Models for fibre dimensions in different softwood species. Simulation and comparison of within and between tree variations for Norway and Sitka spruce, Scots and Loblolly pine

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ABSTRACT

Wood and fibre properties and their variations in softwood species of different origins have been measured, described with models and compared. In the paper, differences in fibre dimensions: length, width and wall thickness, within and between trees are shown for four wood species grown in Europe and North America: Norway spruce (*Picea abies*), Sitka sprice (*Picea sitchensis*), Scots pine (*Pinus silvestris*) and Loblolly pine (*Pinus taeda*). For these wood species, the variability in wood and fibre properties have been analysed and models with different levels of detail have been developed in projects performed in different countries, using similar methodology. Similarities and differences between models for the different wood species and fibre dimensions are discussed regarding model structures and effects of independent variables with strong influence on various properties. Models for cross-sectional averages in stems or logs are emphasized.

In general, the patterns of variation are similar for the four softwood species investigated, but some differences are observed. The spruce and pine species are pair wise more similar to each other. The most pronounced difference is observed for the fibre wall thickness close to the ground. The spruce species studied show a reduction in fibre wall thickness in the lower part of the stem when approaching the ground, whereas the fibre wall thickness increases for the pine species.

For all the wood species, the models with the highest coefficients of determination (R^2-value) are obtained for fibre length, with values around 0.80. The models for fibre wall thickness show rather low R^2-values for the spruces, down to around 0.50, while these values are higher for the pine species, around 0.65. This difference may partly be an effect of the larger variation between heights in the pine trees. The R^2-values for fibre width are in between these numbers. The models described for Sitka spruce are based on a small sample and data material and are somewhat weaker.

The models presented will be further developed and validated based on new sample and data materials, including more variables and regions, together with different partners. The goal is to develop good models for the variability in important wood and fibre properties of forest trees, useful also in applications for improved wood and fibre utilization. Tools for this are already developed. In the paper, toolboxes for simulation are used to illustrate differences within and between trees of the four softwood specie, using the models together with typical input data on age, growth conditions, etc. for the countries involved. With these tools, the models can also be used to investigate differences between industrial raw materials, when different selection criteria are applied. Such use of the models is illustrated. Estimated fibre dimensions are shown for pulpwood logs and sawmill chips from thinning and final cutting at different ages of trees of different wood species.

BACKGROUND

In most programs for tree improvement and in the development of forestry practices, growth and yield have been emphasized. Growth and yield are of utmost importance, but the quality of wood-based products and the production cost and the operation efficiency of the forest-based industry are in many cases largely influenced by the material properties of the wood. A current challenge to forestry and the forest products industry is to develop tools and practices for the supply of more uniform and suitable raw materials for different conversion processes, to enable the manufacture of lower cost and/or improved quality products. This is true for products based on solid wood as well as on fibres.

The properties of wood and fibres in trees vary considerably, not only among species but also among regions, individual forest stands and trees and, not the least, within trees. The properties of the individual tree are determined by its hereditary character and from environmental impacts on the cell divisions in cambium and meristems (Larson 1994). The differences between individual trees and parts of trees are enlarged by external disturbances and damage. Some of the differences, like the impact of cambial age and of changes in growth rates from climatic conditions, are structural and possible to predict. Other differences, like effects of external disturbances on individual trees in a stand, occur as random variations.

For the development of efficient tools and practices for optimal use of the wood resources, it is crucial to know the variability of important wood and fibre properties in the raw material base. How large are the differences? How are they structured? What is possible to predict? Such information may be formulated into models, useful for prediction of properties to support proper allocation. Research and development in this field are, however, hardly possible without efficient measurement methods. Fortunately, such methods are now available for many important properties of wood and wood cells.

In the paper, the fibre dimensions: length, width and wall thickness, are compared for softwood of different origins, based on results from a number of projects performed at STFI-Packforsk, in cooperation with different partners. Four softwood species in different regions are compared:

Wood species	**Country**	**References**
Norway spruce (*Picea abies*)	a) Sweden b) Four European countries	a)Ekenstedt et al 2003 b) Lundqvist et al 2004
Sitka sprice (*Picea sitchensis*)	Great Britain	Hedenberg et al 2005
Scots pine (*Pinus sylvestris*)	Sweden	Ekenstedt et al 2003
Loblolly pine (*Pinus taeda*)	USA	Lundqvist et al 2005

Differences and variations are illustrated with measurement data and described with models developed for these species and regions, using similar methodology. Such methods for sampling, sample preparation, measurements, modelling, simulation, optimization and evaluation have been successively refined during many years and an arsenal of measurement methods is available in the STFI-Packforsk Wood and Fibre Measurement Laboratory. The partners from the different regions have contributed with expertise on the regional resources and forestry practices.

In the reports and papers referred to above, each investigation and its results are described in detail and more references are given. In the current paper, models are compiled for averages of fibre dimensions in arbitrary cross-sections of stems. Similarities and differences between models for various species and fibre dimensions are discussed. The structures of the models, effects of independent variables with strong influences, etc. are commented and compared between the species.

The models presented are not in their final state, even if they are already implemented in toolboxes for simulation of wood resources and evaluation of raw material assortments from mills and products. The models will be further developed and validated based on new sample and data materials, including more variables and regions, built up in new projects in cooperation with different partners. New investigations are currently performed for all the four softwood species. The goal is to develop good models, which will contribute to a better understanding of the variability in properties of forest trees, and which will be useful in applications for improved wood and fibre utilization, to the benefit of forestry, industry and society.

METHODS

In all the studies referred to, the sampling strategies applied were designed to provide information on the effects of the major sources of variation in the wood and fibre properties to be investigated, as a basis for modelling. Stands of different site indices and climatic conditions (latitude and altitude) were selected for sampling. Also stands of different ages were sampled, as the plant materials used and practices applied in silviculture may have changed over the life time of the trees. The factors preferably used for selected may differ, depending on the wood species, region and the application in mind. A difficulty when investigating commercial long rotation time forests is that data on the genetic origin of the trees is normally not available. From each stand, trees of three size classes were sampled: large, medium and small trees. Samples were taken at different heights along the stems. Data on the sampled stands and trees were collected in the forest.

The sample preparation and measurement procedures were designed to provide information about the radial variations in wood and fibre properties in the stem. For measurements performed on fibres, radial sub-samples were produced for groups of growth rings, representing juvenile wood, young mature wood and mature wood. The fibres of the radial sub-samples were liberated through maceration (Franklin 1945) and analyzed for length and width with a STFI FiberMaster instrument (Karlsson, Fransson 1999). The radial variations in fibre width, fibre wall thickness, wood density and microfibril angle (MFA) were determined with a SilviScan instrument (Evans 1994; 1999) and the wood stiffness (MOE) was estimated (Evans 2005). The growth ring patterns of the stem cross-sections were analyzed in the STFI Wood Measurement Laboratory with image analysis (Olsson 2000). Number of growth rings, widths of all rings and earlywood and latewood content of each ring were determined. All data were compiled into a Microsoft Access database. For pre-processing of data and presentations, Microsoft Excel, MathWorks Matlab and software developed by STFI-Packforsk were used.

The aim with the modelling has been to arrive at robust models, based on input data that can be readily obtained in normal commercial applications. The models presented have been tested with linear regression (general least squares) or non-linear regression (Gauss-Newton), using the GLM and NLIN procedures provided in the SAS software package (Anon. 2000).

SAMPLES AND DATA

The five projects providing samples, data and models for the comparisons in this paper are briefly described:

Norway spruce, Sweden (NSS): Results from two projects on Norway spruce are included. The first project, "Forest – Pulp – Paper", was performed by STFI and Skogforsk and funded by NUTEK/VINNOVA, the Swedish Agency for Innovation Systems. Stands from four regions in Sweden were sampled, covering latitudes from N 57° to N 66° (Ekenstedt et al 2003).

Norway spruce, Europe (NSE): The other project contributing on Norway spruce is "EuroFiber" (Lundqvist et al 2003; 2004). It was funded by the European Commission and a consortium of paper companies, with the objective to improve the utilization of European spruce resources. It was performed by three research institutes (STFI, Skogforsk and AFOCEL), one process supplier (Andritz) and three paper companies (Holmen, Norske Skog and Stora Enso) and was coordinated by STFI. Stands of Norway spruce were investigated in Estonia, France, Norway and Sweden. Trials were made in five paper mills.

Sitka spruce, Europe (SSGB): The "EuroFiber" project also included the investigation of Sitka Spruce (Hedenberg et al 2005). A limited number of stands in Wales and Scotland were sampled.

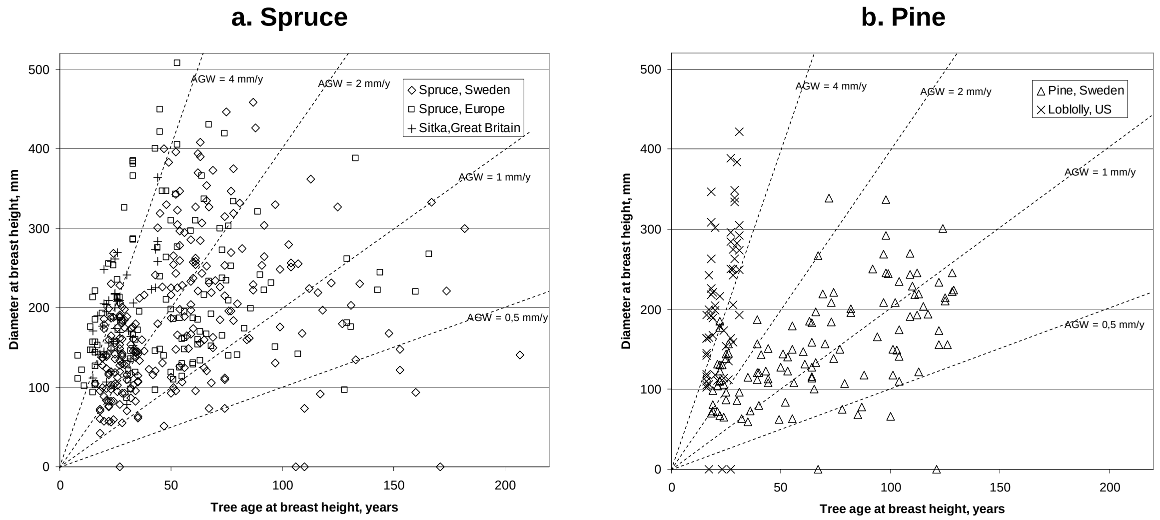
Scots pine, Sweden (SPS): The project "Forest – Pulp – Paper" also included investigations of Scots pine in Sweden (Ekenstedt et al 2003) over the same range of latitudes as for Norway spruce.

Loblolly pine, southeast USA (LPUS): Loblolly pine was investigated by STFI and International Paper within the STFI major project "Optimal Fiber Utilization" (Lundqvist et al 2005). Most of the sampling was performed in South Carolina, in coastal and Piedmont areas. Stands in Florida and Alabama were also included.

Graphs on variations

In figure 1, the ages, diameters at breast height and growth rates are shown for all the trees of different wood species from regions sampled in the five projects presented above. Large differences are observed between very fast-grown loblolly pine trees, fast-grown Sitka spruce trees and trees of Norway spruce and Scots pine covering a wide range of ages and growth rates. In figure 2 and 3, the corresponding differences between the samples are shown for the fibre dimensions.

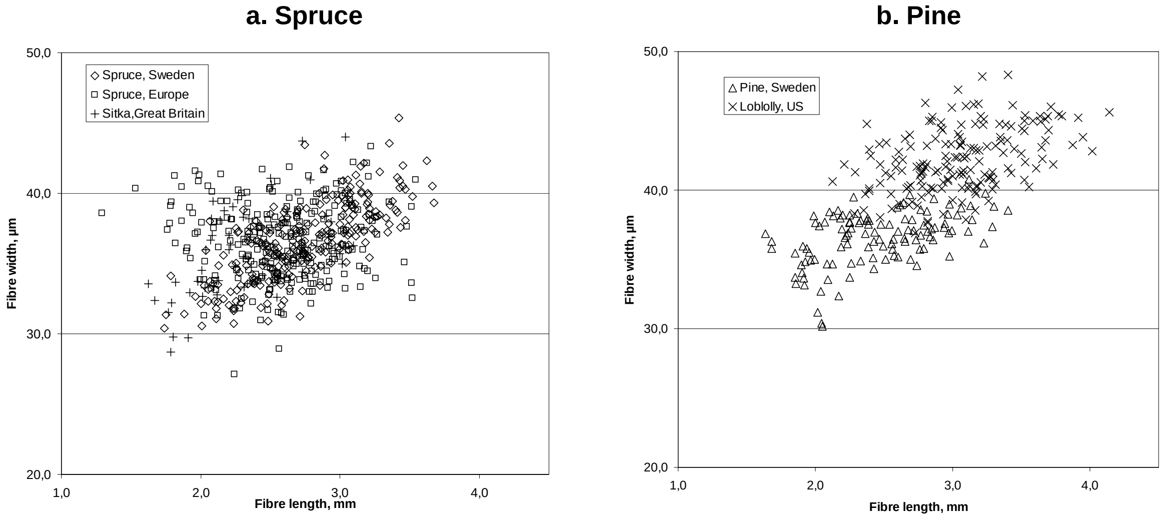
Detailed statistics of the data used for modelling is given in the appendix. The variables, notations and units used in the appendix, the models and the discussion below are listed in table 1.



a. Spruce

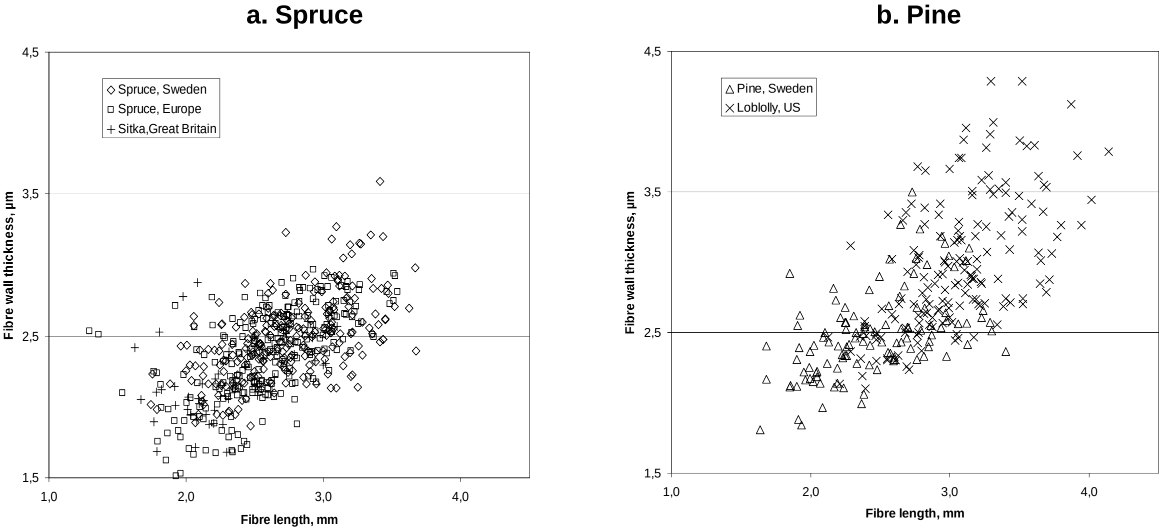
b. Pine

Figure 1: Ages, diameters at breast height and growth rates of the trees sampled in the studies forming the basis for the comparison of the four softwood species.


a. Spruce

b. Pine

Figure 2: Fibre length and fibre width (averages of stem cross-sections) for the samples included in the studies, which form the basis for the comparison of the four softwood species.


a. Spruce

b. Pine

Figure 2: Fibre length and fibre wall thickness (averages of stem cross-sections) for the samples included in the studies, which form the basis for the comparison of the four softwood species.

Table 1. Variables, notations and units used in the models and some background variables

Dependent variables		*Independent variables*	
FL =	fibre length, mm	R =	radius of stem cross-section, cm
FW =	fibre width, µm	N =	number of growth rings in cross-section
FWT =	fibre wall thickness, µm	AGW =	average growth ring width, mm
		h =	height in tree of cross-section, m
Background variables		h_{rel} =	relative height in tree of cross-section ($0<h_{rel}<1$)
	Age of tree	alt =	altitude above sea level, m
D_{BH} =	Diameter at breast height, cm	lat =	latitude, °, North
LC =	Latewood content %	tsum =	day-°C (In Sweden and for Norway spruce in Europe) [a)]

[a)] The temperature-sum is estimated from lat and alt with a model based on Swedish conditions (Morén, Perttu 1994)

MODELS FOR FIBRE DIMENSIONS

The model developed for the fibre dimensions of the four species in the different regions are compiled in table 2. These models relate to averages of arbitrary cross-sectional at different heights of trees grown under different conditions.

In the development of the models, an ambition has been to arrive at robust models, where the effect of each independent variable may be easily understood and preferably is described with a single term in the model. Cross-terms have been tested, but have not really improved the result. Therefore, they have been avoided at this stage. It should, however, not be ruled out that such terms may be introduced at a later stage when more data covering a wider set of growth conditions have become available. Such new data may allow the use of models with more parameters, if that is found to be beneficial.

In the model, the terms expressing the influences of different independent variables are listed in order of influence. These influences are of course dependent on the variations of the independent variables in the data sets used for modelling. The sampling schemes have been designed to cover the factors expected to be most influential in each region. All factors are, however, not equally well covered and the factors emphasized may differ between the studies. Modifications may occur when more data is gathered, especially in the models for Sitka spruce and loblolly pine, with are based on rather limited numbers of samples.

To facilitate the comparisons between effects on properties for different species, the models in the table have been formulated in as similar ways as possible. Some influences are clearly non-linear and in these cases logarithmic or exponential transformations have been used. One should not speculate too much in why the one transformation was better than the other for various properties and species. The differences are not very large and the explanation might be simple as that it may be easier to adapt a logarithmic function with one parameter than an exponential function with two parameters if the size of the data set is smaller. This is a further reason why some of the model structures may be modified in the continued work to improve and validate the models based on more data.

Even if no cross-terms are used in the models (at this stage), one should keep in mind that direct or indirect relationships occur also between “independent variables”. An obvious example is the relationship between R, N and AGW. In the models shown, R and N are never used in the same model. Another example is that R and N decrease with increasing height in the tree. A third example, which has to be considered when comparing properties of wood species or trees growing under different conditions, is that trees are often harvested when they have reached a size suitable for sawing. Taking fibre length as an example: Slow growth tends to bring shorter fibres, but the slow-grown tree will have a high number of growth rings when it is harvested, which counter-acts this effect. Such relationships have to be considered when applying the models.

The models are not to be used below breast height or close to the top of the tree (for the innermost growth rings). Nor should they be uncritically applied for growth conditions not included in the modelling data set, see appendix.

Variation in fibre length

For fibre length, the most influential independent variable is N, the number of growth rings of the cross-section. This is observed for all the wood species and regions investigated. According to the two models for Norway spruce, the fibres are on average about 1 mm longer in a cross-section at 30 years of age and about 1.5 mm longer at 60 years, as compared to the same cross section at 5 years age. According to the other models, these increases with number of growth rings are somewhat smaller for Sitka spruce, somewhat larger for Scots pine and still a bit larger for loblolly pine.

Exponential dependencies, expressed as for the influence of N on fibre length, are very easy to interpret. When the independent variable is 0, this term has no effect. The maximum effect of the term equals the coefficient (2.20 for N in model FLNSS) and 63 % of this maximum effect is reached when the independent variable equals its divisor, the time constant (29.35 for model FLNSS), and it has reached 86 % of its maximum effect at twice the time constant.

The fibre length models for Norway spruce and Scots pine suggest that AGW, the radial growth rate, is the second most influential independent variable. This term expresses that the fibres are shorter if the growth rings are narrow (and everything else is the same). For Norway spruce, this shortening is considerable for AGW below 1 mm, but a change in AGW from 2 mm to 4 mm affects the fibre length with less than 0.1 mm. The model for Scots pine in Sweden indicates a stronger effect. The models for the more fast-grown species Sitka spruce and loblolly pine indicates no influence from grow rate.

For all the wood species, the models express a reduction in fibre length in the lower part of the stem. The effect is clear at breast height and some meters further up, but less than 10-15 % or 0.1 mm of it prevails above 25 % of the tree height.

Table 2. Models for average fibre length, fibre width and fibre wall thickness of arbitrary cross-sections in Norway spruce, Sitka spruce, Scots pine and loblolly pine trees, developed from data from different countries.

Fibre length	**N**	**R^2**	**RMSE**	**Model**
Norway spruce (*Picea abies*), Sweden: $FL = 0.86+2.20*[1-\exp(-N/29.35)] -1.55*\exp(-AGW/0.74) - 0.70*\exp(-h_{rel}/0.14) +0.00056*tsum$	326	0.81	0.18	FL NSS
Norway spruce (*Picea abies*), Europe: $FL = 2.37 + 0.59*\ln(N) - 1.75*\exp(-AGW/0.49) - 0.56*\exp(-h_{rel}/0.10) - 0.026*lat - 0.00037*alt$	347	0.81	0.18	FL NSE
Sitka spruce (*Picea sitchensis*), Great Britain: $FL = 1.72 + 0.48*\ln(N) + 0.11*\ln(h) - 0.0018*alt$	59	0.66	0.20	FL SSGB
Scots pine (*Pinus sylvestris*), Sweden: $FL = - 0.56 + 0.69*(\ln(N) + 0.33*\ln(AGW) - 0.65*\exp(-h_{rel}/0.13) + 0.00043*tsum$	172	0.83	0.15	FL SPS
Loblolly pine (*Pinus taeda*), USA: $FL = 2.04 + 2.39*[1 - \exp(-N/22.81)] - 0.95*\exp(-h_{rel}/0.11) + 0.28*REG$	167	0.81	0.18	FL LPUS

Fibre width	**N**	**R^2**	**RMSE**	**Model**
Norway spruce (*Picea abies*), Sweden: $FW = 32.57 +11.13*[1 - \exp(-R/5.75)] - 19.7*\exp(-h_{rel}/0.022) + 0.5*\ln(AGW) - 0.12*lat$	326	0.68	1.44	FW NSS
Norway spruce (Picea abies), Europe: $FW = 26.11 + 11.07*[1 - \exp(-R/6.97)] - 4.29*\exp(-h_{rel}/0.05) + 0.14*\ln(AGW)$	347	0.68	1.30	FW NSE
Sitka spruce (*Picea sitchensis*), Great Britain: $FW = 4.90 + 2.74*\ln(R) - 0.0023*NS + 2.00*\ln(AGW) + 0.43*lat$	59	0.46	1.61	FW SSGB
Scots pine (*Pinus sylvestris*), Sweden: $FW = 23.99 + 3.18*\ln(R) - 5.25*\exp(-AGW/1.87)$	172	0.64	1.28	FW SPS
Loblolly pine (*Pinus taeda*), USA: $FW = 30.87 + 3.04*\ln(R) + 2.12*\ln(h) - 0.25*h$	167	0.56	1.42	FW LPUS

Fibre wall thickness	**N**	**R^2**	**RMSE**	**Model**
Norway spruce (*Picea abies*), Sweden: $FWT = 6.02 - 0.058*lat - 0.21*AGW + 0.75*[1 - \exp(-R/4.96)] - 0.28*\exp(-h/3.10)$	211	0.47	0.23	FWT NSS
Norway spruce (*Picea abies*), Europe: $FWT = 1.48 - 0.12*AGW + 0.21*\ln(R) + 0.071*\ln(h) - 0.00017*alt$	233	0.65	0.20	FWT NSE
Sitka spruce (*Picea sitchensis*), Great Britain: $FWT = 5.99 - 0.039*AGW + 0.0036*N - 0.065*lat - 0.00098*alt$	57	0.50	0.19	FWT SSGB
Scots pine (*Pinus sylvestris*), Sweden: $FWT = 1.16 + 0.24*\ln(R) - 0.23*\ln(h_{rel}) + 0.00030*tsum$	104	0.62	0.23	FWT SPS
Loblolly pine (*Pinus taeda*), USA: $FWT = 2.08 + 2.33*[1 - \exp(-N/25.14)] + 0.67*\exp(-h/13.09)]$	251	0.67	0.35	FWT LPUS

In all the models, there are complementary terms expressing climatic effects related to latitude, altitude or tsum, estimated from the two, indicating longer fibres at lower latitudes and altitudes (everything else is constant). For loblolly pine these data are not available at this stage. Part of the sample material was, however, collected more to the south and close to the coast. These samples had longer fibres. This is expressed by the discrete term in the model FLLPUS. The difference is large and also other factors, such as growth conditions not included in the study or genetics, may have contributed to it.

The coefficients of determination (R^2-value) of the models for fibre length are above 0.80 and the root mean square of the errors (RMSE) on modelling are 0.15-0.18 mm. The exception is the model for Sitka spruce, which is based on a smaller data set. This model has fewer parameters, giving a lower R^2-value and somewhat higher RMSE.

Variation in fibre width

For fibre width, the independent variable with the largest influence is R, the radius of the cross-section. This is observed for all the wood species and regions studied. The fibre width increases with the radius and the increase is rather similar for the wood species: the fibres are on average 3-4 µm broader when the cross-section has a radius of 15 cm, as compared to the same cross-section when it had a radius of 5 cm, everything else the same.

The models for Norway spruce and loblolly pine indicate a “close-to-ground” effect also for the fibre width. High growth rate may increase the fibre width with about 1-1.5 µm, everything else the same. The structures of the models for Sitka spruce and loblolly pine differ from those of Norway spruce and Scots pine, for which data on more stands and trees were used in the modelling. It can not be ruled out that these models will be modified when data on more stands are available.

The fibre width shows a lower relative variation if compared to the fibre length, see figure 2. This is probably part of the reason why lower R^2-values are reached for the fibre width models, between 0.56 and 0.68 rather than 0.80. The RMSE are about 1.4 µm or lower. The model for Sitka, based on the smallest sample set, is an exception with lower capability.

Variation in fibre wall thickness

For fibre wall thickness, there are large differences between the patterns of variability of the spruce and pine species. The models for Norway spruce and Sitka spruce indicate a strong influence of the radial growth rate AGW and also influences from other variables affecting growth, such as latitude and altitude. There are also terms corresponding effects of radius and closeness to ground, similar to those for fibre width, but these terms are less pronounced for wall thickness.

For Scots pine and loblolly pine, the strongest influences are expressed for radius and number of growth rings, respectively. These effects are complemented with a pronounced increase in the wall thickness close to the ground, related to the height in the tree of the cross-section, quite opposite to the small decrease indicated for the two spruce species. This is the largest difference observed in the pattern of variability for fibre dimensions between spruce and pine.

The RMSE values obtained on the modelling of fibre wall thickness are similar for the species, 0.19-0.23 µm, except for loblolly pine, which shows a larger error. But the fibres of loblolly pine have thicker walls. The difference is, thus, not that large in a relative sense. The R^2-values are higher for the pines than for the spruces, which to some extent may be explained by the larger variation in wall thickness of the pine species, due to the thick fibre walls close to the ground. Differences in growth conditions not covered in the studies or in genetic background may also contribute to the low values for the spruces.

COMPARISON BETWEEN WOOD SPECIES AND PARTS OF TREES

Optimal use of wood and fibre resources for improved competitiveness in papermaking has for many years been a priority research area of STFI-Packforsk. Tools have been developed in the form of measurement systems, databases, models and toolboxes, which are linking data and models (in-house and from the literature) with routines for simulation and evaluation, forming an efficient environment for research and development. These tools were used for the comparisons shown below.

The thin graphs in figure 4 and 5 illustrate “average trees” of Norway spruce and Scots pine in the south of Sweden at the ages of 25, 50, 75 and 100 years. More precisely, the graphs are based on averages for all co-dominant trees in the database of the project “Forest-Pulp-Paper” (NSS) from the south of Sweden and ready for final cutting. First the averages for breast height diameter and number of growth rings at breast height were calculated for these trees. Then, a function developed at STFI-Packforsk to describe the average relative widths of growth ring with different numbers was used to estimate the breast height diameters of the average trees at the four ages. Then the database was used to estimate the heights at these ages for the average spruce and pine trees. Models for taper functions were applied (Spångberg et al 2001), providing data about the size and shape of the average trees at the specified ages, see the upper diagram to the left.

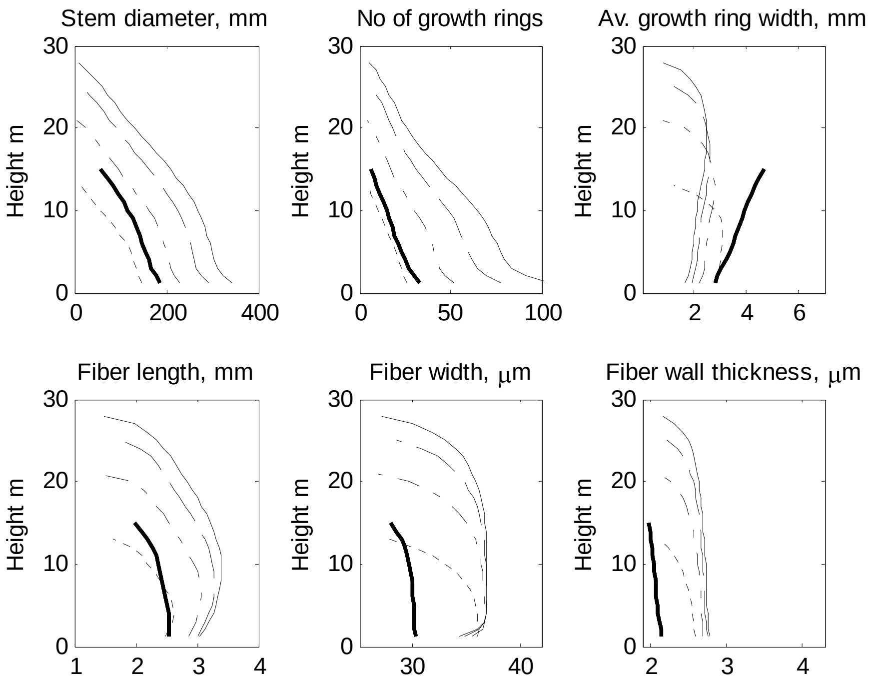


Figure 4. The thin graphs show the stem diameter, number of growth rings, average growth ring width, fiber length, fiber width and fiber wall thickness at different heights for an “average Norway spruce” at the ages of 25 (short dotted lines), 50 (long-short dotted lines), 75 (long dotted lines) and 100 (solid lines) years. The “average tree” is calculated from data on trees from the south of Sweden. The thick graphs show corresponding data for a 40 year old “average Sitka spruce” from Scotland.

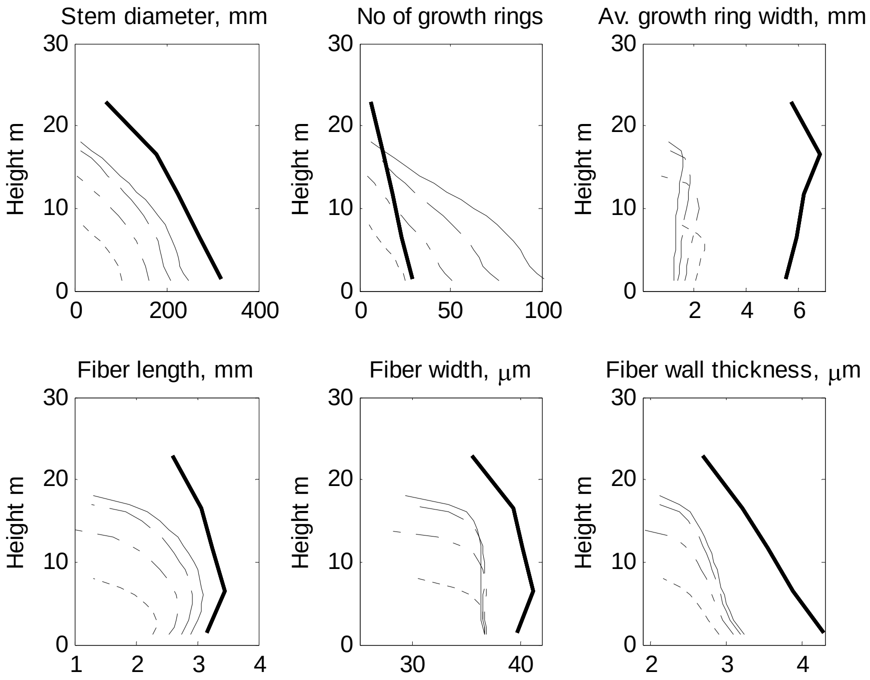


Figure 5. The thin graphs show stem diameter, number of growth rings, average growth ring width, fiber length, fiber width and fiber wall thickness at different heights for an “average Scots pine” at the ages of 25 (short dotted lines), 50 (long-short dotted lines), 75 (long dotted lines) and 100 (solid lines) years. The “average tree” is calculated from data on trees from the south of Sweden. The thick graphs show corresponding data for a 30 year old “average Loblolly pine” from South Carolina.

When the dimensions of the stem had been calculated in this way, another model was used to estimate the number of growth rings at different heights for each age (Wilhelmsson 2001), see the upper middle graphs. This was followed by the calculation of the average growth ring widths (AGW) at different heights, the upper diagram to the right. With this information at hand, together with stand information about the average latitude, etc., the models for fiber dimensions presented above were used to calculate the cross-sectional averages for the fibre length, width and wall thickness at different heights of the average spruce and pine stems at the specified ages, see the lower graphs.

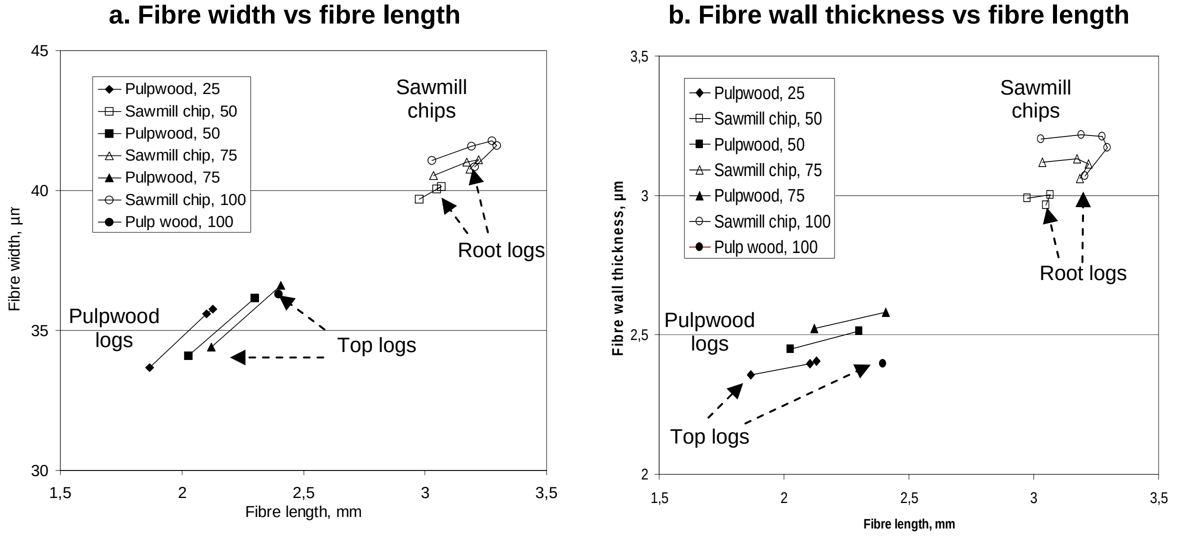
In each diagram of figure 4 on Norway spruce a thick graph has been added, showing similar data for a corresponding average Sitka spruce from Scotland. The average D_{BH}, N and AGW at different heights have been calculated for 40 year old Sitka spruce trees (Mochan 2005), and added to the upper graphs. These data have been used as input data to the models for Sitka spruce described above to estimate the fibre dimensions at different heights, the thick graphs in the lower diagrams. The graphs indicate that the Sitka spruce fibres are comparably small and uniform. It may seem surprising that the average Sitka tree is not larger, considering its broad growth rings. Part of the explanation is that its initial growth is relatively slow before out and the trees are relatively young at point of felling. It took the tree six years to reach breast height, where the graphs start. After that it has, however, been growing faster.

The thick graphs in figure 5 on Scots pine show similar data for a loblolly pine tree from South Carolina. In this case, data for an average tree have not been available. Instead, a typical 30 year old tree was selected among the trees analysed in the loblolly pine project (LPUS). Data on D_{BH}, N and AGW at five heights were taken form the database, see the upper diagrams. These data were used as input data to the models above and the fibre dimensions were calculated. The figure indicates that that the typical loblolly pine tree grows very fast and contains very long, wide and thick-walled fibres.

COMPARISON OF INDUSTRIAL RAW MATERIALS

The toolboxes of STFI-Packforsk were used to simulate the thinning and final cutting of the average spruce of different ages shown in figure 4. The bucking of the stems into pulpwood logs and logs for sawmilling was simulated, as well as the production of sawmill chips, a raw material for pulping, from the outer part of the lumber logs. In the bucking simulation, the timber height was set to a diameter of 14 cm and all logs were cut to the length of 4 m. Small top logs were discarded (left in the forest). All logs from harvesting of 25 year old trees were classified as pulpwood logs. When harvesting older trees, the number of lumber logs increased with tree age and, thus, also the volume of sawmill chips. The number of pulpwood logs may, however, decrease with age, due to change of taper of the top part of the tree.

The average fibre dimensions were estimated for the pulpwood logs and for the sawmill chips from each lumber log. The result is shown in figure 6. The smallest fibres are found in the top log and they are especially small in the youngest stand. The size of the fibres in of the pulpwood logs size (length, width, wall thickness) increases downwards when approaching the timber height. The largest fibres are found in the sawmill chips from the second or third lumber log from the ground in the oldest/largest diameter trees. The fibres of sawmill chips from logs closer to the ground are a bit smaller (shorter, slimmer, less thick-walled). This explains the bent shape of the graphs for fibre width and wall thickness versus fibre length.



a. Fibre width vs fibre length

b. Fibre wall thickness vs fibre length

Figure 6. Fibre length, width and wall thickness in pulpwood logs and in sawmill chips from lumber logs produced from the “average spruce trees” of different ages in figure 4, simulated with toolboxes of STFI-Packforsk.

CONCLUSIONS

The differences in fibre dimensions: length, width and wall thickness, within and between trees have been compared for Norway spruce (*Picea abies*), Sitka sprice (*Picea sitchensis*), Scots pine (*Pinus silvestris*) and Loblolly pine (*Pinus taeda*), grown in Europe and North America. In general, the patterns of variation are similar for the four softwood species, but some differences are observed. The spruce and pine species are pair wise more similar to each other. The most pronounced difference is observed for the fibre wall thickness close to the ground. The pines show an increase in fibre wall thickness in the lower part of the stem when approaching the ground, whereas the fibre wall thickness decreases for the spruce species.

For all the wood species, the models with the highest coefficients of determination (R^2-value) are obtained for fibre length, with values around 0.80. For the two spruce species, the R^2-values for fibre wall thickness tend to be rather low, around 0.50. For the pine species, these values are higher, around 0.65, partly due to a larger variation between heights in the trees. The R^2-values for fibre width are in between these numbers. The models described for Sitka spruce are based on a small sample and data material and are somewhat weaker than those for the other wood species.

The models may be used for comparison of fibre properties between wood species, taking differences in growth conditions into account. They may also be used together with other models and data on growth conditions to simulate properties of wood for industrial use. Such use of the models is illustrated by a calculation of fibre dimensions in various raw materials for the production of pulp. The goal of the modelling work is to develop good models for the variability in important wood and fibre properties of forest trees, useful also in applications for improved wood and fibre utilization.

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APPENDIX

In the table below, statistics are given on the variations in fibre dimensions, the independent variables and some background variables of the samples used for modelling (cross-sectional averages) of property variations in different wood species grown in different countries.

Wood species	Variable		Number of		Average	St.dev.	Min	Max
		Stands	Trees	Samples				
Norway spruce (Picea abies), Sweden								
Dependent variables	FL, mm	42	126	326	2.6	0.42	1.4	3.6
	FW, µm	42	126	326	32.5	2.52	25.4	40.0
	FWT, µm	42	126	211	2.7	0.31	2.0	4.0
Independent variables	R, mm	42	126	326	68.0	39.62	9.9	229.1
	N. of rings	42	126	326	34.3	24.37	3	174
	AGW, mm	42	126	326	2.36	1.03	0.46	5.94
	h, m	42	126	326	19.2	6.34	6.8	33.1
	latitude, °	42	126	326	59.39	2.96	56.58	65.78
	altitude, m	42	126	326	199	103	60	440
	tsum, day-°C	42	126	326	1177	222	667	1409
Background variables	Age of tree	42	251	251	67	39.9	22	222
	D_{BH}, cm	42	251	251	18.3	8.48	4.3	47.1
	LC, %	42	126	326	21.4	4.84	9.5	35.9

The table is continued

Wood species	Variable	Number of			Average	St.dev.	Min	Max
		Stands	Trees	Samples				
Norway spruce (Picea abies), Estonia, France, Norway and Sweden								
Dependent variables	FL, mm	35	105	347	2.6	0.40	1.3	3.6
	FW, µm	35	105	347	32.65	2.29	26.5	38.2
	FWT, µm	35	105	233	2.3	0.33	1.5	3.0
Independent variables	R, mm	35	105	347	75.2	42.1	16.6	219.7
	N. of rings	35	105	347	34.4	27.3	4	190
	AGW, mm	35	105	347	3.06	1.92	0.37	9.82
	h, m	35	105	347	8.37	6.66	9.0	29.0
	latitude, °	35	105	347	54.76	5.61	46.28	60.55
	altitude, m	35	105	347	344.9	316.3	22	1230
	tsum, day-°C	35	105	586	1311	241	823	1750
Background variables	Age of tree	35	127	127	69.6	50.3	13	250
	D_{BH}, cm	35	123	123	21.1	8.46	9.2	43.1
	LC, %	35	105	347	19.9	6.85	5.9	38.4
Sitka spruce (Picea sitchensis), Great Britain								
Dependent variables	FL, mm	8	48	67	2.3	0.35	1.6	3.1
	FW, µm	8	48	67	32.2	2.07	27.4	37.3
	FWT, µm	8	48	65	2.1	0.26	1.7	2.7
Independent variables	R, mm	8	48	67	67.6	30.83	23.1	137.7
	N. of rings	8	48	67	16.2	10.06	4	44
	AGW, mm	8	46	67	4.8	1.31	2.3	8.8
	h, m	8	48	67	7.55	5.88	1.0	23.7
	lat., °	8	48	67	53.37	1.31	52.75	55.88
	alt., m	8	48	67	184	89.9	40	300
	NS	8	48	67	1723	516	1113	2406
Background variables	Age of tree	8	46	46	26.4	8.03	15	44
	D_{BH}, cm	8	48	48	19.9	6.33	9.0	43.0
Scots pine (Pinus sylvestris), Sweden								
Dependent variables	FL, mm	20	60	172	2.3	0.37	1.6	3.4
	FW, µm	20	60	172	34.0	2.13	27.3	38.4
	FWT, µm	20	60	104	2.7	0.31	2.0	4.0
Independent variables	R, mm	20	60	172	53.8	27.25	14.9	155.1
	N. of rings	20	60	172	40.2	28.98	4	125
	AGW, mm	20	60	172	1.80	0.94	0.43	5.67
	h, m	20	60	172	14.7	4.24	7.5	25.6
	lat., °	20	60	172	61.24	4.19	56.65	65.76
	alt., m	20	60	172	221	103	80	385
	tsum, day-°C	20	60	172	1058	275	691	1404
Background variables	Age of tree	20	120	120	83.2	39.9	23	154
	D_{BH}, cm	20	116	116	15.4	6.36	5.9	34.5
Loblolly pine (Pinus taeda), USA								
Dependent variables	FL, mm	12	60	168	3.1	0.40	2.1	4.1
	FW, µm	12	60	168	38.4	2.11	33.3	42.6
	FWT, µm	12	60	251	3.5	0.60	2.1	5.1
Independent variables	R, mm	12	60	251	7.9	4.00	2.9	21.1
	N. of rings	12	60	251	15.7	7.27	4	31
	AGW, mm	12	60	251	5.32	1.77	2.19	12.52
	h, m	12	60	251	8.7	6.5	1.2	26.6
Background variables	Age of tree	12	60	60	24	5.66	17	32
	D_{BH}, cm	12	60	60	22.2	7.96	10.2	40.5
	LC, %	12	60	251	25.6	8.56	6.6	48.7