

**Models for the timber quality  
assessment of the actual forest resource.  
Methodology for Sitka Spruce.**

**Dr Jean-Michel Leban,  
John Eadie Memorial Fellow 2002  
Institut National de la Recherche Agronomique (INRA)  
Champenoux, Nancy.**

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## 1. Introduction and Background

Over the next 20 years the supply of softwood timber from British conifer plantations is expected to double to around 10,000,000 m<sup>3</sup> and the majority of this will be Sitka spruce (70%). Changes in both silvicultural practice and the planting of more exposed upland areas during the rapid expansion of forestry in the 1960s and 1970s have led to concerns about the future quality of this increasing supply. In particular there are concerns about decreasing wood density, larger juvenile cores, increase area and frequency of knots, increased incidence of compression wood and poorer stem form. In addition, there is now a very strong push from policy makers to alter silvicultural systems from the even-aged clear fell system to systems to continuous cover forestry systems. The impacts of this more recent silvicultural change will not be felt for some years but it is very important to be able to have a better idea of what will happen to the quality of supply coming onto the market.

Currently, the practical implications of these changes on timber utilisation can not be easily quantified with existing knowledge. Furthermore, there are no tools available to guide foresters as to the effect of their silvicultural decisions on the future timber quality of stands, which is of increasing importance with the growing use of alternative silvicultural systems.

The only reasonable approach to providing predictive tools within a reasonable time frame is by computer modelling. Field experiments will be too expensive, take too long and provide only information about the specific situations studied. A decision was taken to follow the modelling approach of the Qualitie du Bois team at INRA, Nancy (Leban *et al.*, 1996). This team has developed a wood quality model for Norway spruce (WinEPIFN, Saint André *et al.*, 1995), which predicts the density distribution and knot location within the stems of Norway spruce from information on tree age, height and diameter at breast height (dbh).

Timber quality assessment can be investigated at two different levels at the primary conversion stage of the forestry wood chain:

- (1) the assessment of the expected timber quality from available forest resource at the stand level or at a regional level;
- (2) the individual log's timber value assessment at the sawmill, before its conversion into boards.

In the first context the methodology developed is based upon models that simulate the expected timber quality from standing trees by means of the usual forest inventory measurements. Another method, more suitable for the second context, is to build models that simulate the expected internal log structure by the mean of external shape measurements. In both cases, the general idea is to be able to determine the expected value of timber before conversion into logs and boards respectively in order,

- (i) to determine as precisely as possible the right raw material to be bought and
- (ii) to maximise the log conversion by taking into account the internal log wood structure before sawing and the customer quality specifications.

In this work our contribution is focused on the modelling of the actual forest resource for standing trees.

### 1.1. Previous work.

In New Zealand, a Method for Assessment of Recoverable Volume by Log types was developed by Chris Goulding of FRI for radiata pine (FRI, MicroMARVL, 1990). The idea was to establish, for stands that are ready or nearly ready for harvest, a forest inventory by (i) measuring the tree size and (ii) by coding the tree shape for quality (diameter, straightness, curvature, big branches etc.), in order to be able to maximise the log conversion by using optimisation algorithms.

This method is a good example of a methodology for (i) quantifying the visual observations that are made during a stand inventory and (ii) for optimising the conversion of logs by using this information.

However, there is no detailed information available about the inner wood properties of the stems such as ring width, wood density, branch pattern or amount of juvenile wood.

A similar idea was also developed in other countries such as in Sweden (Björklund *et al.*, 1997). These authors underlined the necessity to improve the communication between foresters and forest products manufacturers. They proposed to establish "Tree models" built by using the Swedish stem bank (Grönlund *et al.*, 1997). They produced "Trees models" that enabled the simulation of (i) the growth characteristics (distances between whorls, average ring width at products oriented locations in the stem), (ii) the knot structure (knot type zones), (iii) the wood density and (iv) the heartwood-sap wood relationships. The explanatory variables used were the site index, age and latitude, the silvicultural parameters and individual tree measurements such as dbh, height etc..

In France a method was developed for Norway spruce from even aged stands. This species represents more than 700,000 ha in France and most of them are planted. The Norway spruce stems are relatively straight and more than 70% of the harvested volumes are converted into timber for construction purposes. The idea was to use individual tree measurements as inputs, such as they are performed for a forest inventory, in order to be able to simulate the past growth of the trees from a stand. This method has been developed into a software package, Win-EPIFN (Saint-André *et al.*, 1997) for which the input data are a list of sample trees (from one stand) described by their age, height, dbh and their statistical weight, i.e., the number of trees represented by each sample tree. The software can quickly process a large number of sample trees (a couple of thousands). The models embedded in the software, consist of a set of equations and submodels which predict, for each sample tree:

- past height and dbh growth;
- bark thickness,
- stem taper and stem inner ring width distribution (ring age and ring width);
- past crown recession with the evolution of the height to the first dead branch, the first living branch, and the first living whorl;
- branch characteristics (number per annual shoot, position, size and insertion angle);
- the variation of wood density within the stem (and other wood properties such as grain angle, stiffness, modulus of rupture, shrinkage etc.).

For each 'reconstructed' sample tree, Win-EPIFN simulates log cutting and log grading, and finally board sawing in each log.

In its present version, the sawing pattern implemented in Win-EPIFN is based on a single board size excluding wane. The sawing pattern is chosen to maximise the number of such boards. Each simulated board is described by its (predicted) average ring width, average wood density and KAR (Knot Area Ratio, Thunell, 1976). Board grading is available in the software based on the French standard. This software has already been used for preliminary analysis of the changes in timber quality between two successive surveys of the French National Forest Inventory in the North-eastern part of France (Leban *et al.*, 1999).

In this context of "Tree models", the first challenge is probably the implementation of these methods and tools into the first segment of the "Forest Wood Chain". This step is difficult in most of our European countries, probably because both foresters and sawmill engineers lack the sophisticated skills to match the sophisticated tools and techniques now almost available. We must keep in mind that the efficiency of such methods, if applied at the forest inventory level, needs very fast "Virtual Processing".

For research the main interest in using the models is that they increase our understanding of wood quality, which makes possible the prediction of the main internal wood quality feature by the means of external field measurement only (compression wood, grain angle, fibre length, juvenile core etc.).

In this project the objective is to build the main models cited above for Sitka spruce in UK. The methodology developed for Norway spruce in France will be used. Data has already collected by the different UK teams and gathered by the Forestry Commission in Roslin, the work has aimed at

building models for wood density variation of Sitka spruce wood, stem taper and branch size and insertion angle.

## **1.2. Data Collection by Forest Research**

Data to support the development of the timber quality model have been obtained from a number of destructive sampling studies. To obtain information on wood density and grain angle trees were selected at four spacings from two sites; Kershope Forest and Glengarry Forest. The Glengarry Forest plots were planted in 1935 at 0.9, 1.4, 1.8 and 2.4 m spacings and the Kershope Forest plots in 1967 at 1.8, 2.4, 3.5 and 5.0 m. For each spacing, 3 trees were selected from the sub-dominant, co-dominant and dominant classes in order to cover the full diameter range; providing 9 trees per spacing. Discs of 2-4 cm width were cut at 1.5m intervals along the entire length of the tree. The discs were air dried to 12% moisture content and scanned using a computer tomography (CT) system to obtain the density distribution across the disc. The CT scan data has been analysed using an image analysis programme to obtain information on the mean, maximum and minimum densities for each ring along East-West and North-South slices, together with the ring width, distance of the ring from the pith and the overall mean disc density. The data have been used to create initial mathematical relationships for density as a function of ring width and age of the ring relative to the pith.

Additional thicker discs were cut at 3m intervals up the tree. The discs were split along an East-West axis and the grain angle measured every 5 growth rings. Analysis of the data has shown a strong correlation between grain angle and tree spacing.

Information on knot distribution within the tree stem was obtained using the methodology developed by Colin and Houllier (1992). A total of 60 trees with ages from 13-65 years were sampled. In each stand the selection was across the diameter classes. On every second whorl from the tip of the tree the branch location relative to the top of the growth unit, the horizontal and vertical branch diameter, branch azimuth, branch insertion angle and whether the branch was alive or dead and whether the branch was from the whorl or interwhorl was measured.

## **2. Modelling Wood density.**

Dr. M.P. Denne of the University of Wales, Bangor, kindly provided the data set used for the initial analysis. Five trees were sampled from three plots on a 52 year-old unthinned spacing trial based at Clocaenog, North Wales. More details of the site and the collection of the data can be found in Simpson and Denne (1997).

### **2.1. Model selection.**

The proposed model consists of the product of two functions that describe two different biological processes. The first one describes the effect of ring age (or cambial age) counted from the pith. This permits the model to take into account the effects of tree ageing and especially the higher wood density associated with the rings close to the pith. The second function describes the effect of ring width variations on wood density. Ring width variations reflect the growing conditions experienced by the tree and reflect, for example, the effects of stocking as expressed in terms of number of stems per ha. For a given site the annual increase in basal area is distributed among all the standing trees as a function of their individual size.

As it is known that for softwoods

- (i) each annual ring is made with two layers *i.e.* early and late wood,
- (ii) the wood density of early wood is lower than for late wood.

However, the resolution of the density data obtained for modelling was of not sufficiently fine scale to provide this level of detail. Hence, a mean value of wood density per ring was used rather than modelling earlywood and latewood proportions and densities.

The following expression was selected to describe the variation of specific gravity with cambial age and ring width. It is based on previous work with Norway spruce:

$$\text{Specific Gravity} = \text{EXP}(a/CA) * (b + c/RW)$$

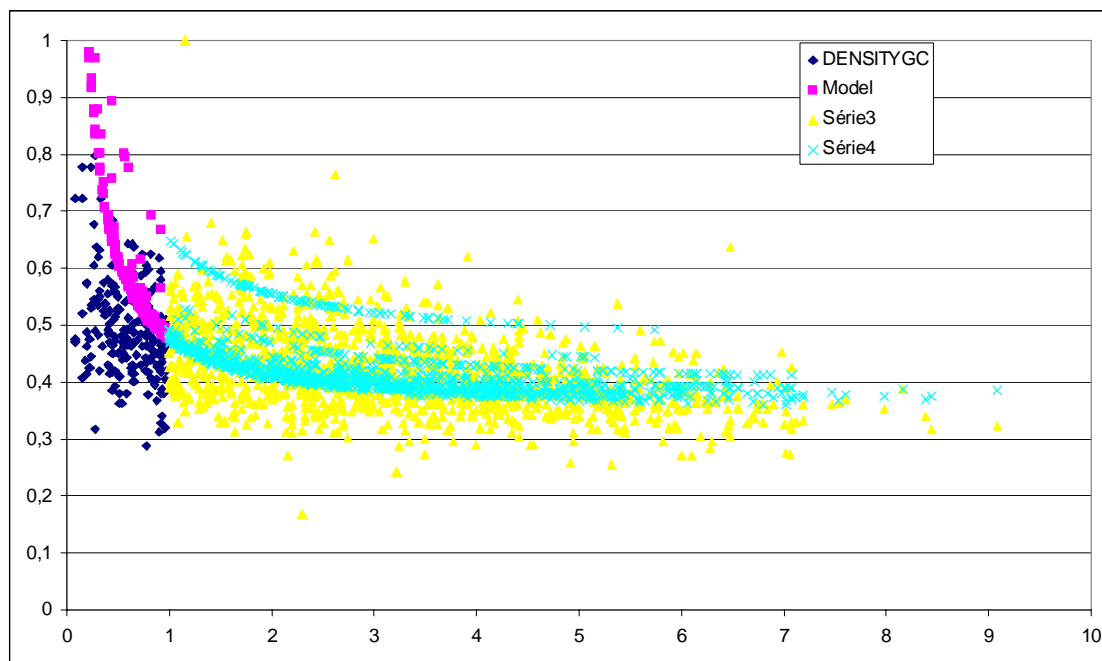
Where: CA = cambial age, RW = Ring width

	a	b	c	No. of obs.	R-square
RW>1 mm	0,663	0,329	0,138	1272	0,463
ALL	0,61	0,377	0,034	1510	0,346

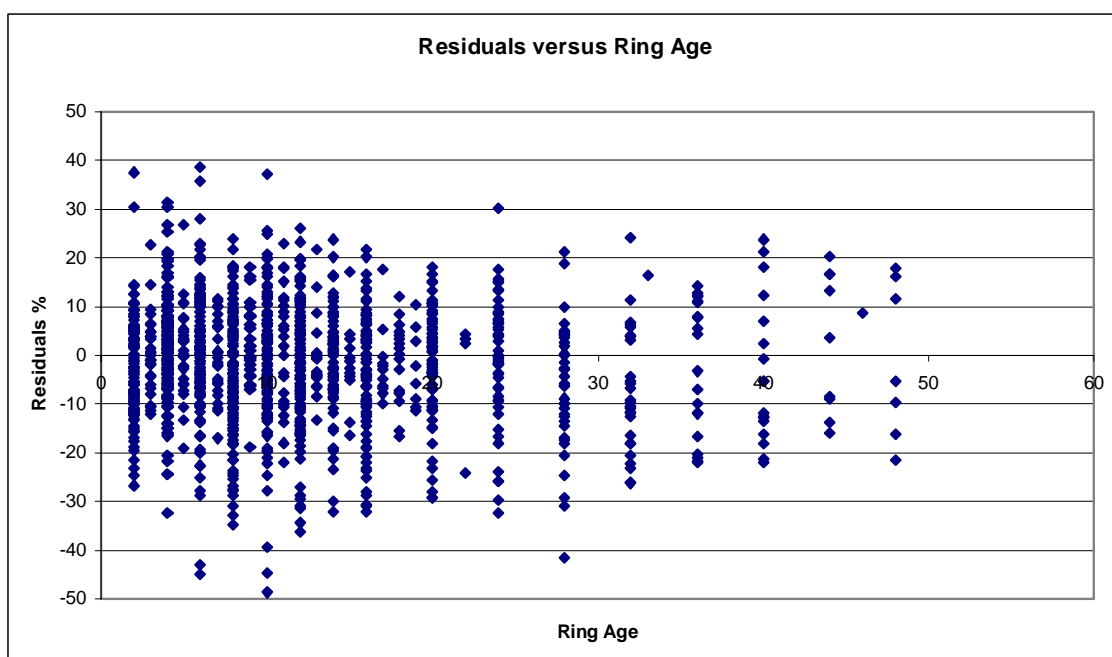
The whole data set was analysed and it was decided to remove the rings for which the width was lower than 1 mm. Simulated values are compared to the raw data for the whole data set in figure 1. The residuals are examined versus each variable used in the model and there is no bias to be corrected (figure 2 & 3). The same correct behaviour is also observed when the residuals are represented versus the growth unit number (which reflects the variations in height in the trees). This means that both ring width and age explain the main effect of change in specific gravity moving up the height of the trees.

This preliminary model has the appeal of simplicity. Each parameter can be easily understood in biological terms and this can be of interest for the comparison between sites, provenances or species (for instance comparison with Norway spruce). With this support the next step will be to test the model using data sets from sites sampled at different latitudes in UK. These are currently being checked for errors and will be available for analysis shortly.

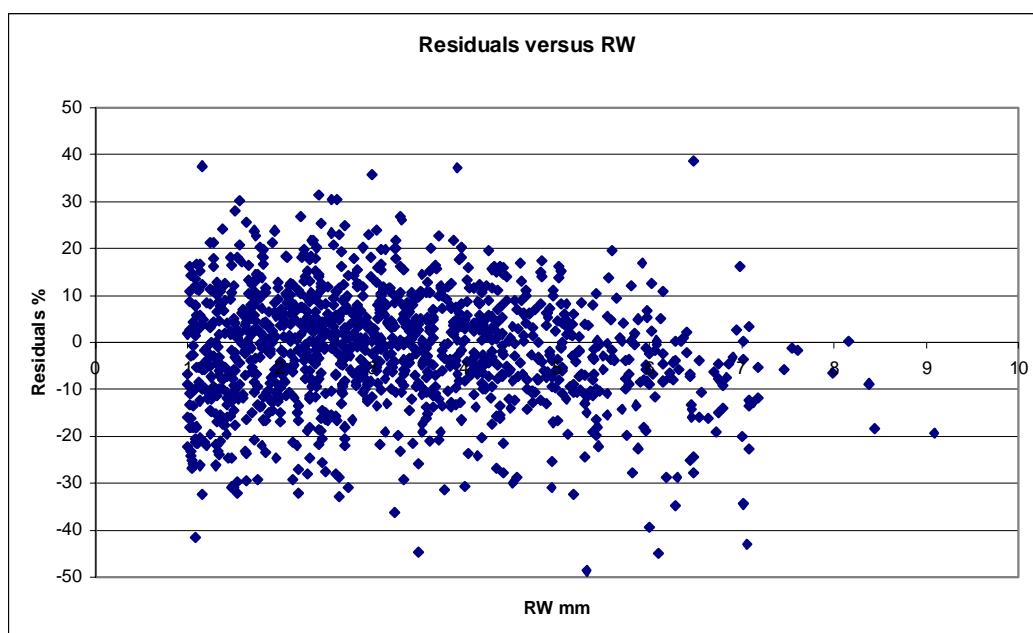
**Figure 1:** A comparison of the model against the raw data from Clocaenog for specific gravity variation with ring width (mm). Ring widths smaller than 1mm were not included in the analysis for the model



**Figure 2:** Residuals v ring age (years) for the Clocaenog wood specific gravity model



**Figure 3:** Residuals v ring width (mm) for rings >1 mm for the Clocaenog wood specific gravity model



## 2.2. Fitting the model on the Kershope data set.

A separate data set was provided by Barry Gardiner based on unpublished work undertaken by J. Forbes at Forest Research. It was obtained by a different methodology than the one involved for the Clocaenog data set (five trees sampled from three plots, Simpson and Denne 1997). The wood density data were calculated on a ring by ring basis using CT scanned images of wooden disks. These disks were sampled

in another geographic location (Kershope) and four discs were taken at different heights from 18 trees from six stands. All the stands were younger than the Clocaenog stands (see maximum ring age in tables). It should be noted that the maximum resolution of the CT scanner was 2 mm. The basic statistics for the first data set are in tables 1 and 2. In table 1 we present the values for the whole Clocaenog data set. In table 2 we present basic statistics for rings larger than 1.75 mm. This limit corresponds to the lowest ring width value observed on the new data set.

**Table 1.** Clocaenog data set

	<b>Density</b>	<b>RW (mm)</b>	<b>Ring age</b>
N	1510	1510	1510
Minimum	168	0.080	2.000
Maximum	1000	9.080	48.000
Mean	<b>435</b>	<b>2.823</b>	<b>14.797</b>
SD	80	1.708	11.176

**Table 2.** Clocaenog data for ring widths higher than 1.75 mm

	<b>Density</b>	<b>RW (mm)</b>	<b>Ring age</b>
N	1026	1026	1026
Minimum	168	1.750	2.000
Maximum	766	9.080	44.000
Mean	<b>413</b>	<b>3.683</b>	<b>10.623</b>
SD	68	1.379	6.994

In the following tables we report on the wood density values obtained for the second whole data set from Kershope as well as the breakdown figures by stand. Apparently abnormal values, 78 in total, have been cleared from these data, these include artefacts such as high-density values for wide rings (higher than 800kg/m<sup>3</sup>) or very wide rings almost impossible to obtain (higher than 12 mm). These errors of measurements are probably explained by the low resolution of the CT scanner which could not discern separate rings that were very close. In addition, the densities measured by the CT scanner were for discs conditioned to 12% moisture content whereas the Clocaenog data provided oven dried specific gravity. In order to compare data a standard correction was applied to the Kershope data to take into account the higher moisture content (Brown *et al.*, 1952).

**Table 3:** Ring width, wood density and ring age for the whole Kershope data set, 18 trees, 6 stands.

Nb=2599	RINGWIDTH	RINGNOFROM	DENSITYGC
Mean	5.124	10.48	435.79
SD	1.79	6.24	70.4



**Table 4:** Ring width, wood density and ring age by stand with 3 trees by stand.

<b>STANDID</b>	<b>1703</b>		
Nb=449	RINGWIDTH	RINGNOFROM	DENSITYGC
Mean	4.8	10.3	443.4
SD	1.8	6.1	64.9
<b>STANDID</b>	<b>1704</b>		
Nb=466	RINGWIDTH	RINGNOFROM	DENSITYGC
Mean	5.4	10.9	444.2
SD	1.8	6.3	76.4
<b>STANDID</b>	<b>1709</b>		
Nb=286	RINGWIDTH	RINGNOFROM	DENSITYGC
Mean	4.3	8.4	457.1
SD	1.7	5.3	57.2
<b>STANDID</b>	<b>1713</b>		
Nb=492	RINGWIDTH	RINGNOFROM	DENSITYGC
Mean	4.8	11.2	452.8
SD	1.7	6.5	62.2
<b>STANDID</b>	<b>1717</b>		
Nb=466	RINGWIDTH	RINGNOFROM	DENSITYGC
Mean	5.9	10.8	391.1
SD	1.7	6.3	73.4
<b>STANDID</b>	<b>1721</b>		
Nb=440	RINGWIDTH	RINGNOFROM	DENSITYGC
Mean	5.2	10.4	433.6
SD	1.7	6.3	61.8

It was decided to simulate the wood density data from the Kershope stands by the mean of the model build from the Clocaenog data, for ring width greater than 1.75 mm, and by using the actual ring width and ring age for predicting the wood density.

$$\text{Wood density} = \text{EXP}(0.663/\text{CA}) * (329 + 138/\text{RW})$$

Where: CA = cambial age, RW = Ring width

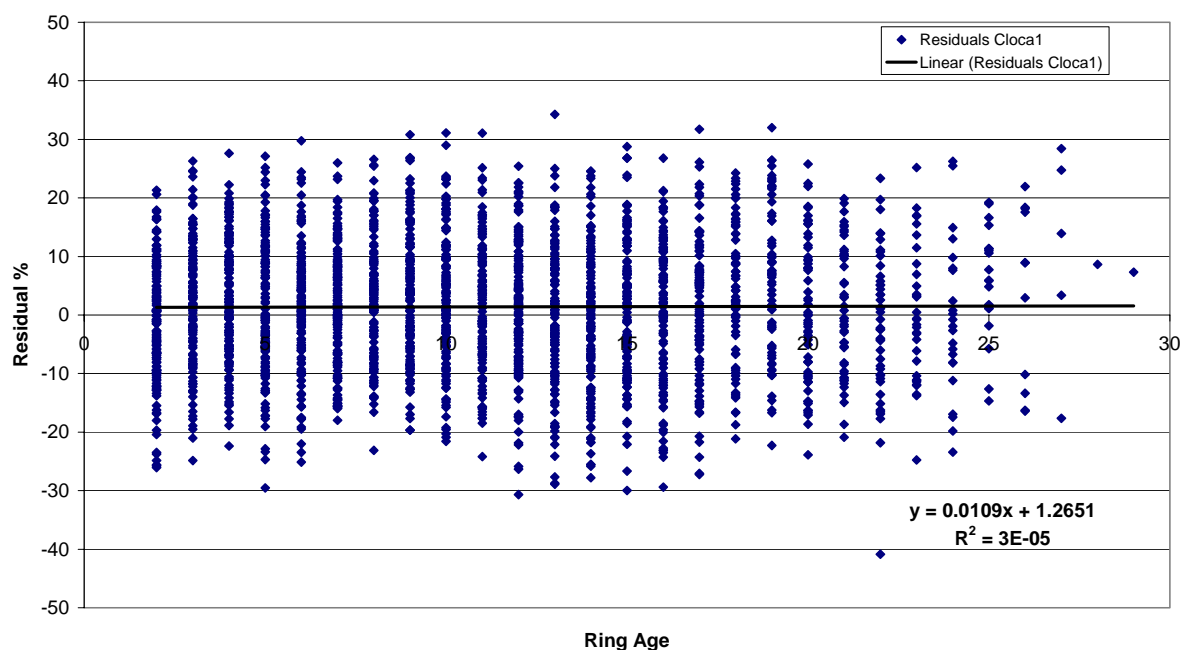
This expression is derived from the equation obtained above by multiplying the parameter values for b and c by 1000. This enabled the simulation of wood density expressed in kg/m<sup>3</sup> instead of specific gravity.

The residuals are computed as follow:

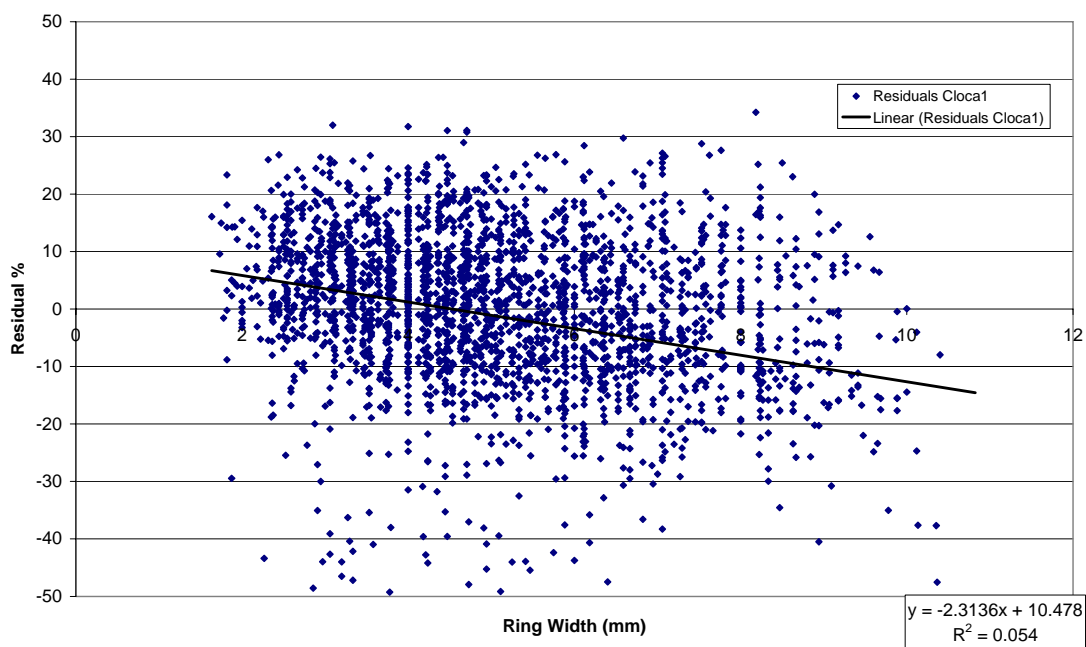
$$\text{residual} = 100 * (\text{measured value} - \text{simulated value}) / \text{measured value}.$$

If the residual are positive than it means that the simulation underestimated the data and *vice et versa*. The residuals are plotted against the 2 variables used in the model.

**Figure 4:** Residuals against ring age for Kershope data simulated with the model fitted on Clocaenog data.



**Figure 5:** Residuals against ring width for Kershope data simulated with the model fitted on Clocaenog data.



The model has a correct behaviour for residuals plotted against ring width and ring age. There is no significant trend for the correlation between residuals and ring width. For low ring width the model slightly underestimates the data while for wider ring width, it overestimates the data. For ring age there is a slight systematic underestimation of about 1.3%.

### 2.3. Conclusion on the Wood Density Model

The wood density simulated on the Kershope data are slightly underestimated compared to the actual data. This small systematic bias is probably explained by the fact that two different methods were used for measuring the wood density: (i) specific gravity for the Clocaenog data and (ii) weight density at 12 % MC for the Kershope data. Furthermore, the ring width was also obtained by two different methods, one manual, the other automatically from the CT scanned images. However, considering the very different methods used, the behaviour of the model for density is very encouraging.

Interestingly the fact that the data from Clocaenog was collected from breast height discs whereas the Kershope data was obtained from discs at different heights up the tree does not seem to have affected the behaviour of the model. It seems that ring width and ring age are sufficient to explain the observed patterns of variation in wood density and that height up the tree is not a strong factor once they are taken into account.

### 3. Models for stem taper and branch pattern for Sitka spruce.

In this part we have developed new models for (i) the stem taper and (ii) for the branch pattern, diameter, number of branches, and insertion angle of branches, observed for Sitka spruce. The stem taper model was built by using all the data available from 60 trees sampled from 9 stands, whereas the models for branches were fitted for 59 trees from 9 stands.

The following variables have been used for the analysis and modelling work.

Variable Name	Description	Unit
Age :	tree age	(year)
th :	total height	(m)
Dbh :	diameter at breast height	(cm)
Hsd :	Th(m)/dbh(m)	no unit
Crownwd :	crown width	(m)
H1bm :	height of the first dead branch	(m)
H1bv :	height of the first living branch	(m)
H1vv :	height of the first living whorl	(m)
Crbm :	(th-h1bm)/th	no unit
Crbv :	(th-h1bv)/th	no unit
Crvv :	(th-h1vv)/th	no unit

#### 3.1. Models for stem taper equation.

In this model, five parameters control the shape of the stem ( $\theta_1$  to  $\theta_5$ ) as shown in figure 6.  $\theta_1$  and  $\theta_2$  control the higher part of the curve, i.e. the top of the tree. The term controlling the butt part of the curve, with parameters  $\theta_3$  and  $\theta_4$ , was assumed to be a multiplicative term in order to be in the variable exponent.  $\theta_5$  can be assumed to be the tree diameter if there was no buttressing whereas  $\theta_3$  is the “size of the buttress” and can be thought of as the diameter which must be added to  $\theta_5$  to give the diameter at ground level.  $\theta_4$  was assumed to be that part of the curve, expressed in terms of relative height, affected by the buttress (see figure 6).

$$d(z, HT) = \theta_5 \left(1 - \frac{z}{HT}\right)^{k(z, \theta)} \left(1 + \theta_3 e^{-\theta_4 \frac{z}{HT}}\right) \quad (1)$$

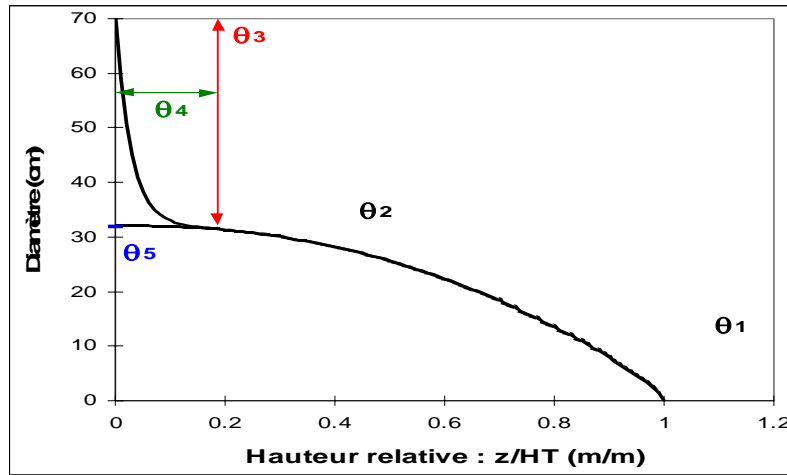
with  $k(z, \theta) = \theta_1 + \theta_2 \left(1 - \frac{z}{HT}\right)$

$d(z)$  : stem diameter on bark.

$z$  : height in the tree measured from the bottom (m).

$HT$  : total tree height (m).

**Figure 6:** The relative effects of the parameters  $\theta_{1-5}$  on tree shape in terms of relative height and diameter.



### 3.1.2 Model fitting on individual trees

Non linear regression was applied using SAS software on PC using Marquardt's method for non-linear regression (SAS, 1989). We used root mean squared error (RMSE) as a measure of the quality of the model. Although autocorrelation and heteroscedasticity were likely for taper equation, we did not take them into account. Our results, especially the estimated standard errors and confidence intervals of the estimated model parameters, are hence rigorous, but we did not try to improve their precision and their accuracy.

This model was first fitted on each of the 12 trees sampled taken from two stands in Glengarry Forest. In the following table we have reported the results for the parameters values  $\theta_{1-5}$  gained for each tree (Note 1 row = 1 tree).

**Table 5:** Data and model parameters,  $\theta_{1-5}$ , for stem taper for 12 trees sampled in Glengarry forest (Note D = dominant; C = co-dominant; S = suppressed)

stand	tree	age	ht	dbh	HSD	crownwd	h1bm	h1bv	h1vv	$\theta_1$	$\theta_2$	$\theta_3$	$\theta_4$	$\theta_5$
Gleng1	C1	65	31.6	37.5	84.3	4.6	1.51	21.3	23.44	0.68	-1.19	0.52	8.63	26.34
Gleng1	C2	65	31.62	34.4	91.9	3.95	1.37	18.55	20.92	0.68	-1.34	0.70	4.86	22.73
Gleng1	C3	65	29.61	35.4	83.6	4.9	1.5	21.3	22.27	0.68	-0.87	0.38	11.00	29.29
Gleng1	D1	65	32.03	47.6	67.3	4.45	2.23	21.38	24.03	0.61	-0.95	0.70	4.70	26.16
Gleng1	D2	65	34.06	45.8	74.4	3.57	1.57	2.38	22.9	0.62	-1.52	0.70	5.71	27.52
Gleng1	D3	65	36.43	46.9	77.7	5.45	1.64	19.38	23.04	0.80	-1.46	0.60	10.07	34.62
Gleng2	D1	65	35.16	39.7	88.6	4.61	1.9	22.67	23.45	0.73	-0.79	0.42	11.00	31.54
Gleng2	D2	65	30.5	41.5	73.5	5.7	3	19.75	20.9	0.70	-0.50	0.42	11.00	35.00
Gleng2	D3	65	34.32	42	81.7	4.75	1.09	22.15	22.15	0.69	-1.60	0.70	6.01	25.74
Gleng2	S1	65	30.14	32.7	92.2	3.1	1.67	20	23.15	0.60	-0.91	0.49	5.08	23.24
Gleng2	S2	65	31.74	33.6	94.5	2.9	1.42	24.15	25.5	0.60	-0.82	0.49	11.00	26.82
Gleng2	S3	65	30.95	31.2	99.2	3.15	1.82	21.45	23.15	0.66	-0.99	0.46	4.98	22.76

### 3.1.3 General fitting of the stem taper model for Glengarry

The second step is to analyse the relationships between the individual tree parameter values and the individual tree values for DBH, Age and Total height. We noted that  $\theta_1$  was correlated with the ratio  $th/dbh$  which reflects the social status of the trees in the stand. The final model based on all the trees in Glengarry is given by equation 2.

The parameter values and the matrix of correlation between parameters are given in table 6. Residuals are reported on figure 7.

$$d(z, HT, D130) = \theta_5 D130 \left(1 - \frac{z}{HT}\right)^{k(z, \theta)} \left(1 + \theta_3 e^{-\theta_4 \frac{z}{HT}}\right) \quad (2)$$

with

$$k(z, \theta) = \theta_1 (HT, D130) + \theta_2 \left(1 - \frac{z}{HT}\right)$$

$$\theta_1 (HT, D130) = \theta_{1,0} + \theta_{1,1} \left(\frac{HT}{D130}\right)$$

$d(z)$  : stem diameter over bark(cm).

$z$  : height in the tree measured from the bottom (m)

$HT$  : total tree height (m)

$D130$  : DBH over bark (m).

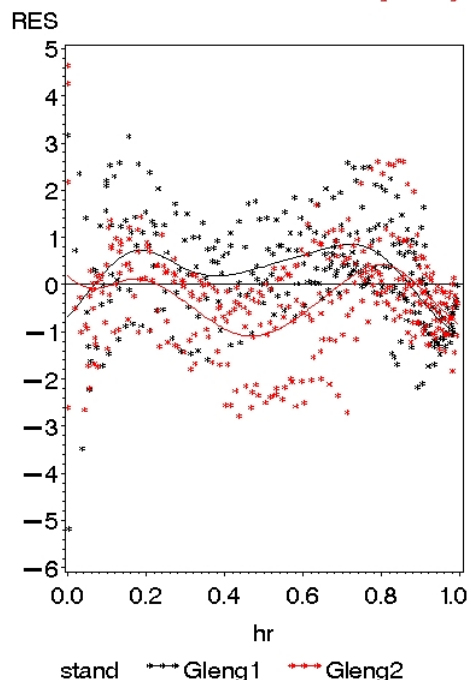
**Table 6:** Results for the stem taper model fitted on data from Glengarry (12 trees)

Source	Df	Sum of square	Mean Square
Regression	6	343266	57211.0
Residual	606	825.5	1.3622
Total (uncorrected)	612	344092	
Total (corrected)	611	82681.5	

Parameter	Estimate	Asymptotic error	Confidence interval at 95 %	
			Minimum	Maximum
$\theta_{10}$	0.8626	0.0317	0.8004	0.9248
$\theta_{11}$	-0.00184	0.000369	-0.00256	-0.00111
$\theta_2$	-0.7299	0.0646	-0.8569	-0.6030
$\theta_3$	0.3160	0.0270	0.2629	0.3691
$\theta_4$	13.1389	1.4789	10.2343	16.0434
$\theta_5$	0.8559	0.0182	0.8201	0.8916

Corr	$\theta_{10}$	$\theta_{11}$	$\theta_2$	$\theta_3$	$\theta_4$	$\theta_5$
$\theta_{10}$	1.0000000	-0.9815125	-0.0511245	0.0090106	0.0321214	0.0006881
$\theta_{11}$	-0.9815125	1.0000000	0.0335762	-0.0264910	0.0173682	0.0272999
$\theta_2$	-0.0511245	0.0335762	1.0000000	-0.8850280	0.7946439	0.9625936
$\theta_3$	0.0090106	-0.0264910	-0.8850280	1.0000000	-0.6540713	-0.9018448
$\theta_4$	0.0321214	0.0173682	0.7946439	-0.6540713	1.0000000	0.8793362
$\theta_5$	0.0006881	0.0272999	0.9625936	-0.9018448	0.8793362	1.0000000

**Figure 7:** Residuals plotted against relative tree height (1 = top) for the general model of stem taper for Glengarry.



### 3.1.4 Fitting the stem taper model on other stands with different ages

The model obtained from the Glengarry stands was also fitted to stem shape data collected from 7 other stands from other locations and of different ages. It was then possible to take into account the effect of the stand age on the two parameters  $\theta_1$  and  $\theta_2$ , which act on the top of the tree. The values obtained for each of the parameters per stand are reported in table 7.

**Table 7:** Parameters for stem taper models for stands of different ages

Forest	stand	age	$\theta_{10}$	$\theta_{11}$	$\theta_{20}$	$\theta_{30}$	$\theta_{40}$	$\theta_{51}$
Glengarry	Glengarry 1	65	0.6679	0.0000	-1.6150	0.7893	5.9594	0.6022
Glengarry	Glengarry 2	65	1.0442	-0.0040	-0.4149	0.2647	26.1883	0.9254
Glentress	Cloich	30	3.0657	-0.0067	2.3620	1.4852	-4.8621	0.4781
Kielder	Harecairn Moss	47	0.7962	-0.0016	-2.6151	1.6025	5.7102	0.4197
Kielder	Hawkhope Burn	36	0.7841	-0.0003	-0.5935	0.3664	18.1516	0.8766
Kielder	Highfield	35	0.8182	-0.0007	-1.4341	0.8997	5.3332	0.5821
Kershope	Kershope 34	32	1.1945	-0.0041	-1.1425	0.4291	12.3822	0.7964
Kershope	Kershope 50	14	0.7771	0.0027	-0.0989	0.2397	17.6090	1.0707
Glentress	Leadburn	16	1.5350	-0.0083	-0.8866	0.3171	9.3448	0.8702

### 3.1.5 The general stem taper model for all stands.

The model was then altered, as can be seen in equation 3, in order to take into account the stand age effect on  $\theta_1$ ,  $\theta_2$  and  $\theta_4$  and fitted again on the whole data set. The results are given in table 8 and the residuals are plotted on figures 8a and 8b.

$$d(z, HT, D130) = \theta_5 D130 \left(1 - \frac{z}{HT}\right)^{k(z, \theta)} \left(1 + \theta_3 e^{-\theta_4 \frac{z}{HT}}\right) \quad (3)$$

with

$$k(z, \theta) = \theta_1 (HT, D130) + \theta_2 \left(1 - \frac{z}{HT}\right)$$

$$\theta_1 (HT, D130) = \theta_{1,0} + \theta_{1,1} \left(\frac{HT}{D130}\right)$$

$$\theta_2 (age) = \theta_{2,0} + \theta_{2,1} (age)$$

$$\theta_4 (age) = \theta_{4,0} + \theta_{4,1} (age)$$

$d(z)$  : stem diameter over bark (cm).

$z$  : height in the tree measured from the bottom (m).

$HT$  : Total tree height (m).

$D130$  : breast height diameter on bark (m).

**Table 8:** Results for the stem taper model fitted on 9 stands (regression, parameter values, correlation between parameters, graphs for residuals)

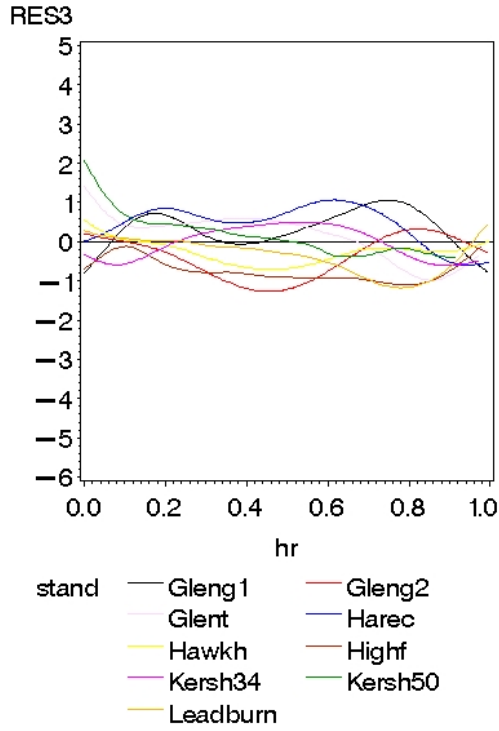
Source	Df	Sum of square	Mean Square
Regression	8	649157	81144.7
Residual	2024	2442.5	1.2068
Total (uncorrected)	2032	651600	
Total (corrected)	2031	190252	

Parameter	Estimate	Asymptotic error	Confidence interval at 95 %	
			Minimum	Maximum
$\theta_{10}$	0.9448	0.0156	0.9141	0.9754
$\theta_{11}$	-0.00246	0.000177	-0.00281	-0.00211
$\theta_{20}$	-0.356	0.0512	-0.4564	-0.2556
$\theta_{21}$	-0.00838	0.000623	-0.00961	-0.00716
$\theta_3$	0.3422	0.02	0.303	0.3814
$\theta_{40}$	3.0361	0.8609	1.3476	4.7245
$\theta_{41}$	0.1892	0.0262	0.1378	0.2406
$\theta_5$	0.8478	0.013	0.8222	0.8733

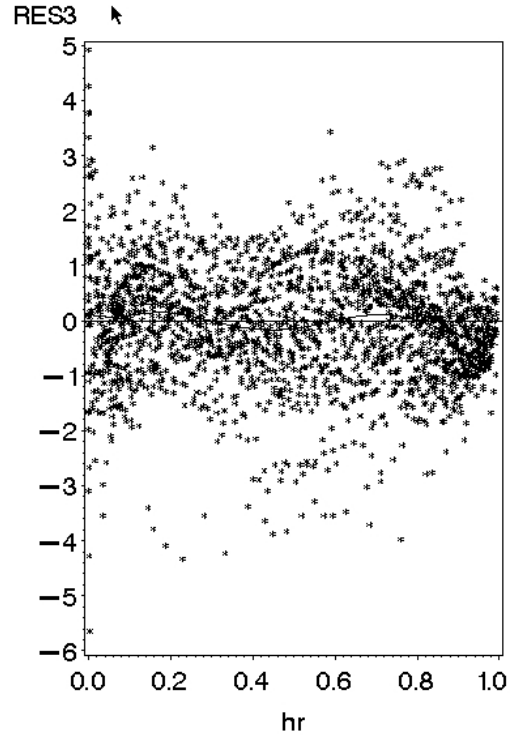
Corr	$\theta_{10}$	$\theta_{11}$	$\theta_{20}$	$\theta_{21}$	$\theta_3$	$\theta_{40}$	$\theta_{41}$	$\theta_5$
$\theta_{10}$	1.0000	-0.9522	-0.1661	0.1301	0.0126	0.0137	0.0237	-0.0025
$\theta_{11}$	-0.9522	1.0000	0.1104	-0.1250	-0.0216	0.0029	0.0059	0.0223
$\theta_{20}$	-0.1661	0.1104	1.0000	-0.4262	-0.7278	-0.4912	0.6949	0.7318
$\theta_{21}$	0.1301	-0.1250	-0.4262	1.0000	-0.2030	0.4522	-0.1189	0.2496
$\theta_3$	0.0126	-0.0216	-0.7278	-0.2030	1.0000	0.2589	-0.6628	-0.9474
$\theta_{40}$	0.0137	0.0029	-0.4912	0.4522	0.2589	1.0000	-0.7534	-0.1955
$\theta_{41}$	0.0237	0.0059	0.6949	-0.1189	-0.6628	-0.7534	1.0000	0.7142
$\theta_5$	-0.0025	0.0223	0.7318	0.2496	-0.9474	-0.1955	0.7142	1.0000



**Figure 8a:** Residuals plotted on a site basis



**Figure 8b:** Residuals plotted for a general model



### 3.2. Models for Branch diameter.

After screening the data and on the basis of our experience, we decided to test the following model for describing the branch diameter variations from the bottom up to the top of each tree. The parameters of the model represent explicitly, the branch diameter at the bottom of the tree ( $a + i$ ), the branch diameter at the top of the tree,  $a$  and the shape parameter,  $b$ , for the curve describing the change in branch angle up the tree. The effect of changing the parameter  $b$  can be seen in figure 9b.

$$DBRA = a + i(1 - hr)e^{-b \times hr} \quad (4)$$

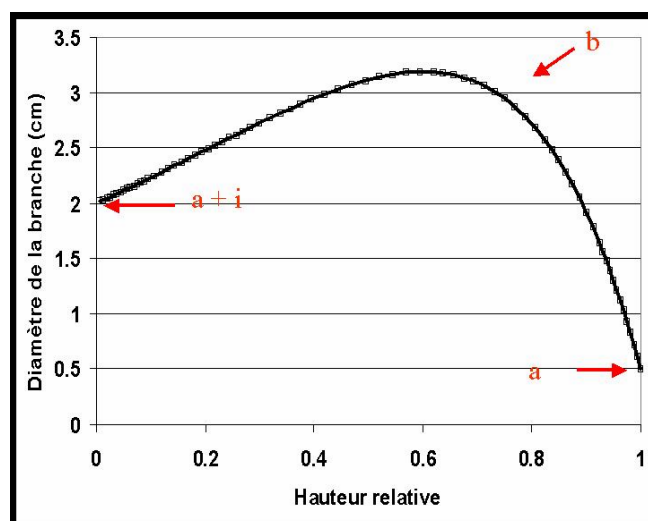
with

DBRA : Mean branch diameter at height of the growth unit, measured from the apex.

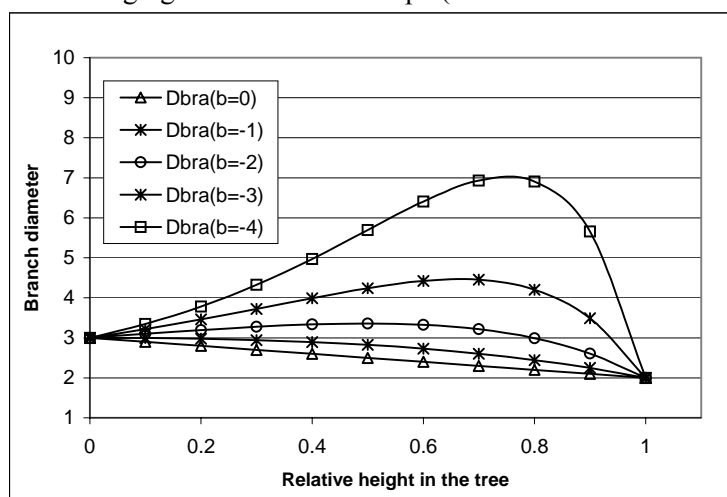
hr : relative height in the tree.

$a$ ,  $i$  and  $b$  are parameters (see figure 9).

**Figure 9a:** Graphical branch diameter model description.



**Figure 9b:** The effect of changing **b** on the model shape (where **a** is fixed at 2 and **i** = 1)



The data available were obtained from 59 trees sampled in 9 stands from 5 forests, Glengarry, Glentress, Kershope, Kielder and Leadburn which covered a wide range of ages, from 16 up to 65 years and initial spacings (see breakdown stand data in table 9).

**Table 9:** Stand ages and spacing for the branch measurement.

Forest	Stand	age	Spacing
Glengarry	Glengarry1	65	2.4
Glengarry	Glengarry2	65	1.8
Glentress	Glentress	30	2
Kershope	Kershope 34	32	1.8-2.4
Kershope	Kershope 50	14	2
Kielder	Harecairn Moss	47	1.7
Kielder	Hawkhope Burn	36	1.7
Kielder	Highfield	35	1.9
Leadburn	Leadburn	16	2.6

### 3.2.1 Individual Tree fitting of the branch diameter model.

The model (equation 4) was fitted on a tree by tree basis using the branch data. It described correctly the data all along each stem. In tables 11.1 to 11.5, we report on the parameter values obtained and on the individual tree measurements performed during the inventory (1 row = 1 tree). This set of individual tree parameters used with the branch model presented above (equation 4) summarises the branch diameter variation at each relative height for each tree.

**Table 10:** Description of the variable used in the branch diameter analysis.

	Variable Description	Unit
Age :	tree age	(year)
Th :	total height	(m)
Dbh :	diameter at breast height	(cm)
Hsd :	th/dbh	(m/m)
Crownwd :	crown width	(m)
H1bm :	height of the first dead branch	(m)
H1bv :	height of the first living branch	(m)
H1vv :	height of the first living whorl	(m)
Crbm :	$(th-h1bm)/th$	no unit
Crbv :	$(th-h1bv)/th$	no unit
Crvv :	$(th-h1vv)/th$	no unit

**Table 11.1:** Tree data and parameters for a branch diameter model, Glengarry forest.

Stand	Tree	i	a	b	age	Th	dbh	hsd	h1bm	h1bv	H1vv	crbm	crbv	crvv
Gleng1	C1	1.477	1.149	-2.216	58	31.6	37.5	84.27	1.51	21.3	23.44	95.22	32.59	25.82
Gleng1	C2	0.839	0.871	-3.195	58	31.62	34.4	91.92	1.37	18.55	20.92	95.67	41.33	33.84
Gleng1	C3	1.734	1.272	-2.207	58	29.61	35.4	83.64	1.5	21.3	22.27	94.93	28.06	24.79
Gleng1	D1	1.345	0.974	-2.446	58	32.03	47.6	67.29	2.23	21.38	24.03	93.04	33.25	24.98
Gleng1	D2	1.521	0.952	-2.860	58	34.06	45.8	74.37	1.57	2.38	22.9	95.39	93.01	32.77
Gleng1	D3	1.557	0.165	-3.030	58	36.43	46.9	77.68	1.64	19.38	23.04	95.50	46.80	36.76
Gleng2	D1	1.626	0.609	-2.715	60	35.16	39.7	88.56	1.9	22.67	23.45	94.60	35.52	33.30
Gleng2	D2	2.142	0.846	-2.156	60	30.5	41.5	73.49	3	19.75	20.9	90.16	35.25	31.48
Gleng2	D3	1.130	0.927	-3.039	60	34.32	42	81.71	1.09	22.15	22.15	96.82	35.46	35.46
Gleng2	S1	0.755	0.860	-3.286	60	30.14	32.7	92.17	1.67	20	23.15	94.46	33.64	23.19
Gleng2	S2	0.180	1.718	-4.333	60	31.74	33.6	94.46	1.42	24.15	25.5	95.53	23.91	19.66
Gleng2	S3	1.089	0.956	-2.649	60	30.95	31.2	99.20	1.82	21.45	23.15	94.12	30.69	25.20

**Table 11.2:** Tree data and parameters for a branch diameter model, Glentress forest.

Stand	Tree	i	a	b	age	Th	dbh	hsd	h1bm	h1bv	H1vv	crbm	crbv	crvv
Glent	16	1.066	0.249	-2.430	27	15.63	21.6	72.36	.	.	.	.	.	.
Glent	18	0.995	0.387	-2.224	27	12.98	15.5	83.74	.	.	.	.	.	.
Glent	35	0.877	0.234	-2.747	27	14.05	17.6	79.83	.	.	.	.	.	.
Glent	36	2.320	0.000	-1.328	27	12.6	18.9	66.67	.	.	.	.	.	.
Glent	39	1.498	0.433	-1.658	27	15.2	19	80.00	.	.	.	.	.	.
Glent	40	1.371	0.580	-2.078	27	16	21.3	75.12	.	.	.	.	.	.

**Table 11.3:** Tree data and parameters for a branch diameter model, Kershope forest.

Stand	Tree	i	a	b	age	Th	dbh	hsd	h1bm	h1bv	H1vv	crbm	crbv	crvv
Kersh34	17031	2.286	0.000	-2.229	31	21.1	27.1	77.86	1.34	9.1	9.85	93.65	56.87	53.32
Kersh34	17032	1.529	0.206	-2.517	31	19.2	24	80.00	0	9.55	10.5	100.00	50.26	45.31
Kersh34	17033	1.363	0.534	-1.936	31	19.8	19.8	100.00	1.78	9.9	11.6	91.01	50.00	41.41
Kersh34	17094	1.118	0.211	-2.665	31	16.05	18.8	85.37	0.7	7.35	7.95	95.64	54.21	50.47
Kersh34	17095	1.063	0.736	-2.288	31	16.43	22.8	72.06	0.2	7.6	8.53	98.78	53.74	48.08
Kersh34	17096	1.373	0.280	-2.049	31	14.1	14.6	96.58	0.3	6.5	8.2	97.87	53.90	41.84
Kersh34	17227	1.333	0.000	-2.680	31	21.17	23.5	90.09	0.6	10.35	10.78	97.17	51.11	49.08
Kersh34	17228	1.164	0.556	-2.415	31	16.48	18.2	90.55	0.21	8.42	8.42	98.73	48.91	48.91
Kersh34	171510	0.943	0.046	-2.916	31	19.28	22	87.64	0.75	10.71	10.71	96.11	44.45	44.45
Kersh34	171511	0.430	0.965	-2.614	31	17.15	18.7	91.71	0.85	11.31	11.31	95.04	34.05	34.05
Kersh34	171512	0.502	0.620	-3.320	31	15.92	16.5	96.48	0.73	9.9	9.9	95.41	37.81	37.81
Kersh34	1722S2	0.609	0.498	-2.697	31	17.6	14.9	118.12	0.3	11.72	11.72	98.30	33.41	33.41
Kersh50	1	1.252	0.000	-2.000	16	6.4	13	49.23	0	0	0.65	100.00	100.00	89.84
Kersh50	2	1.655	0.000	-1.611	16	8.12	14.3	56.78	0	0.15	1.32	100.00	98.15	83.74
Kersh50	3	1.168	0.000	-2.144	16	7.72	12.5	61.76	0	0.3	1.25	100.00	96.11	83.81
Kersh50	4	1.088	0.000	-2.215	16	6.89	10.9	63.21	0	0.87	1.34	100.00	87.37	80.55
Kersh50	5	0.537	1.142	-2.481	16	8.37	13	64.38	0	0.74	1.15	100.00	91.16	86.26
Kersh50	6	0.726	0.000	-2.886	16	6.87	10.8	63.61	0	1.05	2.1	100.00	84.72	69.43

**Table 11.4:** Tree data and parameters for a branch diameter model, Harecairn Moss, Kielder forest.

Stand	Tree	i	a	b	age	Th	dbh	hsd	h1bm	h1bv	H1vv	crbm	crbv	crvv
Harec	1G	1.840	0.039	-2.780	52	23.93	34.1	70.18	1.32	12.85	13.49	94.48	46.30	43.63
Harec	2CN	1.482	0.000	-3.036	52	25.35	33	76.82	1.5	12.62	14.87	94.08	50.22	41.34
Harec	3BP	0.508	0.531	-3.676	52	24.2	23	105.22	1.48	13.66	14.9	93.88	43.55	38.43
Harec	4CL	0.742	0.336	-3.102	52	22.8	24.5	93.06	1.76	12.3	14.3	92.28	46.05	37.28
Harec	5T	0.667	0.444	-1.927	52	17.95	12.1	148.35	1.76	12.3	14.3	90.19	31.48	20.33
Harec	6AF	0.885	0.360	-2.444	52	16.64	12.2	136.39	0.6	11.66	13.87	96.39	29.93	16.65
Hawkh	1BF	1.176	0.395	-2.911	50	19.31	32.2	59.97	0.26	10.29	12.49	98.65	46.71	35.32
Hawkh	2BP	0.485	0.856	-3.471	50	20.4	27.5	74.18	0.5	11.57	12.45	97.55	43.28	38.97
Hawkh	3CL	1.190	0.522	-2.259	50	17.39	20.5	84.83	0.2	10.08	11.54	98.85	42.04	33.64
Hawkh	4BT	0.245	1.082	-3.825	50	17.75	20.8	85.34	0.28	11.43	12.51	98.42	35.61	29.52
Hawkh	5aN	0.735	0.046	-2.440	50	10.55	10	105.50	0.22	8.85	8.85	97.91	16.11	16.11
Hawkh	6bc	0.532	0.244	-2.153	50	13.51	11.4	118.51	0.23	9.2	11.02	98.30	31.90	18.43
Highf	18Co1	0.920	0.749	-2.518	35	17.31	19.2	90.16	0	10.26	10.26	100.00	40.73	40.73
Highf	26S1	1.170	0.395	-1.722	35	15.45	13.3	116.17	0	7.99	8.64	100.00	48.28	44.08
Highf	43D2	1.298	0.742	-2.542	35	21.4	30.2	70.86	0	7.28	7.89	100.00	65.98	63.13
Highf	6D1	0.858	0.787	-1.925	35	16.4	24.1	68.05	0	1.88	8.53	100.00	88.54	47.99
Highf	78C2	1.258	0.228	-2.458	35	17.87	21.8	81.97	0	6.84	8.82	100.00	61.72	50.64

**Table 11.5:** Tree data and parameters for a branch diameter model, Leadburn forest.

Stand	Tree	i	a	b	age	Th	dbh	hsd	h1bm	h1bv	H1vv	crbm	crbv	crvv
Leadburn	18C1	0.763	0.953	-1.573	22	11.51	17.9	64.30	0	3.36	4.1	100.00	70.81	64.38
Leadburn	24S2	0.650	0.760	-1.477	22	7.85	10.7	73.36	0.2	3.12	4.38	97.45	60.25	44.20
Leadburn	2D1	2.459	0.000	-1.626	22	11.52	24.2	47.60	0	0.18	0.69	100.00	98.44	94.01
Leadburn	3D2	2.052	0.000	-2.175	22	11.44	22.4	51.07	0	0.8	2.8	100.00	93.01	75.52
Leadburn	56C2	1.848	0.000	-2.077	22	10.32	18.7	55.19	0.03	1.28	1.6	99.71	87.60	84.50
Leadburn	7S1	0.889	0.873	0.000	22	7.9	9.4	84.04	0.5	0.71	1.1	93.67	91.01	86.08

*For some cases (trees) the value obtained for “a” is equal to 0. Since the parameter “a” is defined as the branch diameter at the top of the tree, this is a surprising result. In fact it is explained by the bounds given in the statistical program. During the Nlin procedure, we have specified that the parameter “a” can never be lower than 0.*

From these tables, it is possible to observe that the parameter **b**, which controls the shape of the model, is correlated with the total height of the tree. The parameter **a**, which reflects the branch diameter at the tree apex, is considered as a constant. The parameter **i**, which reflects (when added to **a**) the branch diameter at the bottom of the tree, is a function of Dbh and the shape stem ratio Hsd (Th/Dbh).

### 3.2.2 General branch diameter model for all the stands

The model selected does not use crown width as a variable because this variable is not usually measured during forest inventories and because no one model is available for it's prediction. However, this idea can be kept in mind for one further analysis or development since we have crown width measurements for our study trees. The general model formulation is described by equation 5. The results of the regression, the parameter values and the correlation between the parameters are given in tables 12. The residuals are plotted on figure 10.

$DBRA = a_0 + i * (1 - hr) \exp(-b * hr) \quad (5)$	
$i = i_0 + i_1 * Hsd + i_2 * Dbh$	
$b = b_0 + b_1 * Th$	
with	
DBRA : Mean branch diameter at the relative height of the tree.	
hr : relative height in the tree.	
Hsd : stem shape factor (Th/Dbh in m/m)	
a0, i0, i1, i2, b0, b1 are parameters	

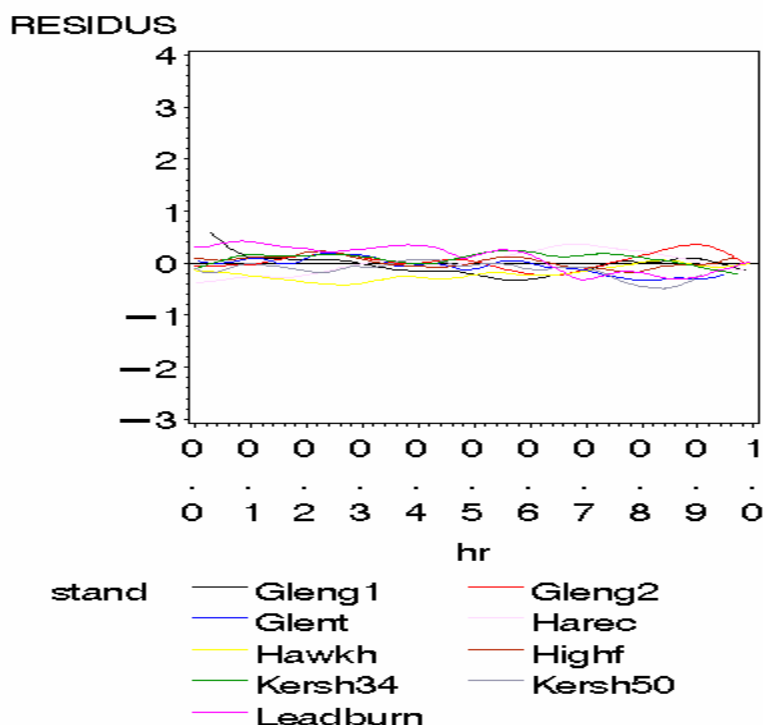
**Table 12:** Results for the general model of branch diameter fitted on 59 trees. (Regression results, parameter values, confidence intervals and correlation between parameters).

Source	Df	Sum of square	Mean Square
Regression	6	23407.1	1183.63
Residual	4735	1807.8	0.3818
Total (uncorrected)	4741	25214.9	
Total (corrected)	4740	4067.3	

Parameter	Estimate	Asymptotic error	Confidence interval at 95 %	
			Minimum	Maximum
i0	0.5363	0.0635	0.4118	0.6609
i1	-0.00312	0.000388	-0.00388	-0.00236
i2	0.0317	0.00113	0.0295	0.0340
a0	0.6074	0.0399	0.5292	0.6856
b0	-2.3073	0.0601	-2.4252	-2.1894
b1	-0.0115	0.00218	-0.0158	-0.00722

Corr	i0	i1	i2	a0	b0	b1
i0	1	-0.7772293	-0.6650164	-0.5849042	0.6699797	-0.6595679
i1	-0.7772293	1	0.4289821	0.1310721	-0.4383057	0.4561404
i2	-0.6650164	0.4289821	1	0.0988895	-0.5630501	0.7637088
a0	-0.5849042	0.1310721	0.0988895	1	-0.2138596	0.1212998
b0	0.6699797	-0.4383057	-0.5630501	-0.2138596	1	-0.9227640
b1	-0.6595679	0.4561404	0.7637088	0.1212998	-0.9227640	1

**Figure 10.** Residuals for the general model of branch diameter for all the stands, plotted against relative height.

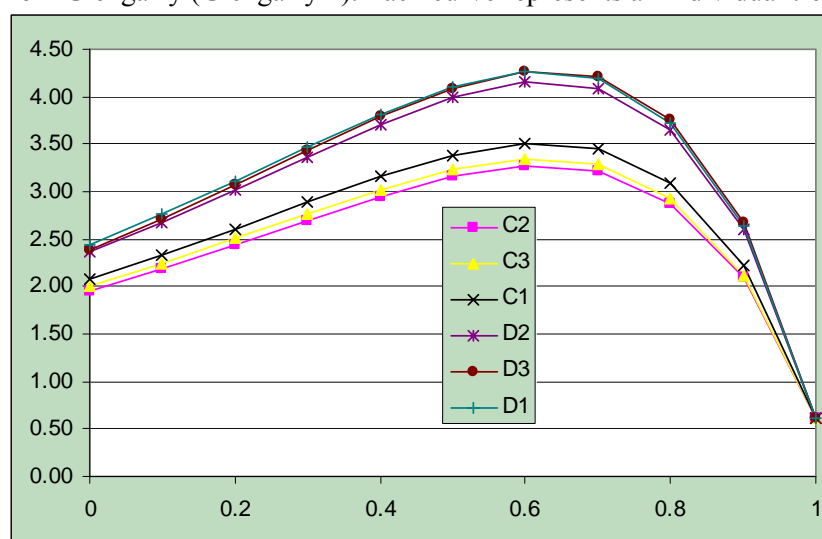


This general model appears to behave correctly for all the stands and it can be used for the Sitka spruce forest resource. The results obtained are good, especially because the model is based on a well designed data set that covers a wide range of stand ages and tree social status within the stands (dominant, co-dominant and sub-dominated).

*Note. This general model was built in order to describe the vertical branch diameter pattern according to the tree size. If this model is used for simulation purposes than it must be kept in mind that this model simulates, for one given tree, at one relative height (i.e. for all the branches of one whorl), one single branch diameter. In order to more accurately reflect the branch diameter variation observed in nature for the branches of one whorl, a random term must be added for each branch diameter simulation. This random value would be obtained from the calculated standard deviation of the branch diameter.*

Figure 11 illustrates the effect of social status, as defined by relative dbh in the stand, on branch diameter. The curves have been simulated for branch diameters using the general model for a single stand of trees (Glengarry1) from the Glengarry forest. Each curve represents the predicted variation in branch diameter compared to relative height up the tree for one tree. The social status of the trees (see tree dimensions in table 11.1) is reflected in the simulated branch diameter, with the dominant trees having larger branch diameters than the co-dominant trees. This demonstrates how important it is to model at the individual tree level when considering wood quality assessment because the end products are made from individuals and not from average trees.

**Figure 11:** Simulated branch diameter (cm) variations against relative height for dominant and co-dominant trees from Glengarry (Glengarry 1). Each curve represents an individual tree.



**Figure 12:** Effect of stand age and spacing on average branch diameter (cm) up the tree per stand.

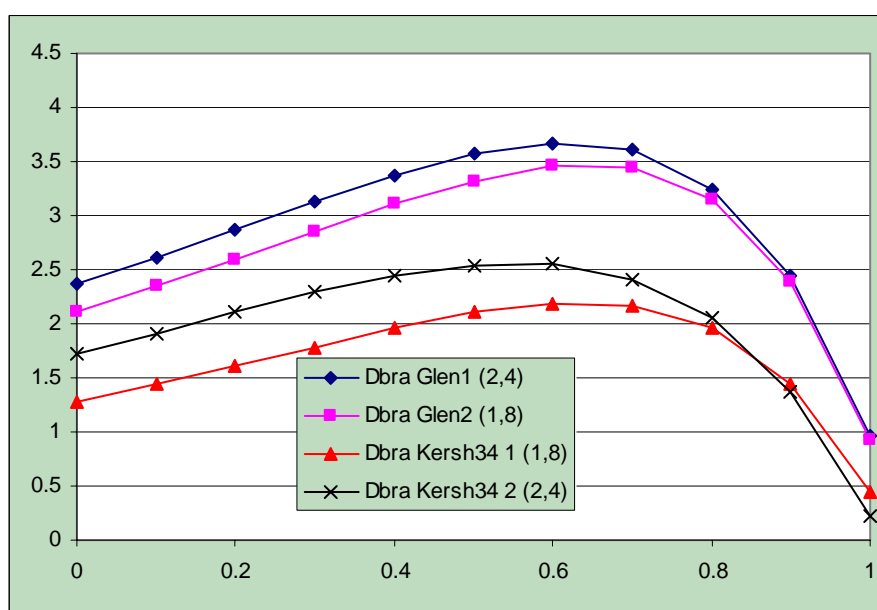


Figure 12 was obtained by fitting the model to Glengarry 1 and 2, and Kershope 34 to provide the average branch diameter as it changes up the tree. This demonstrates the effects of spacing and age on branching since the age of the Glengarry stands was 65 whereas the Kershope stands were 32 years old. Not surprisingly the wider initial spacing produced the larger mean knot size at Kershope, but it is interesting to note that the decision to plant at a wider spacing was still obvious on the mean branch size of the trees 65 years later.

### 3.3. Modelling the number of branches per growth unit (or whorl).

The expression used to describe the number of branches per whorl, equation 6, was selected on the basis of previous work undertaken at INRA for Norway spruce and Douglas fir.

$NBRA = i0 \times luc^a e^{-b \times dinc} \quad (6)$	
with	
luc: length of the annual growth unit or whorl.	
Dinc: distance measured from the apex (m), i0, a and b are parameters.	

#### 3.3.1 Individual tree fitting a branch number model:

The model was fitted on a tree by tree basis to the data from Glengarry (Glengarry 1 and 2). It correctly described the branch number variations all along the tree. In table 13 we report on the results gained for each individual tree (1 row = 1 tree). The correlations between the parameters are low as well as between the dendrometric measurements of the individual trees.

**Table 13:** Parameters and tree data for an individual tree model of the number of branches per whorl

Stand	tree	i0	a	b	age	ht	dbh	HSD	crownwd	h1bm	h1bv	h1vv	crbm	crbv	crvv
Gleng1	C1	4.02	0.32	0.01	58.00	31.60	37.50	84.27	4.60	1.51	21.30	23.44	0.95	0.33	0.26
Gleng1	C2	2.84	0.16	0.01	58.00	31.62	34.40	91.92	3.95	1.37	18.55	20.92	0.96	0.41	0.34
Gleng1	C3	2.14	0.07	0.04	58.00	29.61	35.40	83.64	4.90	1.50	21.30	22.27	0.95	0.28	0.25
Gleng1	D2	2.27	-0.11	0.03	58.00	34.06	45.80	74.37	3.57	1.57	2.38	22.90	0.95	0.93	0.33
Gleng1	D3	3.77	0.11	0.01	58.00	36.43	46.90	77.68	5.45	1.64	19.38	23.04	0.95	0.47	0.37
Gleng2	D1	2.74	0.07	0.01	60.00	35.16	39.70	88.56	4.61	1.90	22.67	23.45	0.95	0.36	0.33
Gleng2	D2	3.40	0.06	0.02	60.00	30.50	41.50	73.49	5.70	3.00	19.75	20.90	0.90	0.35	0.31
Gleng2	D3	2.78	0.10	0.02	60.00	34.32	42.00	81.71	4.75	1.09	22.15	22.15	0.97	0.35	0.35
Gleng2	S1	2.16	0.00	0.02	60.00	30.14	32.70	92.17	3.10	1.67	20.00	23.15	0.94	0.34	0.23
Gleng2	S2	2.89	0.05	0.01	60.00	31.74	33.60	94.46	2.90	1.42	24.15	25.50	0.96	0.24	0.20
Gleng2	S3	2.48	-0.06	0.02	60.00	30.95	31.20	99.20	3.15	1.82	21.45	23.15	0.94	0.31	0.25

#### 3.3.2 General stand model of branch number for Glen1 and Glen2.

We have tried to improve the model by analysing the relationships between the parameter values and the dendrometric measurements of the individual tree. However, because of the lack of observed relationships, this approach did not improve the model. As a consequence the general model (valid for all the trees from the two stands) has the same equation as before (see equation 6). The results of this fitting are reported in tables 14 while the residuals are plotted on figure 13.



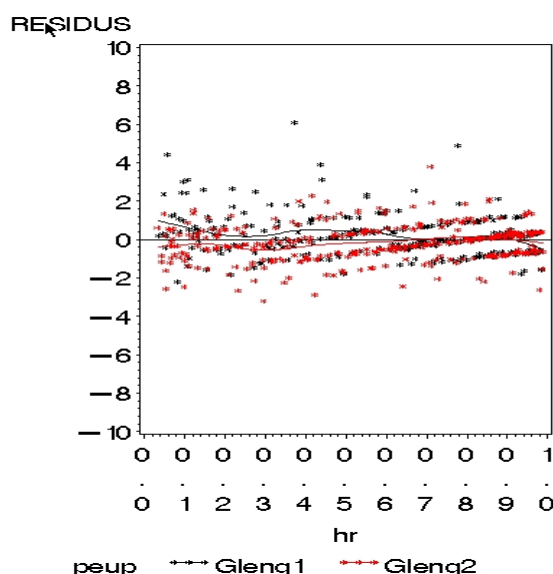
**Table 14:** Results for model fitting on data for number of branches for stands Glen1 and Glen2, 12 trees altogether. (Regression results, parameter values, correlation between parameters, graphs for residuals)

Source	Df	Sum of square	Mean Square
Regression	3	7770.1	2590
Residual	586	636.9	1.0868
Total (uncorrected)	589	8407	
Total (corrected)	588	955.3	

Parameter	Estimate	Asymptotic error	Confidence interval at 95 %	
			Minimum	Maximum
i0	2.8364	0.1008	2.6384	3.0343
a	0.0771	0.0279	0.0224	0.1319
b0	0.0189	0.00138	0.0162	0.0216

Corr	i0	a	b0
i0	1	0.7214249	-0.8631351
a	0.7214249	1	-0.4409133
b0	-0.8631351	-0.4409133	1

**Figure 13:** Residues plotted against relative height for the number of branches per whorl model for two stands in Glengarry (top = 1.0)



### 3.4. Modelling insertion angle for whorl branches.

After screening the data, the model, equation 7, was selected on the basis of previous work done at INRA for Norway spruce. When this angle is 90 degrees, this means that the branch is horizontal and if the angle value is equal to 0 degree, this means that the branch is vertical.

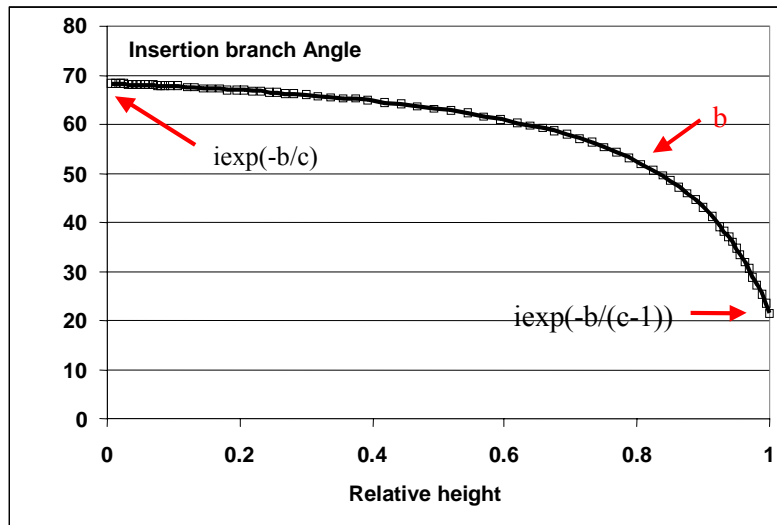
$$INSBRA = i \times e^{-\frac{b}{c-hr}} \quad (7)$$

With

INSBRA : average insertion branch angle for the growth unit (or whorl).

hr : relative height in the tree, i, b and c are parameters.

**Figure 9:** Insertion branch model



### 3.4.1 Individual tree analysis for insertion angle

It was difficult to fit the model to the data during the procedure of individual tree fitting. For several trees in this sample, the angular branch variations with the height in the tree were low. It was then decided to fix the value for the parameter  $c$ . This parameter was arbitrarily fixed to 1.08 (the value obtained previously for Douglas fir, (Daquitaine, 2003)). Then the tree by tree analysis was performed without problem. For each tree the model correctly fits the data. The results are reported in table 15 (1 row = 1 tree). The parameters  $b$  and  $i$  are correlated with the crown attributes while the parameter  $i$  is also correlated with Dbh and with the shape ratio hsd.

**Table 11:** Parameters and tree data for a branch insertion angle model

Stand	tree	i0	b	age	ht	dbh	HSD	crownwd	h1bm	h1bv	h1vv	crbm	crbv	crvv
Glen1	C1	78	0.002	58.00	31.60	37.50	84.27	4.60	1.51	21.30	23.44	0.95	0.33	0.26
Glen1	C2	71	0.0161	58.00	31.62	34.40	91.92	3.95	1.37	18.55	20.92	0.96	0.41	0.34
Glen1	C3	76	0.0139	58.00	29.61	35.40	83.64	4.90	1.50	21.30	22.27	0.95	0.28	0.25
Glen1	D1	79	0.0287	58.00	32.03	47.60	67.29	4.45	2.23	21.38	24.03	0.93	0.33	0.25
Glen1	D2	70	0	58.00	34.06	45.80	74.37	3.57	1.57	2.38	22.90	0.95	0.93	0.33
Glen1	D3	76	0.0194	58.00	36.43	46.90	77.68	5.45	1.64	19.38	23.04	0.95	0.47	0.37
Glen2	D1	85	0.0181	60.00	35.16	39.70	88.56	4.61	1.90	22.67	23.45	0.95	0.36	0.33
Glen2	D2	79	0.0192	60.00	30.50	41.50	73.49	5.70	3.00	19.75	20.90	0.90	0.35	0.31
Glen2	D3	78	0.0044	60.00	34.32	42.00	81.71	4.75	1.09	22.15	22.15	0.97	0.35	0.35
Glen2	S1	77	0.0179	60.00	30.14	32.70	92.17	3.10	1.67	20.00	23.15	0.94	0.34	0.23
Glen2	S2	77	0.0032	60.00	31.74	33.60	94.46	2.90	1.42	24.15	25.50	0.96	0.24	0.20
Glen2	S3	66	0.0288	60.00	30.95	31.20	99.20	3.15	1.82	21.45	23.15	0.94	0.31	0.25

### 3.4.2 General model of insertion angle for stands Glen1 and Glen2.

In this model the crown width was not used as a predictor for the same reason as before (this measurement is not available from the usual forest inventory measurements). The model was improved by introducing the variations to the parameter  $i0$  as a function of the shape ratio hsd and by introducing variations to the parameter  $b$  as a function of the height of the first green whorl, which reflects more or less the stand density. This new model (equation 8) was then fitted to the whole data

set and the results are reported in tables 16 (the parameter **c** is now estimated without constraints) while residuals are represented in figure 15.

$INSBRA = i \times e^{\frac{b}{c-hr}} \quad (8)$	
$i = i0 + i1 \cdot HT/D130$ $b = b0 + b1 \cdot H1VV$	
with INSBRA : average insertion branch angle for the growth unit (or whorl). hr : relative height in the tree. I0, b and c are parameters.	

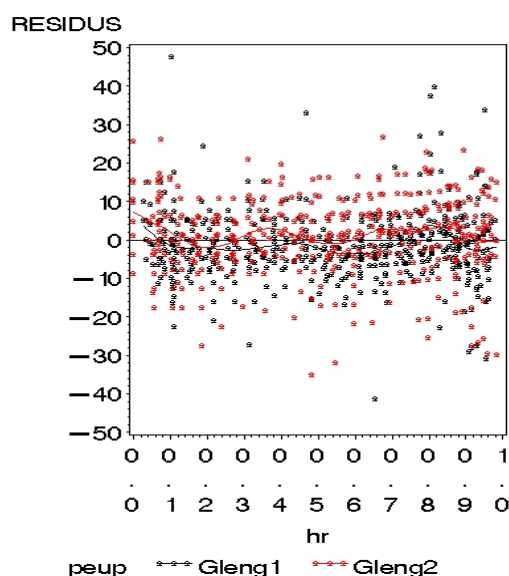
**Table 16:** Results for fitting the general model for insertion angle of branches for stands Glen1 and Glen2, 12 trees altogether. (Regression results, parameter values, correlation between parameters, graphs for residuals)

Source	Df	Sum of square	Mean Square
Regression	5	6096912	1219382
Residual	1131	98412.5	87.0137
Total (uncorrected)	1136	6195325	
Total (corrected)	1135	106930	

Parameter	Estimate	Asymptotic error	Confidence interval at 95 %	
			Minimum	Maximum
<b>i0</b>	88.0883	2.6832	82.8236	93.353
<b>i1</b>	-0.1475	0.031	-0.2082	-0.0867
<b>b0</b>	0.064	0.0254	0.0143	0.1138
<b>b1</b>	-0.00229	0.000994	-0.00424	-0.00034
<b>c</b>	1.0472	0.029	0.9904	1.104

Corr	i0	i1	b0	b1	c
<b>i0</b>	1	-0.9722137	0.2461593	-0.2272577	0.226246
<b>i1</b>	-0.9722137	1	-0.1240412	0.1270678	-0.0570843
<b>b0</b>	0.2461593	-0.1240412	1	-0.9913694	0.7037857
<b>b1</b>	-0.2272577	0.1270678	-0.9913694	1	-0.6157948
<b>c</b>	0.226246	-0.0570843	0.7037857	-0.6157948	1

**Figure 15:** Residues plotted against relative height for the stand level insertion branch angle model for two stands in Glengarry (top = 1.0)



#### 4. Summary and Future Work

Models have now been developed for the wood density, stem taper, branch diameter, number and insertion angle for Sitka spruce using GB data. These models have been developed both on an individual tree basis and at a stand level. The density models have been tested against an independent data set and found to behave realistically and explain approximately 60% of the observed variation. This compares well with other models of wood density, which is well known as a highly variable characteristic both within and between stands (see for example, Simpson and Denne 1997; Savill and Sandells 1983). Density data is still being collected for further refinements and validation of the model. This greater breadth of data should make the model more robust and applicable to a greater range of situations with a higher degree of confidence. Similarly, stem taper data is still being collected with the same aim. The branching models appear to work well and in general the residuals are low when the models are tested.

The next characteristic for inclusion into a general wood quality model is grain angle of the standing trees. Data has been collected from discs and is in the process of being modelled. Unfortunately a full data set was not available during the time span of the Fellowship for the inclusion of the analysis into this report.

The next stage in the development of these models into a practical tool for the forest industry is the development of software that will provide a user friendly decision support system, such as ForestGales and ESC. This will be based on the WinEPIFN package, but will require a stand level growth model to drive it. When a single tree growth model for Sitka spruce becomes available it should be possible to develop a single-tree timber quality model. In addition it is hoped that the timber quality model will be able to feed into the batten performance model developed by Keith Maun of BRE. This will allow users to track the influence of silvicultural decisions all the way through the wood chain to the number and strength of battens produced from their stand.

In the longer term the aim is to incorporate stem form into the model since this is a key criterion involved in buying timber. A purely statistical approach could be attempted with the data and models currently available from several large scale surveys of stem straightness undertaken by Forest Research (Stirling *et al.* 2000; Mochan *et al.*, 2001; Mochan *et al.*, 2002). However, work is currently being planned that could provide a more fundamental understanding of the factors that control the formation of bends in Sitka spruce, which could provide a more robust model. Stem form is also

linked with compression wood formation and the findings from the current EU project investigating compression wood formation will be linked into any treatment of stem form.

In conclusion the project has taken a big step forward towards providing an invaluable tool for the forest industry. The collaboration between INRA and FR has also provided FR with the expertise to model timber quality for other species of interest in GB. The development of the Sitka spruce timber quality model has acted as the proving ground and already data is being collected for Scot pine that will allow the development of a similar set of timber quality models for this species.

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