cell-wall thickness also has a strong influence on the flexibility of the fibres and their tendency to collapse. If the cell-wall thickness and fibre width are known, the papermaking process can be optimized and the properties of the paper improved.

The basic density of wood mainly depends on the ratio of the cell-wall thickness to the fibre width. Differences in log basic densities indicate differences in average fibre properties, but wood with varying proportions of different kind of fibres may have similar densities. Wide fluctuations in density lead to unevenness in the refining process and reduce the quality of the pulp. The basic density also influences the pulp yield and, hence, the volume of raw material needed to produce a tonne of pulp.

Juvenile wood is commonly demarcated as the innermost part of the stem where a number of wood and fibre properties are still considerably different from those of the outer "mature" wood. The definition of juvenile wood varies, since it can be based on diverse properties like microfibril angle, fibre length or basic density. Broadly, for spruce and pine growing under Nordic conditions, juvenile wood may comprise the first 10–25 growth rings (commonly 15–20) nearest to the pith and is typically distinguished by short, thin-walled fibres. Pulpwood from thinnings contains a high proportion of juvenile wood, particularly if it comes from a fast-grown stand. By contrast, wood chips from sawmills contain hardly any juvenile wood at all. The fibres in juvenile wood collapse easily, so a greater number of fibres can be accommodated in a sheet of paper of given thickness, and there will be a higher proportion of fines in mechanical pulp made from such wood. Thus, paper containing a high proportion of fibres from juvenile wood has a large light scattering surface, giving good optical properties and an even printing surface. On the other hand, the short fibre length reduces the tear strength of the paper, and if the strength of the mechanical pulp is too low, expensive reinforcement kraft pulp has to be added.

Heartwood content largely depends on the age of the tree and the longitudinal position (height) in the stem. Sawmill wood chips, tops and young thinnings contain mostly sapwood. Heartwood has a higher content of extractives and lower moisture content than sapwood. The high concentration of extractives in the heartwood of Scots pine may be the main reason that this species does not provide suitable raw material for the manufacture of mechanical pulp.

The quality of sapwood falls when it dries out, since its resistance to barking increases. A low moisture content can also lead to inferior strength and optical properties, due to poor fibre separation, fibre shortening and poorer processing of the cell wall. On the other hand, haulage costs are higher for wood with a high moisture content, since the payload limit is usually based on the total weight of the rig.

BENEFITS OF CHARACTERISING RAW MATERIAL – FIBRE BASED PRODUCTS

Scenario based on forest data and results from laboratory tests (Arlinger et al., 2000)

Product: Kraft-pulp for making paper with high tensile strength. Situation: There is a market for pulps with specific qualities, e.g. pulp with high tensile strength. Ordinary pulpwood does not have appropriate qualities for cost-efficient production of such pulp. Action: Using models for predicting paper properties (Jonasson et al., 2000) or fibre dimensions (Ekenstedt et al., 2003) pulpwood can be characterised according to its effects on tensile strength. Selecting a fraction of pulpwood with a high frequency of easily collapsible fibres makes production of this kind of pulp easier and more cost-effective. The properties of pulpwood from various growth conditions were predicted: Bolts with a diameter of 160 mm and 16 annual rings were predicted to give pulp with a typical tensile index of 118, tear index around 9, and collapse resistance (Jonsson, 1979) below 0,14. Another bolt with a diameter of 160 mm and 55 annual rings, were predicted to give pulp with a typical tensile index of 105, tear index around 14, and collapse resistance 0,19.

Scenario based on forest data, models for predicting wood properties and haulage costs (Moberg & Wilhelmsson, 2003)

Problem: Uncertainty regarding the most efficient strategy for wood procurement. Solution: Predictive models can be used in strategic planning to determine the properties of the raw material to be supplied to the mill. Strategic haulage costs can also be analysed. The models also have an operational role, providing information for stand scheduling, bucking and sorting, in order to increase the proportion of wood with the desired properties. The results may be applied to dynamic procurement areas and dynamic assortments (and classes within assortments) based on fluctuating factors such as product specifications and market conditions.

Table 5 gives a brief overview of the relationships between fibre properties and their potential relevance to pulp and paper product- and process-related issues at industrial sites.

Scenario Forest fuel – small diameter roundwood

Product: Energy produced from roundwood. Problem: Cost/benefit analyses with regard to energy supply in relation to haulage distance. Solution: Predicting the energy per m^3sub or per tonne fresh wood. Result: A log with 100 mm mean diameter and 11 annual rings was predicted to have a maximum content of energy at 2.04 MWh/m^3sub (Green density/m^3sub including bark predicted to 1 068 kg). A log with the same diameter but with 32 annual rings was predicted to have a maximum content of energy at 2.46 MWh/m^3sub (Green density/m^3sub including bark predicted to 1 086 kg). The densest log had 21 % more energy per m^3sub and 19 % more per tonne fresh wood.

Table 5.
Properties (and their industrial relevance) of pulp, paper and fibre products.

Property	Units	Industrial relevance
Basic density	kg/m³s.ub	Pulp yield. Correlation with fibre dimensions.
Green density at felling	kg/m³s.ub +bark	To be compared with green density at transportation/delivery
Green density at transportation/delivery	kg/m³s.ub +bark	Freshness criterion. Weight at transportation. To be compared with corresponding values at felling and basic density
Decay, % of volume	%	Discoloration, pulp yield
Degree of decay	%	Characterisation of the average dry substance content of decayed wood
Fibre dimensions Fibre length Fibre width Fibre (cell) wall thickness	 mm µm µm	Fibre dimensions affect industrial processes. Energy used for grinding or refining and the collapsibility of the fibres are related to the ratio between fibre width and the fibre wall thickness. The degree of fibre (cellwall) collapse and the number of bonds per surface unit. Collapse resistance could be expressed by a relationship between fibre width and fibre (cell wall) width (Jonsson, 1979). Strength properties (Tensile, tear, burst etc.) Optical properties, surface properties Permeability (porosity)
Microfibril angle	°	Strength, shape stability, process energy consumption
Fibre flexibility (Form-factor)	%	Surface and strength properties
Latewood	%	Distributions of variation in fibre width and cell-wall thickness (see fibre dimensions)
Reaction wood	no/yes	Characterised by short and comparatively wide fibres with thick walls (see fibre)
Sound knot %	% of vol.	Different type of fibres
Loose knot %	% of vol.	Discoloration and undesirable fibres.
Bark thickness	mm	Diameter under bark and volume of wood and bark
Debarked % of surface	%	Drying rate - freshness criterion and reduced volume of bark
Bark volume	% of m³s.ub	Energy
Bark dry substance	kg/m³	Energy
Bark moisture content	%	Energy
+ Chemical characterisation		See Table 6. Lignin content correlates with energy consumption
+ Energy utilisation		See Table 7.

Table 6.
Chemical characterisation.

Property	Units	Industrial relevance
Cellulose	% of dry weight	Chemical utilisation
Lignins	% of d.w.	"
Hemicelluloses	% of d.w.	"
Extractives	% of d.w.	Environmental declaration, taste and smell, emissions. Dilution of extractives
Minerals	PPM of d.w.	Environmental declaration of paper, solid wood properties. Ash from burning processes (energy utilisation)
Metals	PPM of d.w.	Environmental declaration of paper, solid wood properties. Ash from burning processes (energy utilisation)

Table 7.
Energy utilisation.

Property	Units	Industrial relevance
Stem wood	% of volume	
Basic wood density	kg/m³fub	Proportional to energy content
Green density	kg/m³fub	Important for energy utilisation
Dry substance	%	"
Moisture content	%	Technically important
Decay, % of volume	%	To adjust predicted basic wood density
Degree of the decay	%	Characterisation of the average dry substance of decayed wood
Bark	% of volume	Total volume available
Bark loss	% of volume	Total volume lost
Basic bark density	kg/m³fub	Proportional to energy content
Green density, bark	kg/m³fub	Important for energy utilisation
Dry substance, bark	%	"
Moisture content	%	Technically important
Branchwood	% of volume	Total volume
Technically available	% of volume	Total volume available
Basic branch wood density	kg/m³fub	Proportional to energy content
Green branchwood density	kg/m³fub	Important for energy utilisation
Dry substance	%	"
Moisture content	%	Technically important
Needles	% of volume	
Technically available	% of volume	Total volume available
Dry substance	%	Important for energy utilisation
Moisture content	%	Technically important
Chemical characterisation		See table 6.

Acquisition of key variables

Most wood and fibre properties mentioned in this report can be predicted to a meaningful degree using data on the diameter (bh), age (bh or total), height of the trees, the wood's longitudinal position in the stem and the geographic position of the stand (estimated temperature sum). If these key variables are gathered systematically at forest inventories a general characterisation of properties of industrial relevance can be achieved.

Economic relevance

The potential economic benefits of predicting stem, wood and fibre properties at forest planning and harvesting stages heavily depend on the degree of integration of forest operations and industrial production. System analyses of specific conditions, in which all of the processes in a production chain are considered, are needed to calculate overall costs and revenues. Cases where attempts have been made to analyse the economic effects of improving the characterisation of stem, wood and fibre properties for specific industrial concerns indicate that it has clear economic benefits for the overall system (total gains exceed total costs) compared to continued use of common assortments without further characterisation.

Finally an example of a tentative valuation of some important product properties are presented in figure 4 (Adjusted prices of lumber and pulpwood). Observe that pricing of properties are fictive, however judged to be within a possible range. The input data used are presented in tables 8 • 10. The results from predicting the wood and fibre properties are roughly as follows: Two pieces of spruce wood with basic densities of 410 kg/m^{3}sw and 330 kg/m^{3}sw may provide sawn boards with average Modulus of rupture (MOR) values of around 50 MPa and 35 MPa and Modulus of elasticity (MOE) values of 14 GPa and 10.5 Gpa, respectively (based on functions by Höibö (1991) and conversion from air dry density to basic density (Air dry density • 115 % × Basic density). Kraft pulping of the same pieces of wood may provide predicted tear indices of 14 and 9, and tensile indices of 106 and 118, respectively [based on Jonasson et. al (2000), all Kraft pulp properties also depend on process parameters]. About 4.7 m^{3}sw u.b of the high density wood would be required to make a tonne of Kraft pulp, compared to as much as 5.8 m^{3}sw u.b of the low density wood. The maximum content of energy from the two logs may, by average, amount to 1.9 and 2.4 MWh/m^{3}sw u.b + bark respectively.

Table 8.
Key properties (input data) used for characterizing (predicting) properties of the compared logs (A and B) in figure 4.

Input data	Log A	Log B
Stand origin Latitude °N	60	60
Altitude (m)	100	100
Species	Picea abies	Picea abies
Diameter of tree (bh) o.b	280	280
Number of annual rings (bh)	150	35
Log mean diameter o.b	160	160

Table 9.
Relative change (fictive values from Lumber producer 1) in log price based on MOE (Moduls of elasticity).

Property	Normal values at 100% price level	% effect on price of 1 % change of the property
MOE (GPa)	12	0,5

Table 10.
Relative change (fictive values for pulpwood class 1) in pulpwood price based on basic density, tensile and tear indices.

Property	Normal values at 100% price level	% effect on price of 1 % change of the property
Basic density kg/m³	370	1
Tensile index (4000 rev)	112	1,5
Tear index (4000 rev)	12,5	0,1

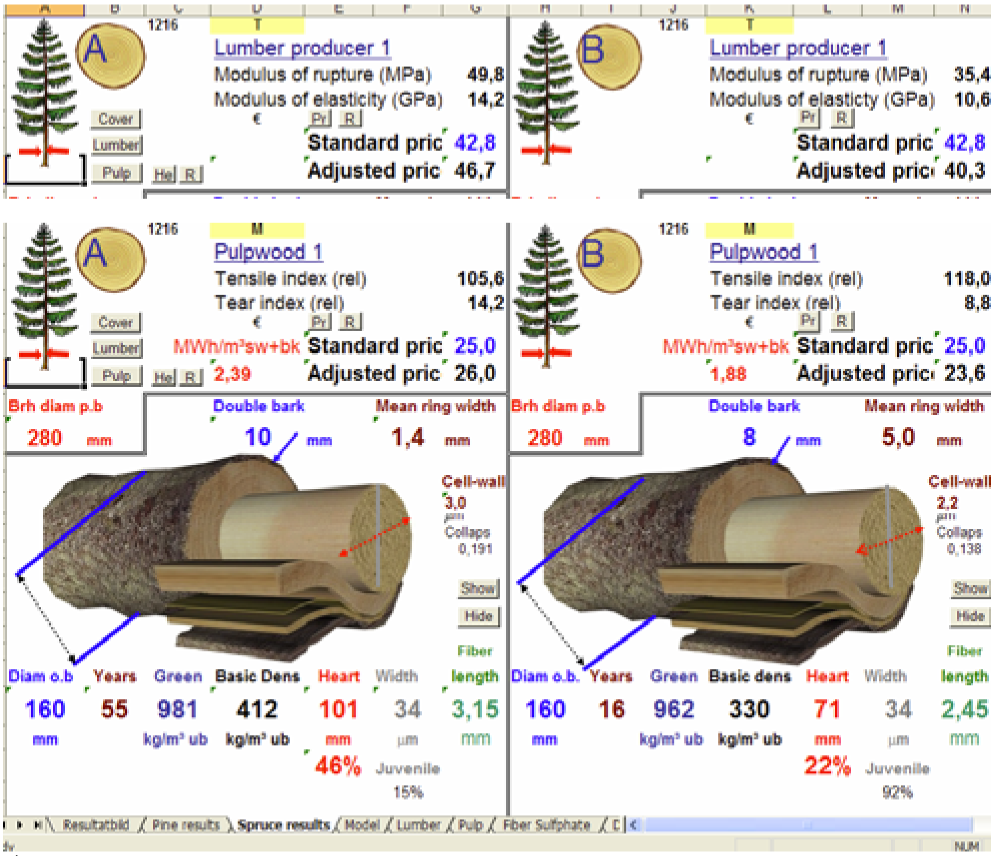

Figure 4.

Predictions of wood and fibre properties in cross-sections (representing log averages) of two logs of the same dimension but from trees of different growth rates (log input data in table 8). Screen dump from an experimental tool. Property models based on Jonsson (1979), Höibö (1991), Jonasson et al. (2000) ,Wilhelmsson et al. (2002), Ekenstedt et al (2003), and unpublished functions (Skogforsk)). Standard prices (average 100% level) and adjusted prices based on figures (fictive) from tables 9–10 given in €/m³sw u,b. (Log pictures animated by Peter Wilhelmsson).

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SOURCE OF STATISTICS

www.svo.se/statistik

www.scb.se

The value of Swedish forest products

The value of products from Swedish forest industries amounted to about 180 billion SEK in the year 2000 (Skogsstyrelsen, 2003). In general, all segments of forest industries face strong international competition, not only from other producers of forest products, but also from alternatives based on other raw materials. Under these circumstances if there is no further development of processes and products the industry's competitiveness and net product values will almost certainly decline to the point where liquidation of the companies would be unavoidable.

Obviously doing nothing is not an economically sustainable option, for either the forest-based industries, or forestry. By contrast, Eriksson et al. (1995) estimated the potential gains that could be accrued by improving common processes and products in the forest-related businesses (including the potential increases in both added value and sale volumes due to improved competitiveness) to be more than 25 billion SEK/year. Long-term trends for forest products show that volumes have increased, while added value has generally decreased (figures 3–5).

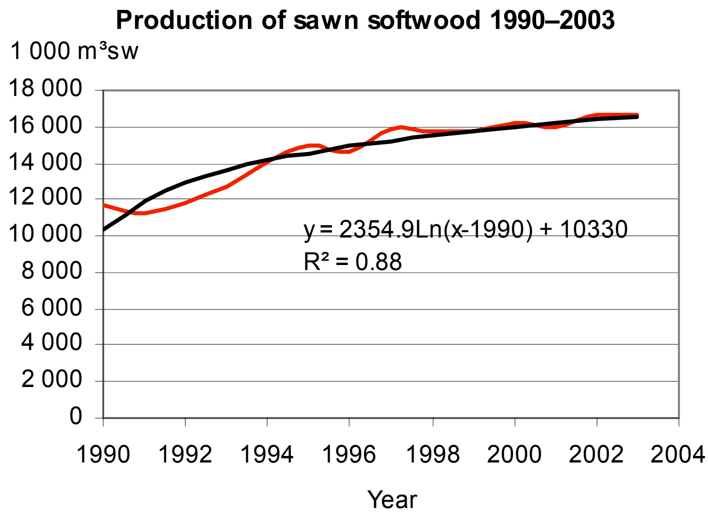

Figure 1.
Total production of sawn softwood in Sweden based on available statistics for the period 1990-2003. Source: Swedish Forest Industries Federation. Trend estimate generated by linear regression where production is a logarithmic.

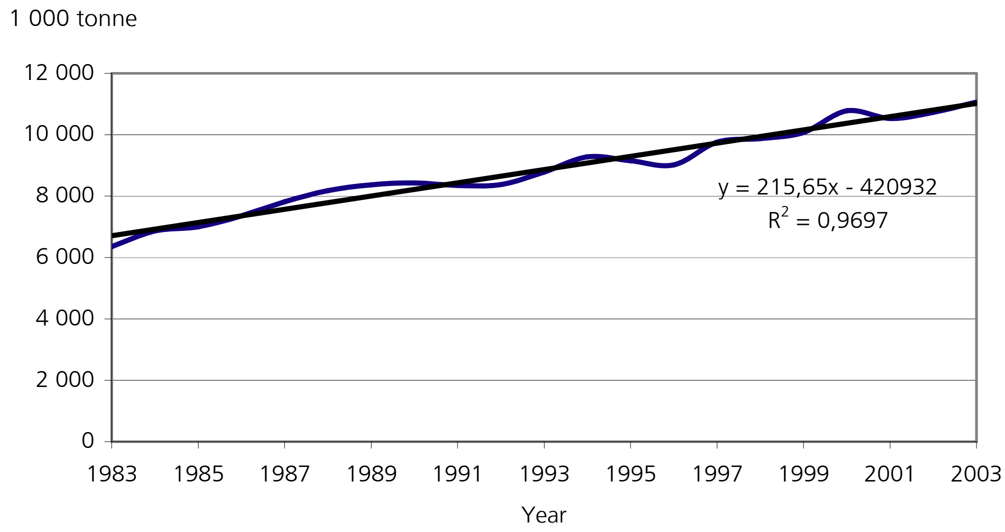

Figure. 2.
Total production of paper and paperboard in Sweden 1983–2003. Trend estimate generated by simple linear regression where production is a function of time. Source: Swedish Forest Industries Federation.

Changes in prices and merchandized volumes, 1983–2003

After adjustment by the Retail Price Index (Swedish KPI), the average declines in real prices/year in the period 1983–2002 were calculated for sawn goods, sawlogs, paper, pulp and pulpwood using price statistics from SCB, SDC & Skogsstyrelsen (2003) and a simple regression function (1):

$$y_x = p \cdot e^{-r \cdot x} \quad (1)$$

where y_x is the estimated price in year x, p is the intercept (~ estimated initial price) and r is the estimated price loss per year.

The results indicate that prices of all sawn goods, pine sawlogs and spruce sawlogs have fallen by about 1.1 %, 2.1 % and 1.3 % per year, respectively (figure 3). Corresponding losses for kraft paper, unbleached kraft pulp and sulphate softwood amounted to about 1.1 %, 1.7 % and 3.3 % per year (figure 4), while those of newsprint and spruce pulpwood averaged 1.6 % and 3.2 %, respectively (figure 5).

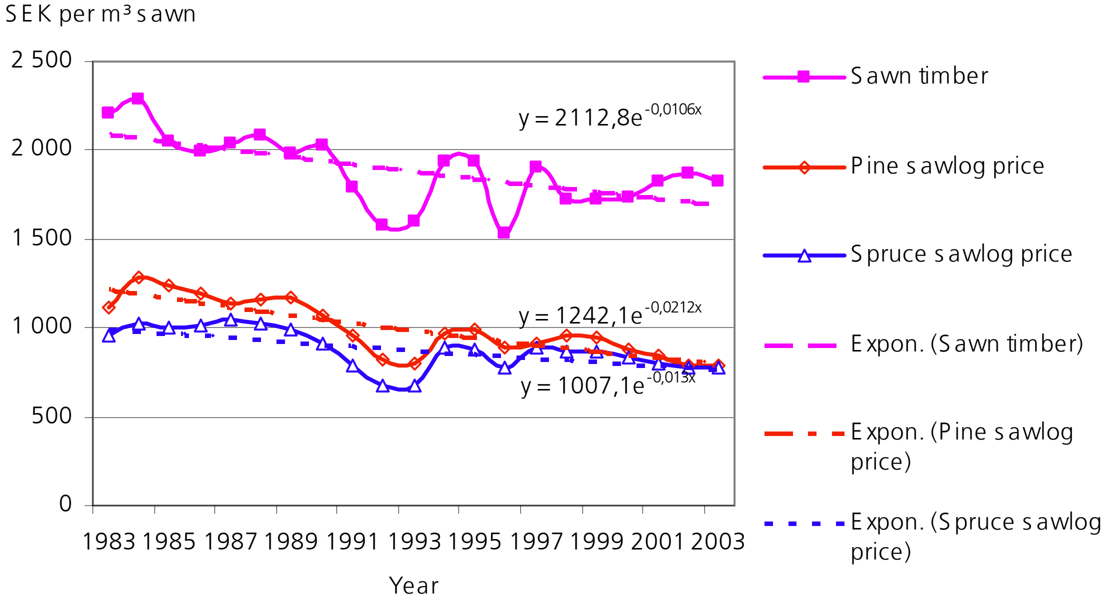

Figure 3.
Real prices of sawn goods and sawlogs (adjusted by the Retail Price Index, Swedish KPI) in 1983–2003 of sawn goods (export prices), pine sawlogs and spruce sawlogs assuming a constant sawing yield (50%) (Source of statistics: SCB, SDC & Skogsstyrelsen, 2004).

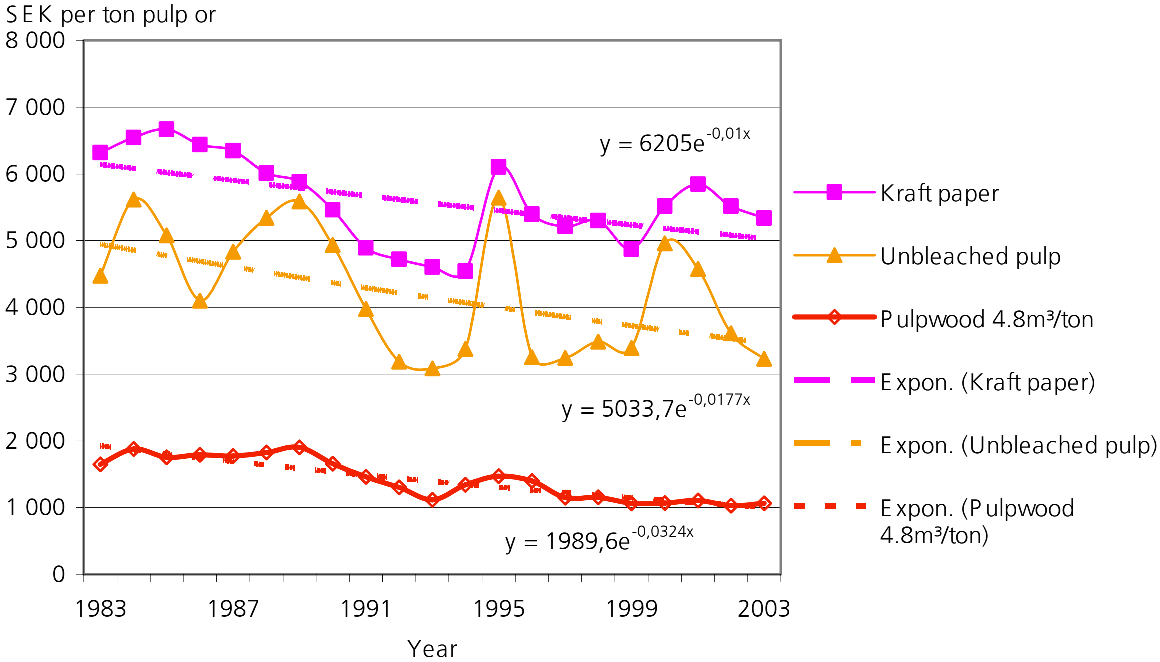

Fig. 4.
Real export prices (adjusted by the Retail Price Index; Swedish KPI) of Kraft paper, pulp and pulpwood in 1983–2003, assuming a constant pulp yield of 4.8 m³/tonne (Source of statistics: SCB, SDC & Skogsstyrelsen, 2004).

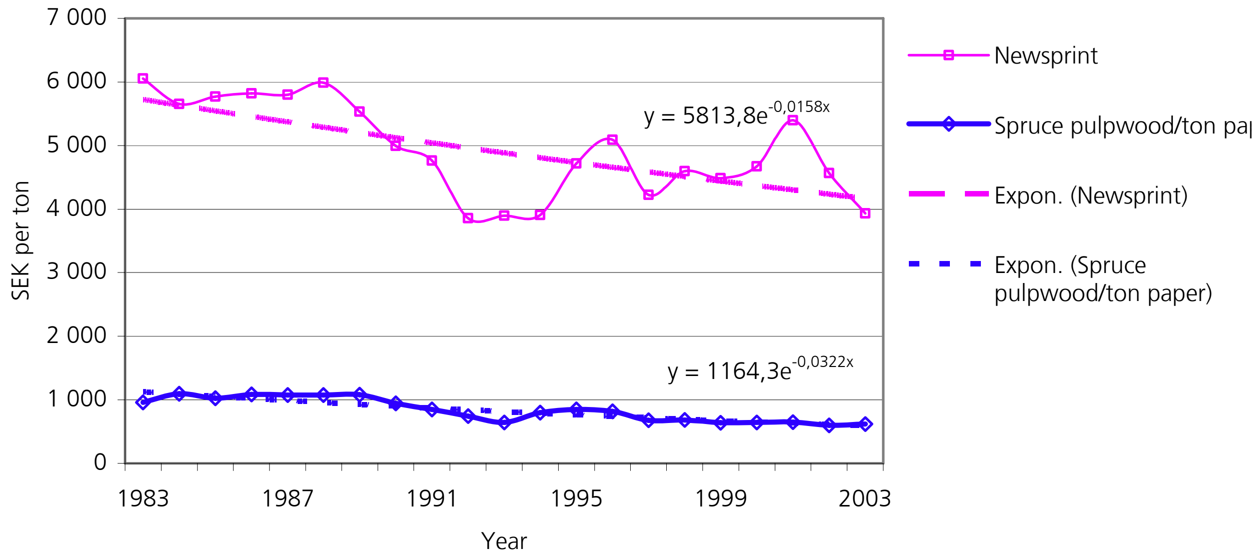

Figure 5.
Real prices (adjusted by the Retail Price Index; Swedish KPI) of newsprint from TMP and spruce pulpwood in 1983-2003, assuming a constant pulp yield of 2.6 m³/tonne (Source of statistics: SCB, SDC & Skogsstyrelsen, 2004).

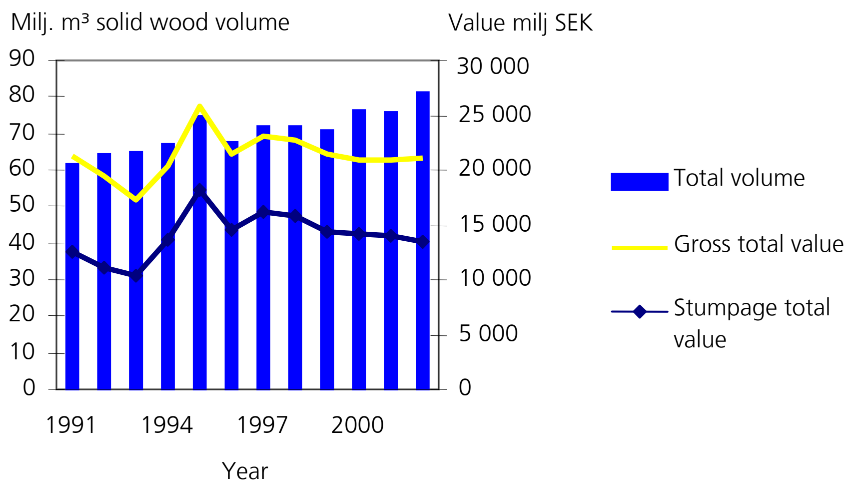

Figure 6.
Annual cut in Sweden (bars and left axis) and its total gross and total stumpage values (adjusted by the Retail Price Index; Swedish KPI) 1991-2002. (Source of statistics: SCB, SDC & Skogsstyrelsen, 2004).

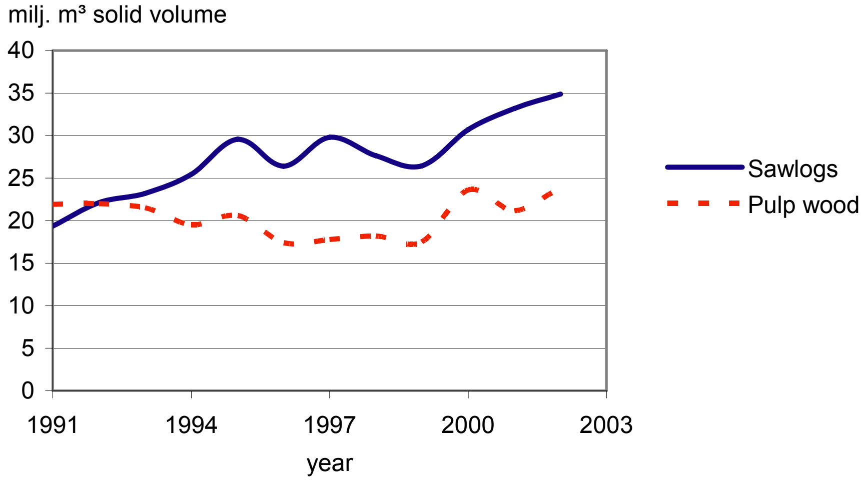

Figure 7.
Annual cut of sawlogs and pulpwood in Sweden 1991–2002. (Skogsstyrelsen, 2003).

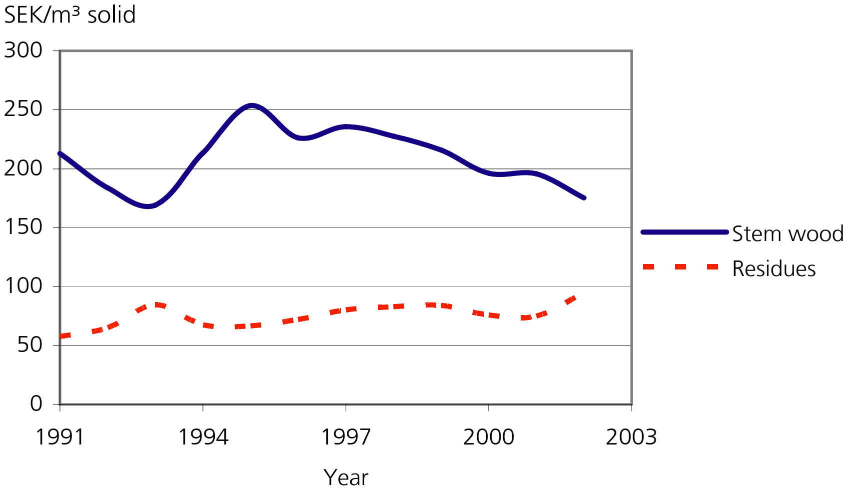

Figure 8.
Stumpage values in SEK per m³ solid wood/residues (adjusted by the Retail Price Index; Swedish KPI) 1991–2002. (Source of statistics: SDC & Skogsstyrelsen, 2004).