Assessment of the Economic (Pulping and Pulp Quality) Effects of Increased Lodgepole Pine in SPF Chip Mixtures

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Abstract

British Columbia's market pulps and mechanical printing papers enjoy an enviable reputation worldwide as the benchmark for intrinsic strength and quality. Spruce–pine–fir (SPF) chip mixtures are widely used in both interior and coastal pulping operations. The current mountain pine beetle infestation, with the increased harvest of lodgepole pine, threatens to shift the balance of SPF from the traditionally used 30/65/5 ratio to a high pine ratio of 80% to 90%.

To evaluate and quantify possible process and pulp-quality implications, statistically designed pilot kraft and mechanical pulping mixing experiments using green spruce, pine and fir were undertaken. These suggest a decrease in pulp yield with increasing pine content for kraft pulping, and possibly an increase in necessary refining energy for thermomechanical pulping (TMP). A small but tolerable decrease in pulp strength is possible for kraft and TMP, whereas opacity and scattering coefficient both increase slightly. No conclusive results for change in brightness for TMP pulp were found. A thorough discussion of fibre properties showed that pine fibres are not necessarily coarser, but they do have a smaller collapse index, which can impact internal bonding and thus sheet strength; however, differences between the species found in this study are small.

Pulp properties, as well as the changes with increasing pine content, were site dependent, but no correlation with site index specifically was found, possibly due to the small sample size. However, the site dependence emphasizes the importance of closely monitoring incoming wood and chip quality in pulp mills to be able to adjust process variables quickly.

Keywords: mountain pine beetle, lodgepole pine, SPF, chip mixtures, mixture experiments, fibre properties, pulp quality, chip quality, kraft and mechanical pulping, site productivity, biogeoclimatic subzone

Résumé

Les pâtes commercialisées et les papiers d'impression mécanique de Colombie-Britannique sont une référence mondiale en ce qui a trait à la qualité et à la résistance intrinsèques. Les mélanges de copeaux d'épinette-pin-sapin (EPS) sont très utilisés dans les opérations de réduction en pâte sur la côte et à l'intérieur de la province. L'infestation actuelle de dendroctones du pin, accompagnée d'une coupe plus intensive de pins tordus, menace de déséquilibrer les ratios d'EPS et de passer du traditionnel 30/65/5 à un ratio en pins élevé allant de 80 à 90 p. 100.

Pour évaluer et quantifier les répercussions possibles des procédés et de la qualité de la pâte, on a effectué des expériences de mélanges de pâte mécaniques en faisant appel au procédé kraft pour mélanger de l'épinette, du pin et du sapin verts. Ces expériences donnent à penser que la production de pâte comprenant une teneur plus forte en pin par le procédé kraft pourrait être réduite, et que l'énergie nécessaire au raffinage pour le procédé de préparation de la pâte thermomécanique (PTM) pourrait être augmentée. Il est possible que la résistance de la pâte diminue légèrement de façon tolérable et que l'opacité et le coefficient de dispersion augmentent quelque peu. Les expériences n'ont donné aucun résultat concluant concernant la modification de la brillance de la PTM. Une discussion exhaustive concernant les propriétés des fibres a permis de déterminer que les fibres du pin ne sont pas nécessairement plus grossières, mais qu'elles ont un indice d'effondrement inférieur, ce qui peut avoir des répercussions sur la résistance interne et donc sur la résistance de la feuille. Les différences entre espèces que cette étude a mises en évidence sont toutefois légères.

Les propriétés de la pâte, ainsi que les modifications apportées par l'augmentation de la teneur en pin, dépendaient du site, mais nous n'avons trouvé aucune corrélation précise avec l'indice du site, peut-être à cause de la petite taille de l'échantillon. Ce lien de dépendance au site souligne tout de même l'importance de bien surveiller la qualité du bois et des copeaux que l'usine de pâte reçoit pour pouvoir adapter rapidement les variables de pro.

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1 Introduction

British Columbia's market kraft and mechanical pulps, produced from interior spruce, pine and fir (SPF) are recognized worldwide as a benchmark for intrinsic strength and quality. The chips used to produce SPF pulp are a residual material from lumber operations. They are produced from the outer slab wood and thus comprise only mature wood. The traditional mixture composition for these chips is about 30% spruce, 65% lodgepole pine and 5% subalpine fir. However, due to the current mountain pine beetle epidemic in B.C. this balance is subjected to climb to a pine content of 80% to 90% as salvage harvesting of currently attacked and dead lodgepole pine stands increases.

Pine is considered the least desirable fibre in SPF mixtures, as it is generally believed to be a higher coarseness fibre and consequently produces a pulp of lower tensile strength. The increasing pine content is expected to negatively impact strength properties of SPF market pulps which could result in a market disadvantage for BC pulp producers. Additionally, the change in chip mixture composition also can lead to associated process difficulties in kraft pulping due to the difference in optimal cooking conditions for the different species.

These issues need to be addressed and a better understanding of problems that can be anticipated with changing chip quality needs to be developed. Guidelines for the use of infested pine beetle wood are needed to ensure that as much as possible of this material is processed, but at the same time market access for BC's pulp manufactures is maintained by preserving a certain standard for market pulp quality even with changing chip supply.

To quantitatively and qualitatively define pulp quality changes with changing chip mixture, statistically defined pilot kraft and thermomechanical pulping experiments were undertaken as part of this study, varying the SPF ratio from 0-100%. To begin with, an evaluation of possibly suitable sampling sites was done by non-destructive sampling of 10 trees at 6 different sites, and subsequent SilviScan analysis for fibre and wood properties of wood cores, determination of extractives content and fibre quality analysis with a fibre quality analyzer (FQA) instrument. Three sites of different site productivity were chosen and trees for the pulping trials were harvested. Only green trees were harvested for this study and no grey stage pine was included. The inclusion of different sites in the pulping trials enables the quantification of site-based variability of SPF mixtures.

After pilot pulping, strength potential of the kraft pulps was determined by PFI mill refining of the pulps and subsequent handsheet testing. The influence of mixture component ratio on pulping and handsheet characteristics was evaluated with statistical models using the STATISTICA software package from StatSoft Inc.. Such models allow the prediction of expected changes for certain scenarios regarding the chip mixture composition and thus are a useful tool for the pulp producer. Additionally, fibre characteristics (average as well as population distribution) of kraft and thermomechanical pulping (TMP) fibres were determined. The influence of these fibre characteristics and their variations between sites on pulp properties, and their role in pulp quality changes with mixture composition changes, are discussed. A selected subset of kraft pulp samples was additional refined with an Escher-Wyss laboratory refiner, to preliminarily evaluate the influence of different refining conditions on low consistency refining behaviour of pure species and mixture pulps.

2 Material and Methods

2.1 Design of the Mixture Experiment

The main part of this study was the pilot pulping of pulp mixtures of different S:P:F ratios from different sample sites. Results from the pulping trials were used to obtain models that are able to predict pulp properties for any mixture ratio. Statistical design methods were used for the mixture trials in order to minimize the number of pulping trials needed for model fitting. Such experimental design methods have been used successfully in predicting pulping of chip mixtures (Lanouette et al. 1998).

The experimental design used in this study was a simplex-centroid design augmented with three interior points. The design emphasizes the response to blends containing all three components with non-zero proportions. It is well suited to detect the lack of a lower-order model, particularly if the shape of the surface inside the triangle is different than the shape of the surface along the edges of the triangle. The design consists of three points (100% spruce, 100% lodgepole pine and 100% subalpine fir) representing single-component mixtures. These points build the three vertices of the mixture triangle. It also consists of three binary blends (two-component mixtures) located at the midpoints of the three sides of the triangle. Additionally, it comprises four tertiary blends (three component mixtures) located in the interior of the triangle including the central point in the design. For such a design, up to 3rd order model equations can be used to fit the experimental data.

For the determination of the experimental error and a possible lack of fit of the model equations, four of the mixture design points were replicated. Also, two validation points to verify the adequacy of the fitted model equations were included in the experiments. These two points were chosen to represent the standard mixture used in the industry before the lodgepole pine content increased (30% spruce, 65% pine and 5% fir) and a mixture with very high lodgepole pine content as would be expected in future chip mixture compositions. Figure 1 shows the complete design.

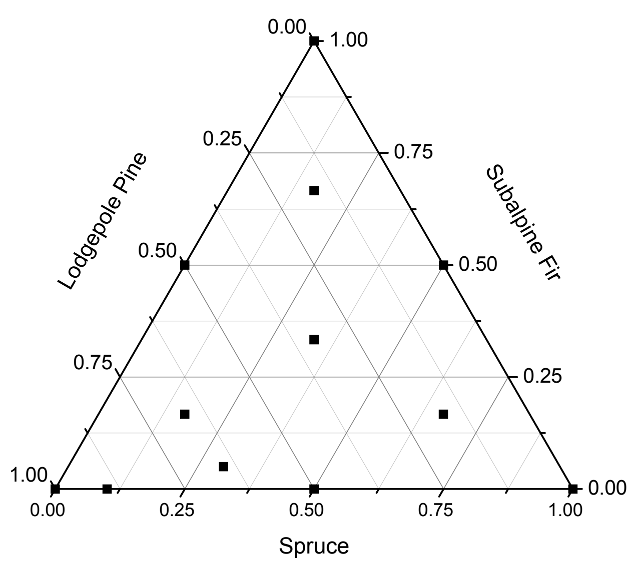

Figure 1. Simplex-centroid mixture design for pulping experiments

2.2 Site and Tree Selection

Initial sample site selection was done using beetle attack history maps (overview flight data), forest stand composition and BEC (biogeoclimatic ecosystem classification) maps. These resources were used to select sites based on stand composition (typical of SPF feedstock), pathenogenic history (all stands had been affected by mountain pine beetle) and stand dynamics (productive capabilities). Potential sites were then checked in the field. Five sample sites were established across the Prince George and Vanderhoof forest districts in British Columbia. Specific coordinates are given in Table 1 below.

Table 1. Locations of SPF sample sites

Site	Latitude North	Longitude West	Elevation (m)
SPF-1	53 40.415	124 24.224	1173
SPF-2	54 15.804	122 47.414	1063
SPF-3	54 00.468	121 48.763	630
SPF-4	53 53.517	124 56.26	1114
SPF-6	53 52.599	122 17.492	747

* Lat./long. data were collected using the WGS_84 coordinate system.

At each site ten trees each of spruce (*Picea glauca* x. *engelmannii*), lodgepole pine (*Pinus contorta* Dougl. Ex Loud. var. *latifolia* Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) (for a total of 30) were marked. All chosen pine trees were beetle-affected at the red attack stage, with trees being dead but not showing any decay. Two, 10-mm increment cores were taken from breast height (1.3 m) through the pith from bark to bark of each tree. Height and diameter were measured for each tree. A biogeoclimatic classification to the site series level was completed for each of the five sites. This determination included soil, vegetation and site data. The BEC classification allowed productivity comparisons of each site by using SIBEC (site index using biogeoclimatic ecosystem classification). Biogeoclimatic ecosystem classification (BEC) was used as a basis for site selection to reflect a range of productivity capabilities in the sample set. Table 2 provides site indices (a measure of potential site productivity based on tree height at 50 years age) for each species at each site.

Table 2. Site indices and biogeoclimatic subzone classification of SPF sample sites

Site	Species	BGC unit	Site Index
SPF-1	Spruce	SBSmc3 (01)	15
SPF-1	Pine	SBSmc3 (01)	18
SPF-1	Fir	SBSmc3 (01)	15
SPF-2	Spruce	SBSmk1 (09/06)	18
SPF-2	Pine	SBSmk1 (09/06)	21
SPF-2	Fir	SBSmk1 (09/06)	15
SPF-3	Spruce	SBSvk1 (02)	15
SPF-3	Pine	SBSvk1 (02)	18
SPF-3	Fir	SBSvk1 (02)	12
SPF-4	Spruce	SBSmc2 (01a)	18
SPF-4	Pine	SBSmc2 (01a)	18
SPF-4	Fir	SBSmc2 (01a)	15
SPF-6	Spruce	SBSwk1(05)	18
SPF-6	Pine	SBSwk1(05)	21
SPF-6	Fir	SBSwk1(06)	15

While there are reasonable differences in productivity between sites, they are not overly prominent. Locating a range of suitable sites was difficult due to chosen criteria for site selection: site composition was supposed to be representative of typical SPF feedstock, and all stands had to be affected by mountain pine beetle. However, spruce and fir generally form forest stands at higher elevations, while the mountain pine beetle thrives in the warmer climate of lower elevations. Only a limited number of sites could thus be identified. Site accessibility was also a problem and further limited the choice.

The sites chosen for the study were sites SPF-1, 2 and 3. SPF-2 was chosen as a high productivity site, because, even though it is at a relatively high elevation, the moist and cool subzone conditions provide good growing conditions. For SPF-1 and SPF-3, productivity numbers do not differ greatly, but subzone characterizations do. SPF-1 is at a higher elevation with moist and cold growing conditions, and shows a transitional nature to the ESSFmv1 subzone (a colder subzone with a shorter growing season). It was thus chosen as a lower productivity site. SPF-3 is at a lower elevation with cool growing conditions, but a drier than mesic site series (02) occurring in a very wet subzone and was thus characterized as a medium productivity site.

Table 3. Density and fibre properties of individual trees selected for harvest and comparison to site averages (site averages are based on 10 sample trees)
S = White spruce, P = Lodgepole pine, B = Subalpine fir

Site	Tree	LWFL [mm]*	Site average LWFL [mm]*	Coarseness [mg/m]*	Site average coarseness [mg/m]*	Density [g/cc]	Site average density [g/cc]
SPF-1	S6	2.55		0.174		0.415	
SPF-1	S10	2.08	2.22	0.170	0.168	0.420	0.400
SPF-1	S5	2.19		0.170		0.431	
SPF-1	P1	2.58		0.199		0.423	
SPF-1	P3	2.46	2.40	0.176	0.187	0.466	0.434
SPF-1	P7	2.54		0.181		0.402	
SPF-1	B2	2.16		0.146		0.340	
SPF-1	B3	2.10	2.22	0.171	0.166	0.439	0.416
SPF-1	B9	2.17		0.179		0.481	
SPF-2	S1	2.48		0.177		0.419	
SPF-2	S2	2.51	2.42	0.164	0.172	0.370	0.386
SPF-2	S3	2.65		0.187		0.360	
SPF-2	P3A	2.50		0.159		0.381	
SPF-2	P5A	2.74	2.63	0.176	0.211	0.346	0.441
SPF-2	P6A	2.33		0.186		0.401	
SPF-2	B2	2.01		0.149		0.368	
SPF-2	B4	2.54	2.31	0.174	0.159	0.388	0.423
SPF-2	B9	2.30		0.158		0.364	
SPF-3	S1	2.94		0.233		0.359	
SPF-3	S3	2.86	2.86	0.199	0.206	0.328	0.371
SPF-3	S10	2.65		0.172		0.450	
SPF-3	P3	2.70		0.209		0.419	
SPF-3	P6	2.37	2.68	0.205	0.187	0.489	0.417
SPF-3	P9	2.68		0.201		0.413	
SPF-3	B2	2.63		0.212		0.395	
SPF-3	B3	2.95	2.62	0.205	0.197	0.404	0.379
SPF-3	B10	2.07		0.143		0.360	

** NB These values are from the 60 to 80 year age class only*

Basic density and fibre properties of the wood cores were determined by SilviScan and Fibre Quality Analyzer (FQA, OpTest Equipment Inc.) analysis. Based on this data, individual trees from the three sites (three trees of each species at each site) were selected for harvest based on fibre length, fibre coarseness and wood density. To minimize in-between tree variation, care was taken to choose trees that were representative for each site. Table 3 shows the fibre and density data for the chosen trees as well as average numbers for the respective site. Fibre coarseness and length (FQA data) for the 60 to 80 year age class of all trees are shown and compared for the different subzones in Appendix A.

2.3 Chip Preparation and Characterization

The selected trees were harvested and transported to the Vancouver laboratory. The trees were debarked and slabbed on a portable woodmizer^{TM} sawmill to separate juvenile from mature wood. Only the mature wood (> 40 years) of each tree was chipped using a 36 inch 10-knife CM&E disc chipper, representing the sawmill residual chip supply of most pulp operations in B.C. Chips of each species from each site were well mixed creating a total of 9 samples.

2.3.1 Kraft Pulping

For kraft pulping, chips were then air-dried to about 90% solid content, classified by the method described by Hatton (1979) and later screened in a Wennberg chip classifier to obtain accept chips in the thickness range of 2 - 6 mm. Accept chips were well mixed before representative samples were taken for determining chip density and for exploratory kraft pulping. The following chip mixtures were prepared on oven-dried wood weight basis according to the design of the mixture experiment (Table 4). Chip basic density was determined by PAPTAC (Pulp and Paper Technical Association of Canada) method A.8P. Loose chip packing density was determined using a method described by Hatton (1979). See Appendix B for chip classification data as well as chip basic and packing density data.

2.3.2 Thermomechanical Pulping

For thermomechanical pulping (TMP), each of the nine chip samples (three species x three sites) were screened on a Burnaby Machinery and Mill Equipment Ltd. two-deck laboratory chip classifier to remove oversize (>32 mm) and fine (<8 mm) material. The solids contents of the chip samples for white spruce, lodgepole pine, and subalpine fir were in the range of 48.3%-65.4%, 67.3%-73.4%, and 49.8%-55.7% wet wood basis, respectively. Chip mixtures in the same proportions as for kraft pulping (Table 4) were prepared and used for thermomechanical pulping.

Table 4. Chip mixture composition for kraft and thermomechancial pulping trials

Sample	Species Composition			Sample	Species Composition			Sample	Species Composition		
SPF1 Blend	S (%)	P (%)	F (%)	SPF2 Blend	S (%)	P (%)	F (%)	SPF3 Blend	S (%)	P (%)	F (%)
1	100	0	0	1	100	0	0	1	100	0	0
2	0	100	0	2	0	100	0	2	0	100	0
3	0	0	100	3	0	0	100	3	0	0	100
4	50	50	0	4	50	50	0	4	50	50	0
5	50	0	50	5	50	0	50	5	50	0	50
6	0	50	50	6	0	50	50	6	0	50	50
7	33.3	33.3	33.3	7	33.3	33.3	33.3	7	33.3	33.3	33.3
8	66.7	16.7	16.7	8	66.7	16.7	16.7	8	66.7	16.7	16.7
9	16.7	66.7	16.7	9	16.7	66.7	16.7	9	16.7	66.7	16.7
10	16.7	16.7	66.7	10	16.7	16.7	66.7	10	16.7	16.7	66.7
11	100	0	0	11	33.3	33.3	33.3	11	50	50	0
12	0	100	0	12	66.7	16.7	16.7	12	50	0	50
13	0	0	100	13	16.7	66.7	16.7	13	0	50	50
14	33.3	33.3	33.3	14	16.7	16.7	66.7	14	33.3	33.3	33.3
15	10	90	0	15	10	90	0	15	10	90	0
16	30	65	5	16	30	65	5	16	30	65	5

2.4 Pulping and Physical Testing

All pulping experiments and testing for physical properties of the pulp were conducted on chip and pulp samples selected at random from the bulk sample.

2.4.1 Kraft Pulping

2.4.1.1 First series and second series pulping

Three representative aliquots of accept chips (2 – 6 mm) from each of the nine samples were kraft cooked in bombs (50 gram, oven-dried charge) within a B-K micro-digester assembly (Keays and Bagley 1970).

The cooking conditions were as follows:

Time to maximum temperature	: 135 min
Maximum cooking temperature	: 170 °C
Effective alkali, % oven-dried weight of wood	: 16
% Sulphidity	: 25
Liquid to wood ratio	: 4.5:1
H-factor	: 900 - 1800

All the pulps produced were washed, oven dried and weighed to determine pulp yield. Pulp kappa number and black liquor residual effective alkali were determined by standard procedures. From these results the optimum cooking conditions required to produce kraft pulps at 30 kappa number were estimated by fitting regression lines through each set of data ($R^2 \geq 0.95$). Once the H-factors required for pulping of individual species were determined, the average H-factor was calculated and used for all subsequent pulping of chip mixture blends.

Based on the average H-factor of 1420, larger quantities of unbleached kraft pulps from each of the 16 blends were produced by pulping four mixtures at a time in a *28L Weverk* laboratory digester. A total of 12 cooks were done on the chip blends from these three sites. The pulps produced were disintegrated, washed, and screened through a 0.20 mm slot vibrating screen plate. Also, fibre length and coarseness of the pulp fibres were analyzed using the Fibre Quality Analyzer (FQA) instrument.

2.4.1.2 PFI mill refining

Four point beating curves were constructed using PFI mill runs of 0, 3000, 6,000 and 12,000 revolutions according to PAPTAC standard C7 for each of the pulps prepared. Canadian standard freeness was determined for each point according to PAPTAC standard C1. Handsheets were formed and tested for physical and optical properties using PAPTAC standard methods.

2.4.1.3 Low consistency Escher-Wyss refining

Selected samples were subjected to low consistency refining using the Escher-Wyss laboratory refiner. While PFI mill refining is an easy and cost-effective way to compare fibre development of different pulps, it refines at very low intensity and very high energy compared to industrial refiners. At similar freeness, it will usually produce a larger increase in tensile strength than industrial refiners, while at the same energy it will produce a smaller freeness drop and smaller tensile strength increase. The refining action of the Escher-Wyss laboratory refiner resembles industrial refiners more closely than the PFI mill, and was therefore used in this study for selected samples to evaluate whether changes in SPF mixture composition will impact low consistency refining results. The Escher-Wyss refiner is a small conical refiner in a re-circulating flow loop, with separate control of specific refining energy (SRE) and specific edge load SEL (refining intensity).

Five samples, all from the same site, were selected for Escher-Wyss refining, including:

100% spruce (SPF-2)
100% pine (SPF-2)
100% fir (SPF-2)
30/65/5 S/P/F (SPF-2)
10/90/0 S/P/F (SPF-2)

The refining conditions were set as follows:

Escher-Wyss cone set	M6/0.7/16
Refiner speed [rpm]	1000
Refining consistency [%]	3.0
Time in repulper [s]	60
Cutting edge length [km/s]	0.522
Target SEL [J/m]	1 and 2.5
Target SRE [kWh/t]	0/50/100/150/200/250

This amounts to 10 separate refining runs (five pulps at each two SEL's). For each refining run, a target motor output is calculated from target SEL and cutting edge length. Motor output is then controlled by automated adjustment of the refiner gap. One litre samples amounting to 30 g OD pulp are drawn at time intervals according to the desired specific refining energy. These samples are used for freeness determination, handsheet testing and FQA analysis.

2.4.2 Thermomechanical Pulping

In first-stage refining a 30.5 cm Sunds Defibrator TMP 300 single-disc laboratory refiner was used. A Labview 6.02 PC system was used to control and/or monitor the refining variables. Pertinent first-stage refining conditions are shown below:

Plates	rotor, No. 3809 modified stator, No. 3804 modified
Preheater pressure	152 kPa
Refiner housing pressure	179-193 kPa
Chip pre-steaming time	10 min (atmospheric pressure)
Pre-heater residence time	10 min
Prex compression ratio	3:1
Refining consistency	25% to 31% od pulp (cyclone exit)
Refining rate	0.36 to 0.46 kg od wood/min

The high freeness first-pass pulps were given one to three further passes in a 30.5 cm Sprout Waldron open-discharge laboratory refiner equipped with type D2A507 plates at 15% to 17% refining consistency. Pulps at three different energy/freeness levels were produced from each of the 48 different chip furnishes in the Canadian standard freeness range from 62 to 251 ml CSF.

After latency removal, each of the 144 pulps (48 blends x 3 freeness levels) was screened on a 6-cut laboratory flat screen and screen rejects were determined. Bauer-McNett fibre classifications were determined on screened pulps and average fibre lengths of screened pulps were determined with the FQA instrument. Handsheets were prepared with white water recirculation to minimize the loss of fines and tested for structural, mechanical and optical properties using PAPTAC standard methods. Handsheet roughness was measured by a Sheffield instrument and the values obtained are expressed in Sheffield Units (SU).

2.5 X-ray Diffraction

Crystallinity and crystallite size of ground pine samples (using 1-mm mesh on Wiley-Thomas mill) were determined by X-ray diffraction, using the D8 Advance diffractometer (Bruker-AXS). DiffracPlus Topas software (Bruker-AXS), which uses the Rietveld method of refinement, was used to fit a cellulose profile to the diffraction pattern, where the total diffracted X-ray intensity is made up of diffracted X-ray intensity from both the crystalline and amorphous regions. The degree of crystallinity was determined using a method to deconvolute the diffraction pattern into crystalline and amorphous areas that is currently developed at PAPRICAN. This is a more accurate approach than the widely used empirical method of Segal et al. (1959) that determines the crystallinity index from the difference in the intensities of the 002 interference and amorphous scatter at $2\theta=18°$.

2.6 Analytical Method

Pulp quality and handsheet properties (for kraft pulps obtained after PFI mill refining) were described with mixture models.

2.6.1 Extrapolation of Data

In order to facilitate data analysis and discussion, all raw data for pulp and handsheet properties were standardized by interpolation or extrapolation to a freeness of 300 mL CSF for PFI mill-refined kraft pulps and to a freeness of 100 mL CSF as well as a specific refining energy of 10.0 MJ/kg for TMP pulps (see Appendix C).

2.6.2 Model Fitting and Analysis

The first step in the analysis was to identify a suitable model that describes the pulping data and physical properties as a function of the independent variables. The independent variables are the fractions of each species used in the chip blends. The experimental design with 10 independent runs permits estimation of a cubic model, however lower order models might also adequately describe the data. Thus, an ANOVA analysis with sequential fit of increasingly higher order models was used to identify an adequate model. In general, the lowest order model that proved to be significant was chosen. Higher order models were considered only in cases where a subsequent evaluation of the simplest model proved unsatisfactory, or where the use of a higher order model improved the model fit significantly.

After a model was chosen, residuals were examined to verify the validity of the model. Data were scanned for outliers, in particular in cases where no significant model was found. As a last step, the models were checked against the validation points.

A detailed description of the process of fitting and validating models is described in Appendix D.

The resulting models were then used to discuss the behaviour of pulping and paper physical properties as a function of species fraction in chip mixtures.

3 Results and Discussion

3.1 Wood and Fibre Property Measurements

In this section the wood and fibre properties of the pure species are discussed. Fibre properties are closely linked to pulp quality and thus are an indicator for the performance that can be expected from the pure species pulps, which also controls the performance of the SPF mixtures.

Several measurements of wood and fibre properties were done. Wood fibre properties were measured with the SilviScan system using the cores that were obtained during sampling. The cores were also used for further FQA measurements of the wood using a maceration technique, as well as for extractives analysis. After pulping, fibre properties were again measured with the FQA. The fibre length distributions of TMP pulps were determined with a BauerMcNett classifier. X-ray diffraction was used to further analyze pine samples on a more fundamental level.

3.1.1 Extractives measurements

Total extractives content was determined for wood cores by acetone extraction using a modified Tappi standard (Tappi method T280 pm-99). The relative content of extractives is shown in Figure 2. For all species, there are noticeable differences in extractives content for trees from different sites, but they are most pronounced for pine. Also, extractives content for pine is always larger than for fir (except at site 4), which again is larger than for spruce. Differences in extractives content between pine on the one hand and spruce and fir on the other are largest at site 3, and smallest at site 1. Pine extractives at sites 2, 3 and 6 are larger than at site 1 and 4. The observed extractives level for lodgepole pine are higher than the range of 1% to 4% reported elsewhere for sound lodgepole pine (Kim 1988, Shrimpton 1973, Lieu et al. 1979), which is indicative of early beetle infestation. High extractives content can have a detrimental influence on mechanical pulping, kraft pulp yield, effluent treatment, the kraft chemical recovery process and on final pulp and paper quality for both kraft and mechanical processes.

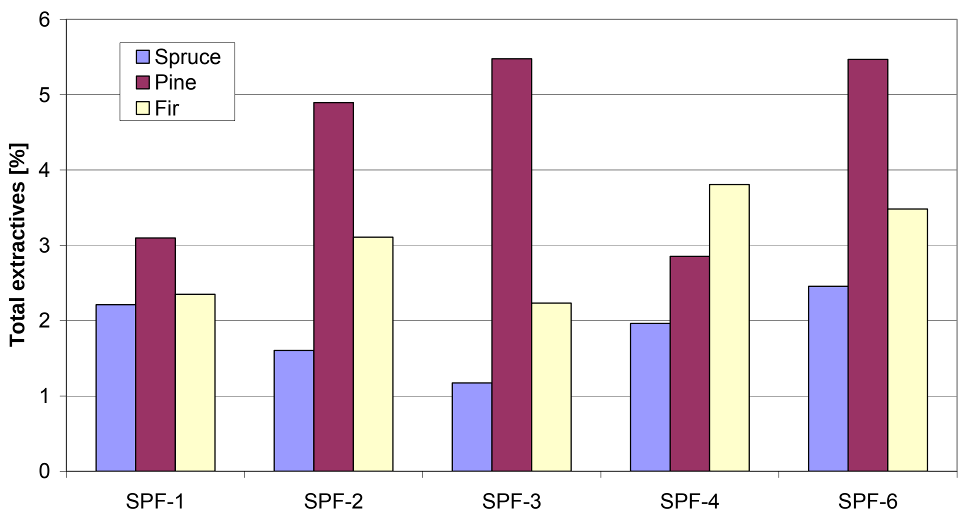

Figure 2. Total extractives content of wood cores (modified Tappi method T280 pm-99)

3.1.2 SilviScan Measurements

The SilviScan technology uses a variety of measurement techniques to directly measure fibre diameter, wood density and microfibril angle from wood cores. Cell wall thickness and coarseness are calculated assuming a constant density of the cell wall of 1500 kg/m^3. SilviScan is the most cost effective means of rapidly determining pith to bark variations in these properties at very high resolution. Considering the large between-tree variations in wood and fibre properties within sample sites, the SilviScan measurements were an invaluable help in choosing representative sample trees for harvest.

SilviScan results can be averaged and presented for the whole core. However, data can also be presented for certain age classes separately, based on growth ring allocation that is possible using the density profiles. Here, average results for age class 60 to 80 representing mature wood are reported as from a pulping perspective, the mature wood part of the trees is of most concern (SPF chips in general are made from mature wood). Averages and 95% confidence intervals of the SilviScan measurements on wood cores obtained during site sampling are shown for all five sites (Figure 3 to Figure 8), but the discussion will mainly focus on the three sites that were chosen for this study, SPF-1, 2 and 3.

The fibre diameter is measured in radial and tangential direction, assuming a rectangular shape of the fibre. From this, an average fibre diameter based on a circular shape was calculated. Diameters of spruce and fir fibres are relatively similar (Figure 3). At site 1 and 2, pine diameter is also comparable to the other two species, but at site 4 and particularly at site 3 pine has a smaller diameter. Overall, there are also differences between sites, with fibres from site 1 and 2 having on average smaller diameters than at the other sites. Note that for fir at site 6 no mature wood data is available, as most fir trees harvested at this site were younger than 60 years.

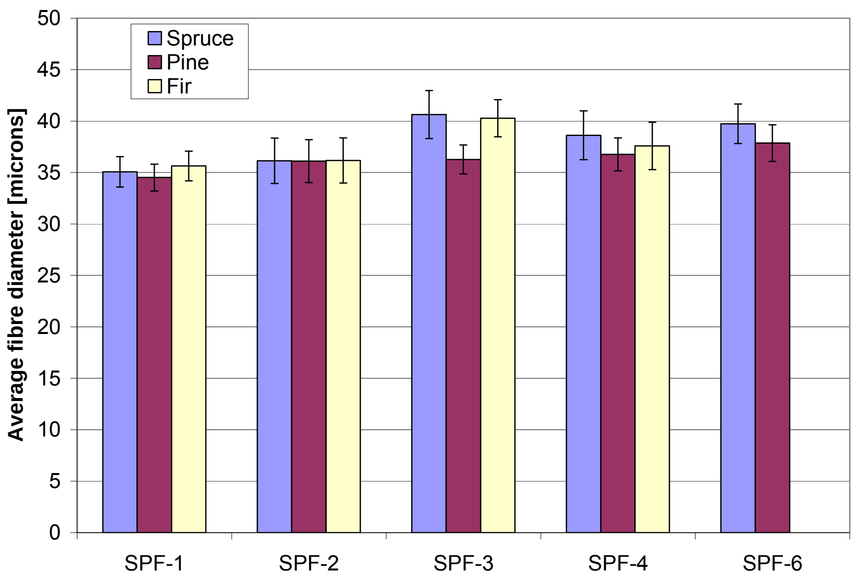

Figure 3. Average diameter D of wood fibres (60 to 80 years) measured by SilviScan. The error bars represent the 95% confidence interval.

Wood density (Figure 4) differs noticeably between species and sites. Pine always has the highest density, while density of fir and spruce are lower and quite similar. For the first three sites, wood densities for all species are highest at site 1, slightly lower at site 2 and lowest at site 3. Differences between these three sites, however. are relatively small when compared to sites 4 and 6, which show a noticeably lower wood density than the first three sites.

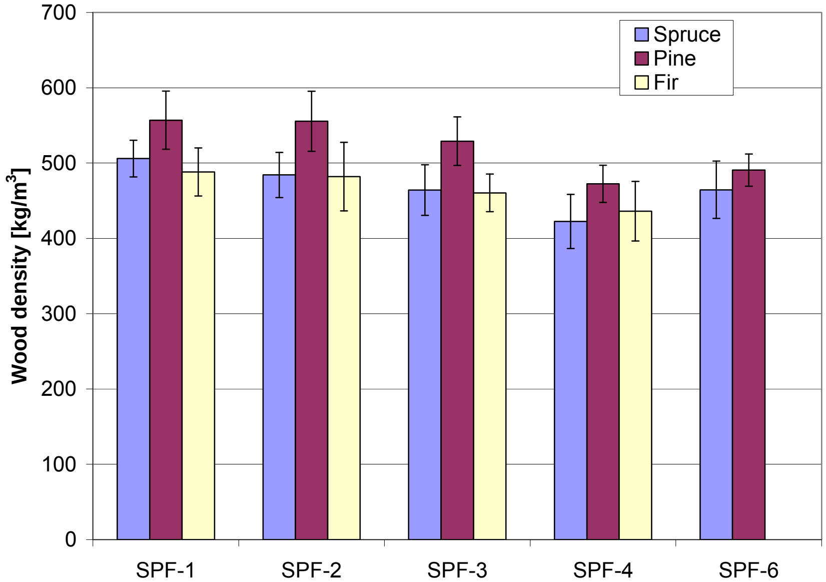

Figure 4. Average wood density (wet basis) of tree cores (60 to 80 years) measured by SilviScan

Wood density can be compared to site characterization or site index as given in Table 2, but site productivity does not necessarily correlate with wood density. According to the site indices, sites 2, 4 and 6 are higher productivity sites than site 1 and 3, but this is not reflected in the wood densities. However, one also needs to consider that variations in density profiles between different trees from one site are large and the sample size thus might have been too small to reveal such correlations. An example of the variations in wood density profiles for three pine tries from site 1 is shown in Figure 5.

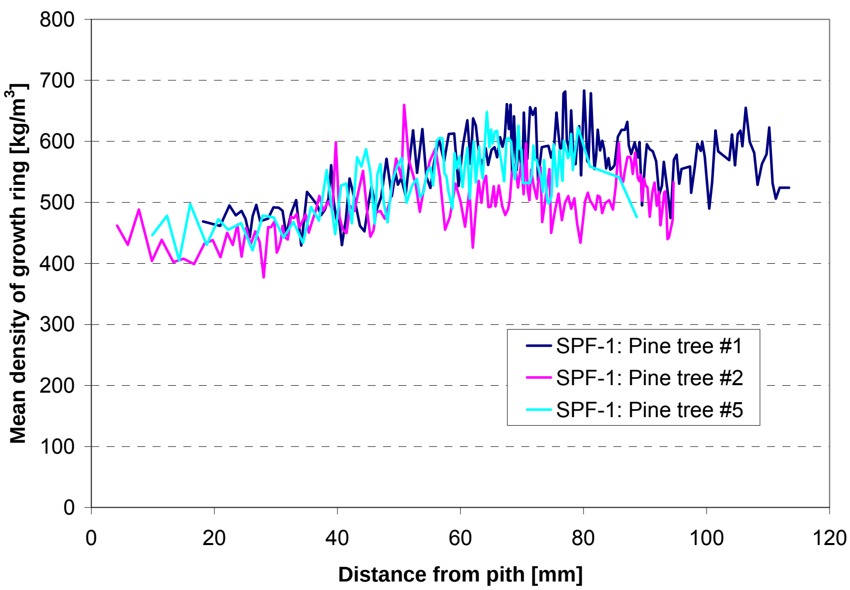

Figure 5. Variations in wood density profiles of wood cores for three pine trees from site SPF-1. Wood density is averaged for every growth ring.

From density and fibre diameter, wall thickness (Figure 6) and coarseness (Figure 7) are calculated. Pine is generally known as a coarse fibre and this is reflected in the coarseness values at site 1, 2 and 5, where coarseness of pine is higher than of spruce and fir. However, site 3 stands out as a high coarseness site for spruce and fir (and site 6 as a high coarseness site for spruce) and thus coarseness of pine at these two sites is lower than that of the other two species. Wall thickness at all sites is relatively similar for spruce and fir, but pine fibres have thicker walls. The difference in wall thickness between pine on the one hand and spruce and fir on the other is largest at site 1 and 2. Site 1 and 2 also show a similar wall thickness distribution for the three species, while at site 3 wall thickness on average is higher and at site 4 it is lower.

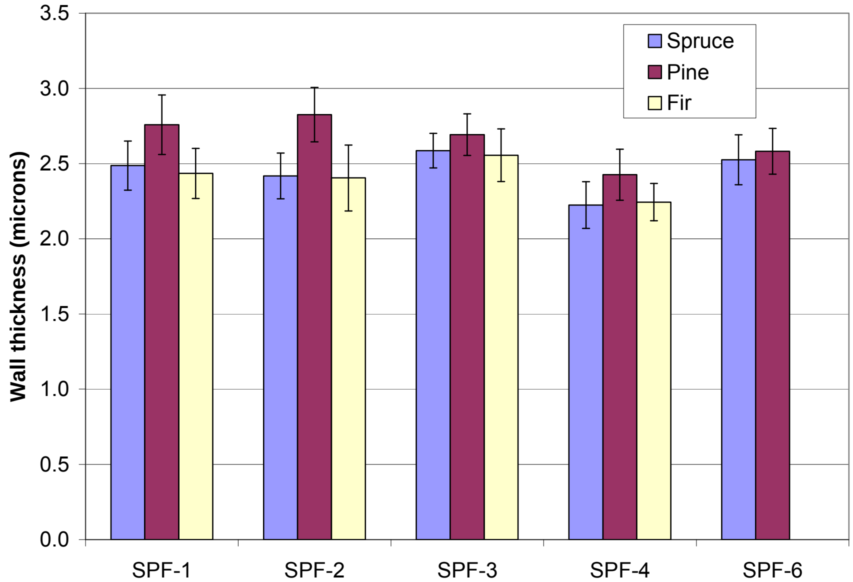

Figure 6. Average wall thickness of wood fibres (age class 60 to 80 years) measured by SilviScan

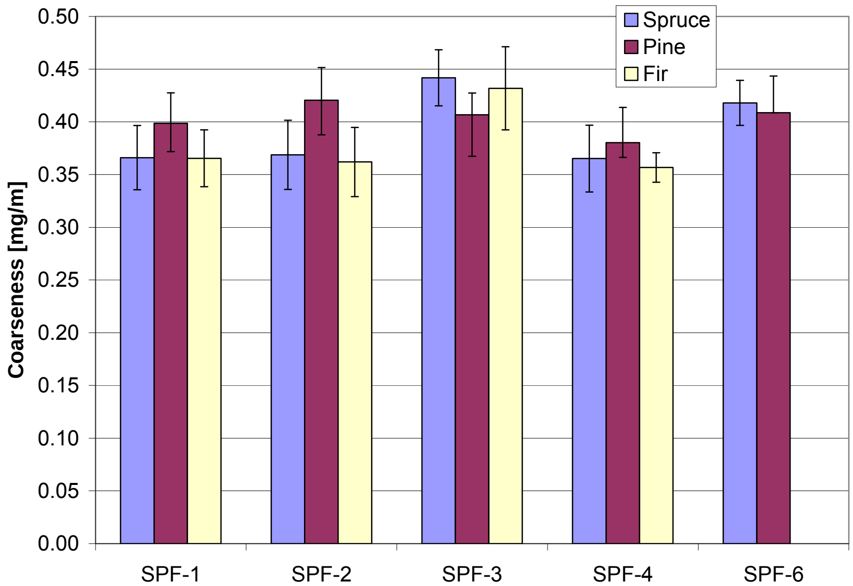

Figure 7. Average coarseness of wood fibres (age class 60 to 80 years) measured by SilviScan

Lastly, the measured microfibril angle (MFA), (Figure 8) at most sites is lowest for pine, and for pine also varies little between different sites. The microfibril angle of spruce can be larger, but a noticeable difference of 3° is seen only at site 1. Fir shows the largest variations in MFA between different sites. Particularly at site 2, the average for fir is about 7 degrees higher than for spruce and pine, however the confidence interval here is large too. The microfibril angle in general is inversely correlated to wood density and the ratio of density/MFA is a good estimator of solid wood longitudinal stiffness, modulus of elasticity (MOE) (Evans et al. 1999).

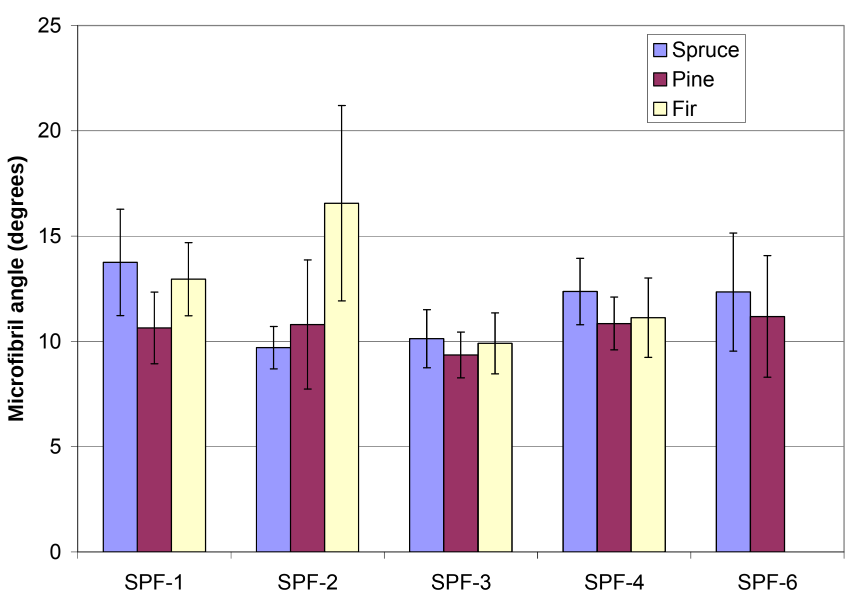

Figure 8. Average microfibril angle of wood fibres (age class 60 to 80 years) measured by SilviScan

Fibre wall thickness, diameter and microfibril angle are important parameters in controlling fibre collapse and fibre conformability. A fibre with a thin wall, large diameter and small fibril angle will be the easiest to collapse, which is important for fibre bonding during papermaking. Collapse behaviour can be described by collapse index *CI* as proposed by Jang and Seth (1998):

$$CI = 1 - \exp\left(-\alpha(\varepsilon, F)G^{\beta}\right) \qquad \text{(Equ. 1)}$$

with $\beta \cong 2$ and G a geometrical factor:

$$G = \frac{LP}{2\pi T} \qquad \text{(Equ. 2)}$$

with *LP* the lumen perimeter and *T* the wall thickness. Factor α depends on collapse force and mechanical properties of the fibre wall. Larger *CI* indicates easier collapse, thus large *G* and *α* are beneficial for fibre conformability. The factor *α* depends on microfibril angle among others and will decrease with increasing MFA (Jang et al. 2002). *G* can be calculated from the SilviScan measurements (with *LP = D-2*T*) and is tabulated in Table 5.

Table 5. Ratio of lumen diameter to wall thickness for wood fibres as a measure for expected fibre conformability

	$G = (LP/2\pi T)$		
	Spruce	Pine	Fir
SPF-1	12.1	10.5	12.6
SPF-2	12.9	10.8	13.0
SPF-3	13.7	11.5	13.8
SPF-4	15.4	13.2	14.8
SPF-6	13.7	12.7	N/A

Based on only the geometrical factor *G* for conformability, spruce and fir fibres are expected to have a higher collapse index than pine (Table 5), due to their thinner walls. Pine fibres have thicker walls than the other two fibres and thus can be expected to conform less well. Larger fibre diameters for spruce and fir at site 3 and 4 also add to the superior conformability. Differences in MFA are small and thus likely will not change this ranking of expected collapse index, except maybe at site 2 where the large MFA of fir will decrease the conformability of fir compared to spruce and pine, and at site 1 where the smaller MFA of pine will improve the conformability of pine relative to spruce and fir.

Note that while fibre coarseness is widely used to describe collapse behaviour, it is an indirect measure that depends on density, fibre diameter and wall thickness. While in many cases a low coarseness fibre shows superior conformability, coarseness is not always the best measure to predict fibre conformability. An example is pine at site 3 and also 6, for which conformability according to *CI* is expected to be inferior compared to spruce and pine, even though the coarseness of pine at these sites is lower. Thus, detailed knowledge of fibre geometry is a better predictor for fibre conformability than coarseness alone.

Also note that while fibre properties between different sites differ, there is no obvious correlation with site productivity as measured by site index.

3.1.3 Fibre Quality Analysis and Density Analysis of Wood Cores

Additionally to the SilviScan measurements, a FQA analysis of the wood cores (by age classes) was conducted to determine coarseness and average fibre length. The FQA analysis is done on fibres obtained from the wood cores using a maceration procedure (with a maceration solution of acetic acid and hydrogen peroxide). Also, wood density was calculated for the wood cores by estimating wood core volume and determining core weight. Coarseness and density results can be compared to SilviScan results.

From the FQA analysis, there is no clear picture of what species has the longest fibres (Figure 9). At site 1 and 2, pine fibres are longest followed by spruce, but at site 3 this is reversed. Fir at all sites has the shortest fibers. On average, fibres are longest at site 3, and still slightly longer at site 2 than at site 1. The FQA analysis results shown here are for age rings of 60-80 years.

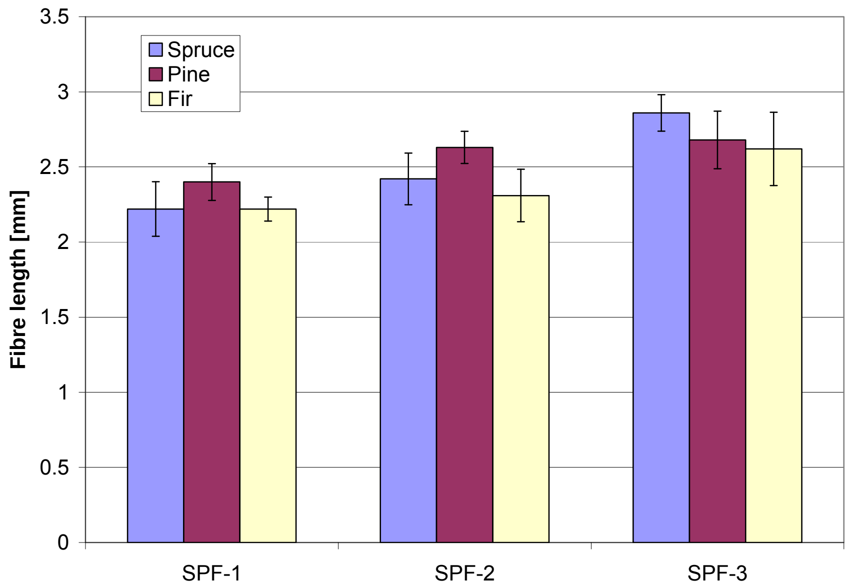

Figure 9. Length weighted average fibre length for wood cores (60 to 80 years) from FQA (error bars show 95% confidence interval)

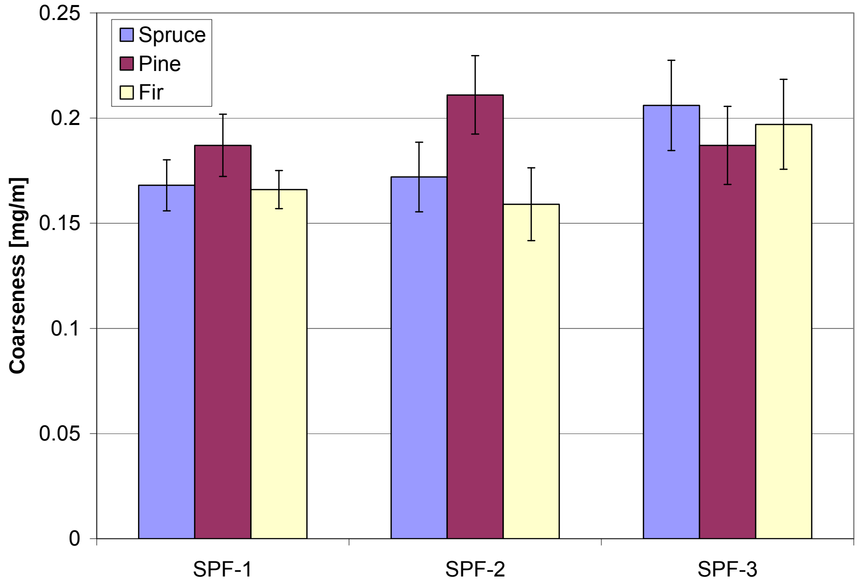

Figure 10. Average fibre coarseness for wood cores (60 to 80 years) from FQA

Comparing coarseness values determined by FQA analysis (Figure 10) to SilviScan measurements, the coarseness distribution between different species for all sites agree very well for the two measurements techniques (even though absolute values are quite different, but this is expected given the two very different measurement principles and considering the fact that for FQA measurements the wood is cooked while the SilviScan analysis is done on solid wood). As before, the difference in coarseness between pine on the one hand and spruce and fir on the other is largest at site 2, and at site 3 pine fibres unexpectedly are less coarse than fibres of the other two species.

The estimated wood densities can also be compared to SilviScan measurements (Figure 11), taking into account though, that the wood densities of wood cores given below are for the whole core, thus including juvenile wood, and also that they are on an oven-dry basis (SilviScan measurements are done on conditioned wood cores). To compare absolute numbers, SilviScan results are thus averaged for the whole wood core as well and corrected to about 80%, which adjusts for the moisture content of the wood cores after conditioning. For spruce and fir, the estimated wood core densities agree relatively well with SilviScan measurements (except for fir at site 2, but the confidence interval here is large). For pine, differences are somewhat larger, with the SilviScan measurements being lower than the wood core data. Overall, both measurement methods return wood densities that at all sites are higher for pine than for spruce and fir.

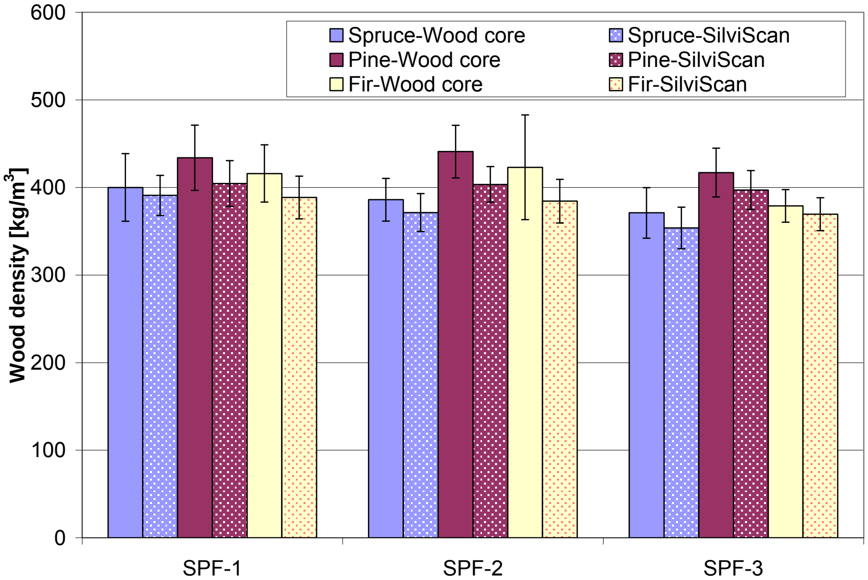

Figure 11. Average wood density of wood cores estimated from weight and volume and comparison to SilviScan measurements

3.1.4 Fibre Quality Analysis of Kraft Pulp Fibres

After kraft pulping, the FQA analysis was repeated to determine average fibre length, coarseness and diameter, as well as distributions of fibre length and diameter. During the kraft pulping process, lignin, and to a certain extent hemicelluloses, are dissolved from the cell wall and thus fibre characteristics change. A comparison of wood fibre data measured before and after pulping indicates how well pulp fibre quality can be predicted from wood measurements.

Comparing the FQA results for length weighted fibre length of kraft pulp fibres (Figure 12) to wood fibre length, only small changes are seen in the relative differences for fibre lengths between different sites and different species (absolute numbers should not be compared because with FQA analysis of wood cores, the cores are cut up, resulting in fibres being cut and thus there is a smaller average fibre length, while in kraft pulping no fibres are cut). At site 1 and 3, the ranking of fibre length of different species is similar to what was seen for wood fibres, only at site 2 the fibre length of spruce fibres exceeds the fibre length of pine for the kraft pulp, but not so for the wood fibres.

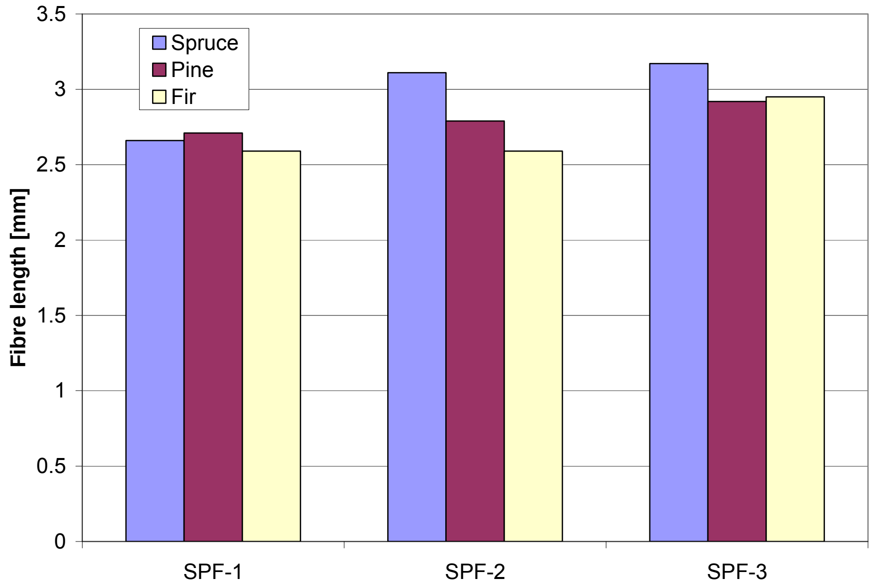

Figure 12. Length weighted average fibre length of kraft pulp fibres (FQA)

Results of coarseness determination for kraft pulp fibres and wood fibres differ (Figure 13). For kraft fibres, coarseness of spruce fibres exceeds the coarseness of pine and fir fibres at all sites, while pine and fir coarseness are relatively similar. For wood fibres as per wood core FQA or SilviScan, coarseness of pine was highest except at site 3. When comparing absolute numbers for coarseness from SilviScan measurements for wood fibres and from FQA analysis of kraft fibres, the coarseness of wood fibres decreases significantly during kraft pulping, due to the lignin and also hemicelluloses that are dissolved from the cell walls. The absolute reduction in coarseness for fir and particularly for pine is, however, higher than for spruce, which agrees with pulp yield numbers which are higher for spruce, followed by fir and pine. Scallan and Green (1975) have shown that reduction in coarseness during kraft pulping is almost proportional to yield loss.

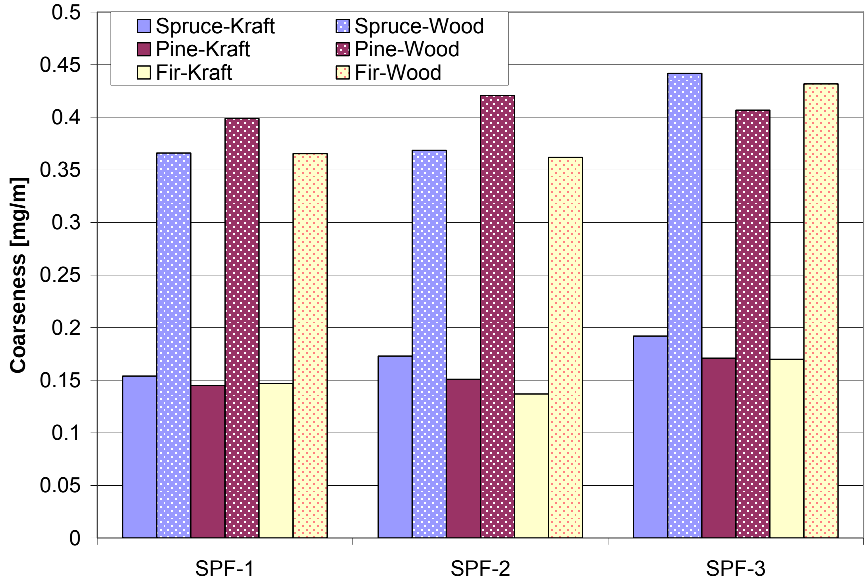

Figure 13. Average coarseness of kraft pulp fibres (FQA) and comparison to wood fibres (SilviScan)

The diameter measured with the FQA for kraft fibres is compared to SilviScan measurements on the wood core (Figure 14). Absolute numbers decrease, but the absolute reduction depends on species and site, due to different amounts of lignin and hemicelluloses being dissolved from the wall. After kraft pulping, spruce fibres have the largest diameter at all sites while pine fibres have the smallest.

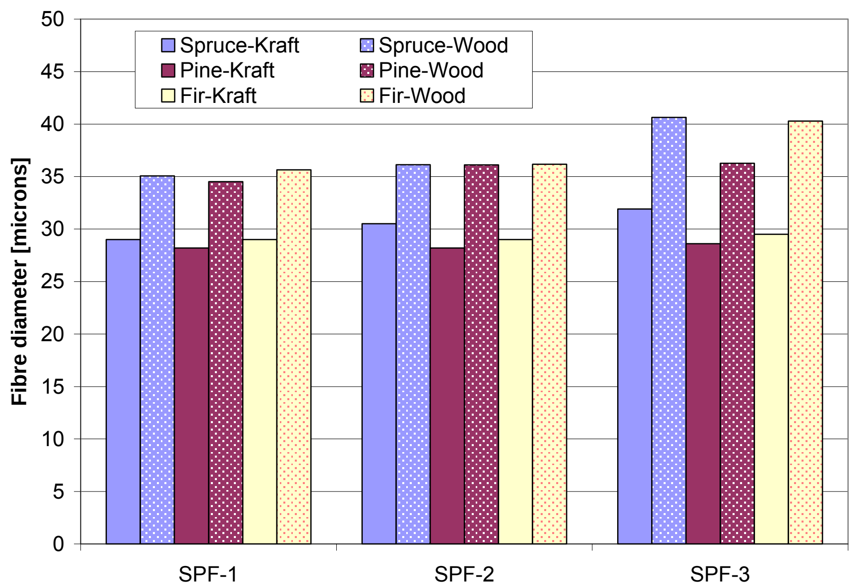

Figure 14. Average fibre diameter of kraft pulp fibres (FQA) and comparison to wood fibres (SilviScan)

Besides average fibre length and diameter (width), the FQA results were also evaluated for length and width distribution. For fibre length distribution, pine shows a very similar distribution for all three samples independent of the site, however for fir and spruce the distribution differs with site. For fir, the distribution at site 3 is slightly shifted to longer fibres compared to site 1 and 2. For spruce, at site 1 the distribution is very markedly shifted to shorter fibre fractions as shown in Figure 15 (see Appendix E for the remaining fibre length and width distribution profiles). This agrees with the average fibre length of fir being longer at site 3 than at site 1 or 2 and for spruce being shorter at site 1 compared to site 2 and 3. It also means that at least for the three sites that were chosen, there is a larger variation in average fibre length and also fibre length distribution for particularly spruce fibres, and also fir fibres than for pine fibres.

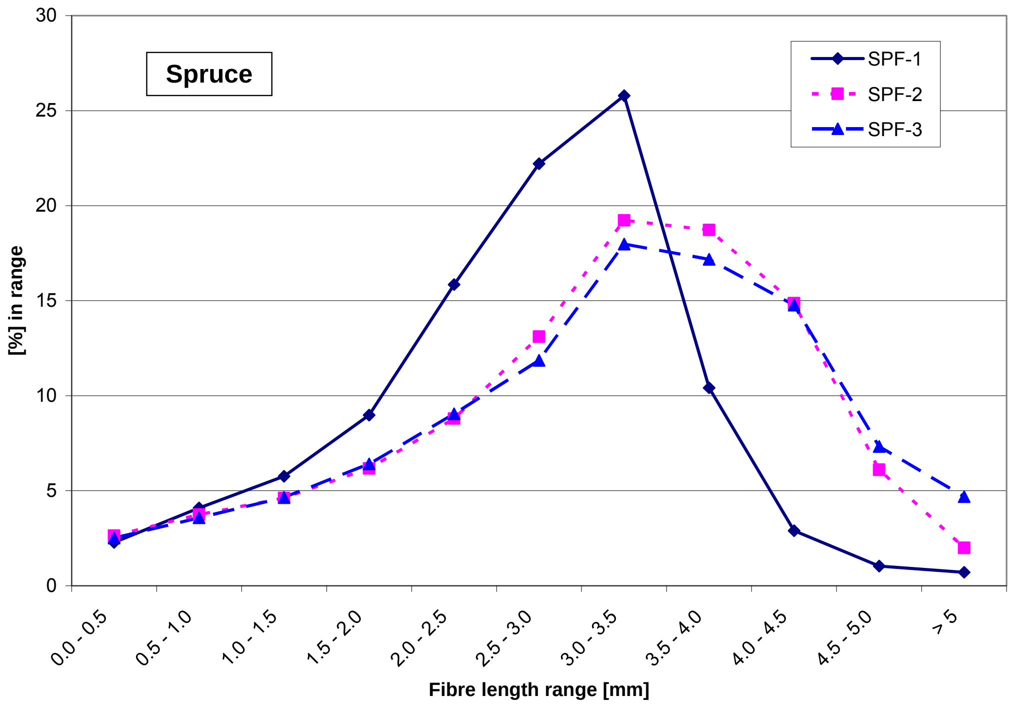

Figure 15. Fibre length distribution of spruce kraft pulp fibres

The fibre width profiles are quite similar for all species when comparing different sites. Only for spruce there are small differences for the larger fibre width categories. Again, this means a somewhat higher overall variability in fibre width and width distribution for spruce (for the chosen three sites).

The fibre distribution profiles from the three sites can be averaged for each species (also see Appendix E). The average fibre distributions for all three species are quite similar, the main difference lies in the amount of possible variation (keeping in mind that the sample size of three sites is rather small). Fibre distributions, in addition to average fibre length and width, give a better picture of expected fibre behaviour than averages alone. Two pulps with the same average fibre length can still behave very differently in papermaking if one has a very wide and the other a very narrow fibre length or width distribution. However, for the three species in this study, there are no significant differences in distributions. While the larger fibre profile variability of spruce can result in a slightly larger variation in pulp quality compared to the other two species, the variability is still low compared to competitor pulps. The low variability in pulp quality is a key attribute of B.C.'s SPF pulps and the expected higher pine content does not seem to be detrimental.

As discussed before, coarseness is not necessarily the best measure for fibre conformability. Wall thickness together with fibre diameter is the better measure, but wall thickness is not known from the FQA analysis. Scallan and Green (1975) found that the reduction in cell wall thickness of softwood fibres during kraft pulping is proportional to yield loss and independent of wood species. They report results for cell wall thickness of oven-dry kraft fibres before and after pulping. We assume that the linear relationship they present also holds for wet fibres. Using this relationship and the cell wall thicknesses measured by SilviScan, we estimate fibre wall thickness after kraft pulping (Table 6).

Table 6. Estimated average wall thickness for kraft pulp fibres

	Fibre wall thickness [μm]		
	Spruce	Pine	Fir
SPF-1	1.4	1.5	1.4
SPF-2	1.4	1.6	1.4
SPF-3	1.5	1.5	1.5

According to these estimates, the fibre wall thickness of kraft fibres is about the same for spruce and for fir, and cell wall thickness of pine might be slightly higher. Differences overall are, however, smaller than for wood fibres.

As fibre diameters are on average larger for spruce than for pine and fir, and while wall thickness is about the same for spruce and fir but larger for pine, it can be concluded that pine fibres are still less conformable than spruce fibres (even though the coarseness of spruce fibres is slightly higher), and fir fibres might range in between. This can be confirmed using the collapse index.

Fibre conformability is compared by calculating the geometrical index *G* of the collapse index as well as quantifying the influence of fibril angle, which for kraft fibres can be directly calculated as shown by Jang (2001). Equation 1 can be rewritten as

$$CI = \left(\frac{\mu F}{E_T}\right)^{\lambda} G^{\beta} \qquad \text{(Equ. 3)}$$

λ and β are approximately equal to 2, μ is a constant and *F* is the collapse force which for comparison purposes is assumed constant. Collapse index is, thus, proportional to G/E_T. E_T is related to MFA and the principal compliance constants of the wall. For a wet fibre wall:

$$E_T(\Theta) = \frac{1 - 4\sin^2 \cdot \Theta \cos^2 \Theta \left(1 - S_{11}/S_{66}\right)}{S_{11} \cdot \cos^4 \Theta} \qquad \text{(Equ. 4)}$$

with Θ the MFA. The relative dependence of E_T, thus is related only to MFA and the ratio of S_{11}/S_{66} (set to 0.74 for softwood kraft at kappa 30, see Page et al. 1977). Numbers for samples of this study are given below (Table 7) together with average numbers estimated for southern pine and Scandinavian spruce pulp for comparison.

Table 7. Collapse index for kraft pulp fibres of this study and comparison to other pulps

	Spruce SPF-1	SPF-2	SPF-3	Pine SPF-1	SPF-2	SPF-3	Fir SPF-1	SPF-2	SPF-3	Scand. pulps	Southern Pine
G	9.8	10.5	10.2	8.9	8.5	9.3	10.0	10.3	9.7	4.3	4.3
MFA	14.0	13.2	14.1	13.6	15.7	15.6	17.7	20.3	13.6	14*	14.1
G/E_T	9.7	10.4	10.5	9.4	8.6	9.0	9.4	9.3	9.6	4.0	4.0

* Fibre angle for Scandinavian pulps was not measured, for comparison purposes it was assumed to be in the same range as B.C. pulps (14º)

Collapse index (as measured by G/E_T) indeed is largest for spruce, followed by fir and pine, however, differences are very small and thus the differences in resulting paper strength properties based on different bonding potentials should also be small. Spruce fibres at site 2 and 3 are slightly longer though as well, which also contributes to paper strength. The differences between B.C. species are particularly small when compared to Scandinavian pulp (mostly spruce) and southern pine. Both have a much smaller collapse index than B.C. species mainly due to a difference in fibre geometry (smaller diameter and larger wall thickness, resulting in lower *G*). This confirms the superior quality of B.C. fibres and also emphasizes that a slight deterioration in fibre quality due to increasing pine content likely is negligible compared to differences in fibre quality between B.C. and other kraft pulps. An increase in pine content in SPF mixtures thus does not threaten the quality-based advantage of B.C. market pulps.

Although spruce fibres after kraft pulping still might be slightly superior in strength potential, the higher coarseness of spruce means less fibres per kilogram of pulp, which is also an important number for reinforcement pulp (which SPF usually is used for). The unusual finding of spruce fibres being coarser than pine also shows the importance of growing conditions for fibre quality. In general, a productive site with good growing conditions results in longer and coarser fibres and thus the sample sites chosen for this study might offer very good growing conditions for spruce. Based on the findings from three sites, a generalization of which fibres are coarsest is not possible, however the results show that the common statement of pine fibres being coarser than spruce is not always true either.

3.1.5 Fibre Quality Analysis and BauerMcNett Analysis of Thermomechanical Pulp

Fibre quality analysis of TMP pulp is meaningful only for average fibre length. Results are shown in Figure 16. As would be expected for a refining process, fibres are shorter than from the kraft pulping process. Spruce fibres are longer than pine fibres at all three sites, and fir fibres are overall longest at site 1 and 3 but shortest at site 2. The relation of fibre lengths among different species within one site has shifted from what was seen for wood fibres (which thus is not necessarily a good predictor of resulting fibre length after refining). There is little difference between the overall average fibre lengths of the different sites.

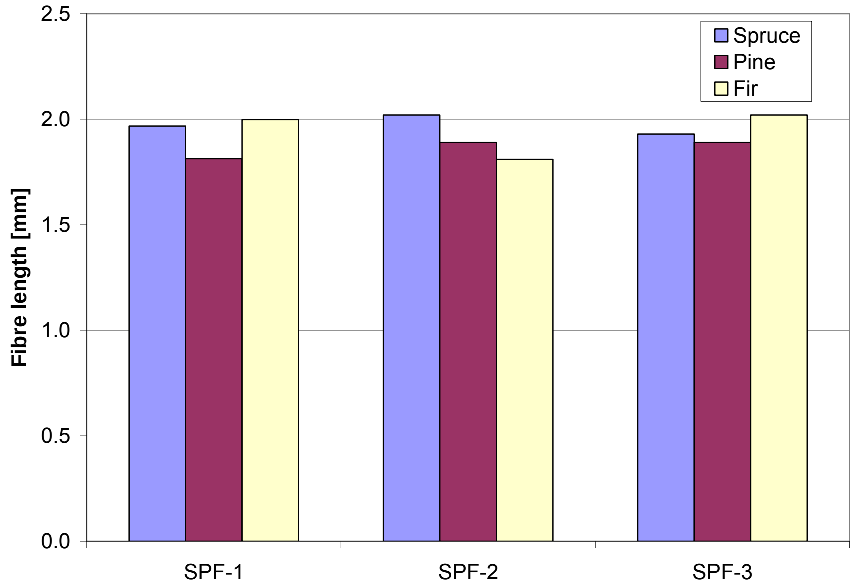

Figure 16. Length weighted average fibre length of TMP pulp fibres (FQA)

Fibre distributions were determined for TMP pulp by BauerMcNett fractionation. In particular, fines content and long fibre fraction are important characteristics for TMP pulp and often are more meaningful for mechanical pulp than the average fibre length. Fines do not only result in a smoother paper with high opacity, but at the same time they can increase the bonding potential of mechanical pulp. The long fibre fraction is important for the obvious reason of providing long fibres to build a network in the paper, which is important for strength properties.

Table 8 shows the complete fibre length distribution numbers (corrected to 100 ml CSF), Figure 17 compares long fibre fraction and Figure 18 shows fines fraction for the different species and different sites.

Table 8. BauerMcNett fibre distribution of TMP pulps corrected to CSF=100ml

	SPF-1			SPF-2			SPF-3		
	Spruce	Pine	Fir	Spruce	Pine	Fir	Spruce	Pine	Fir
R 14 [%]	19.2	12.7	20.2	24.2	18.5	18.5	20.8	15.2	21.6
R 14/28 [%]	28.8	29.9	27.5	26.0	27.6	27.8	26.3	29.3	26.9
R 28/48 [%]	13.5	15.7	12.6	13.4	14.2	13.9	12.4	14.7	13.6
R 48/100 [%]	7.6	8.7	8.0	7.0	7.5	8.2	7.1	7.8	8.3
R 100/200 [%]	4.7	5.6	5.7	5.1	3.9	6.2	5.5	5.0	6.5
Pass 200 [%]	26.2	28.0	25.6	24.0	26.2	25.8	27.6	28.0	23.1

Figure 17. Long fibre fraction (BauerMcNett R-48) of TMP pulp

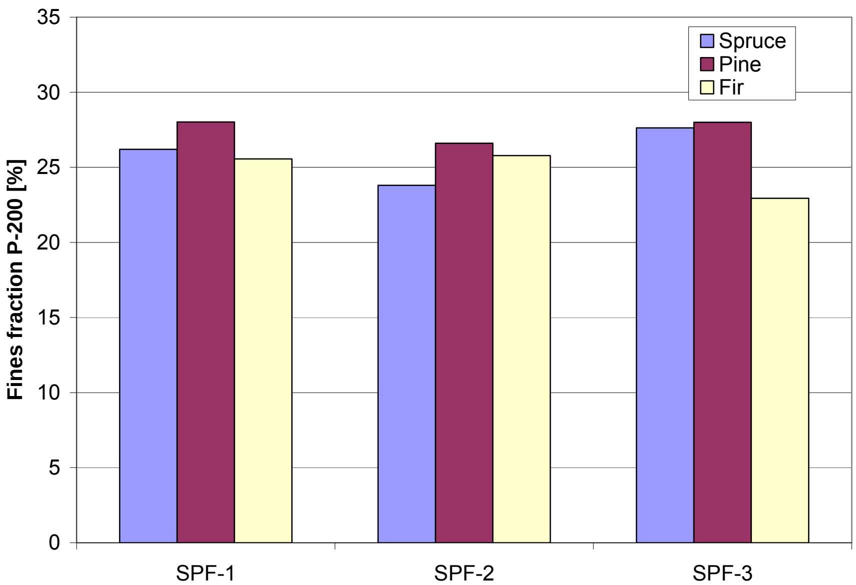

Figure 18. Fines fraction (Bauer McNett P-200) of TMP pulp

There are no significant differences in fibre length distribution for different species and sites. The long fibre fraction correlates with the average fibre length. Fines fraction differs overall between 23% and 28%, and is at all three sites highest for pine, but differences are relatively small. Higher fines content is beneficial for opacity and scattering coefficient, an important property for mechanical printing paper. It also can be beneficial for bonding, if the fines material is comprised of mainly fibrillar material. However, a large amount of parenchyma (ray) cells in the fines material can cause problems mainly due to increased linting tendency during papermaking, as this material does not bond well. Thus, it depends on the composition of fines material if the higher fines content of pine should be seen as a possible advantage or as detrimental.

We, therefore, collected material from the R-200 fraction of the BauerMcNett analysis, and also from the P-200 fraction for two samples, namely the 100% spruce and 100% pine pulps from site SPF-1. The P-200 fraction was filtered through a fine-meshed cloth and the material that was retained on the cloth was gathered as well as some of the filtrate. These three fractions were then examined under the light microscope, using phase contrast. While phase contrast will blur the edges of larger particles, it visualizes very fine, thin particles better than polarized light and thus gives a better impression of the amount of fine material in the sample. Example images are shown in Figure 19. There was no apparent difference in the composition of fines material from spruce and pine pulp. For all fractions, the fines were comprised mainly of fibrillar material and wall fragments, and much fewer ray cells. Due to the lack of apparent difference in composition between these two pulps, we did not proceed any further with a more detailed fines analysis. We concluded that the increased fines material of pine pulp should not be of detrimental influence in SPF mixtures regarding linting propensity, but might be beneficial for opacity and light scattering properties. However, it should be emphasized that this study did not include pulping of grey wood. The influence of adding grey pine to TMP pulped SPF mixtures on fines composition is not known.

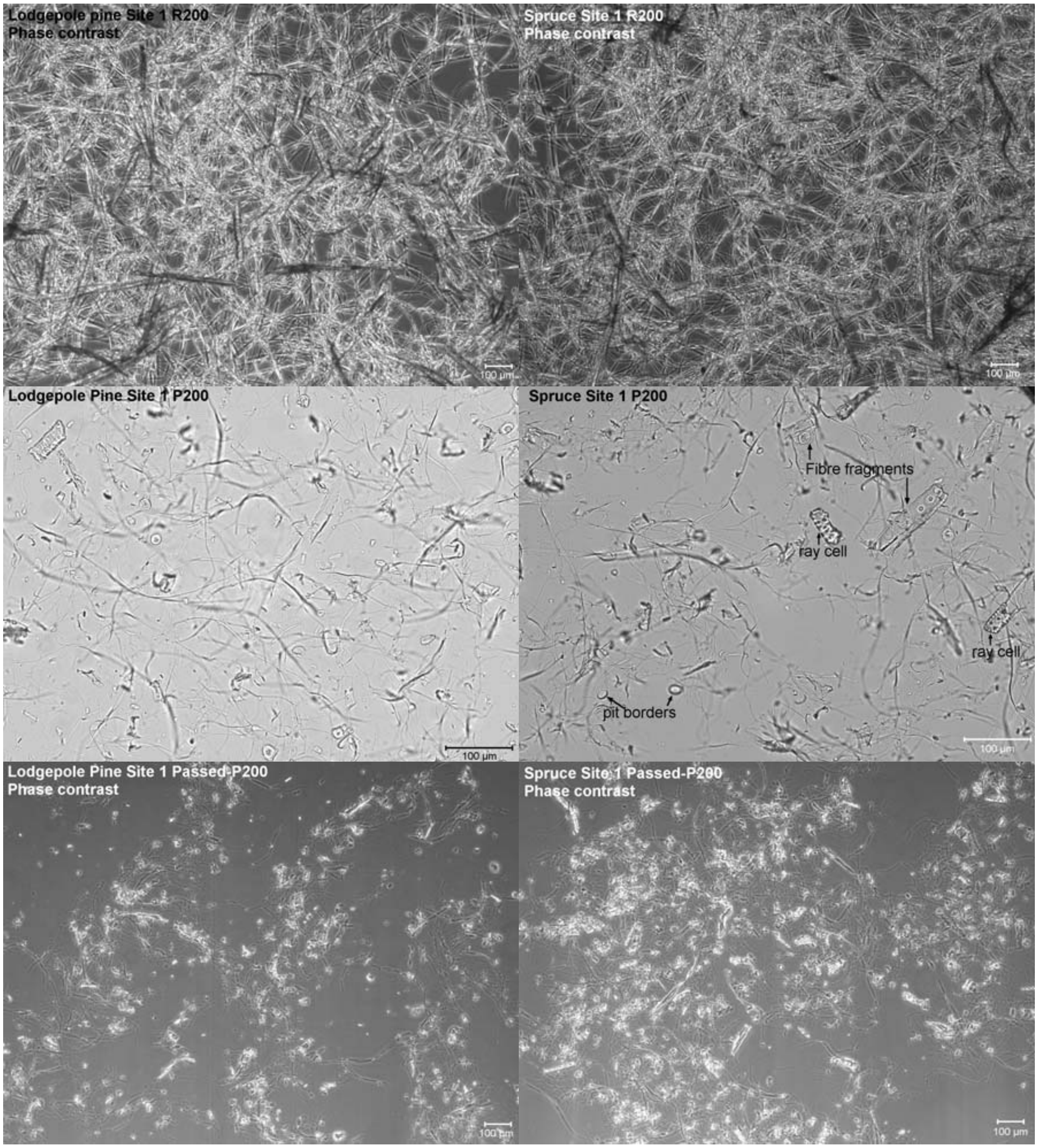

Figure 19. Phase contrast microscope images of the R-200 fraction, the P-200 fraction retained by a fine cloth, and filtrate of the P-200 fraction passing through the cloth ("Passed P-200")

3.1.6 X-ray Diffraction Analysis of Lodgepole Pine Samples

Crystallinity and crystallite size of ground pulp was determined for green chips, TMP and kraft samples of pine trees from sites 1 to 3. Results are shown in Table 9.

Table 9. X-ray diffraction results for pine samples

Sample	Site	Crystallinity [%]	Crystalline area	Amorphous area	Crystallite size [nm]
Chips	SPF-1	37.1	43.4	73.4	10.3
	SPF-2	36.6	42.9	74.2	11.7
	SPF-3	40.1	53.6	80.0	11.3
TMP	SPF-1	37.2	38.7	65.4	6.5
	SPF-2	39.6	47.2	72.0	10.6
	SPF-3	37.9	37.8	61.8	8.0
Kraft	SPF-1	62.8	71.3	42.2	12.9
	SPF-2	63.6	64.4	36.9	13.2
	SPF-3	63.4	70.1	40.4	12.5

The crystallinity of kraft samples is higher than for TMP and chip samples, which shows that crystallinity, and thus the relative integrity, of the cellulose chains will change during kraft pulping. Crystallinity for TMP and chip samples are similar within experimental error, thus no change of crystallinity during TMP pulping takes place, which is sensible as TMP pulping merely is a mechanical alteration of the wood matrix.

There are also no differences in crystallinity between the different sites, thus it can be assumed that mountain pine beetle attack and the establishment of associated fungi will not result in a change in crystallinity, at least not at this stage of mountain pine beetle attack.

3.2 Chip Quality and Chip Size Distribution

Chip quality plays an important role in the outcome of pulping, and the chip size distribution is important for the overall yield that can be expected. Chip size distribution and quality data are given in Appendix B.

The relative amount of accept chips of all samples is in the range of 85% to 92%. At all sites, pine shows a slightly lower number for accept chips than do spruce or fir. At the same time, the ratio of overlarge chips is higher.

Chip packing density and chip basic density (measured on the accept chips for kraft pulping) vary with species and site, but both are higher for pine than for spruce or fir chips. Chip basic density can be compared to SilviScan data for age rings 60-80 years of the wood cores, as illustrated in Figure 20. Density of wood chips is still highest for pine at all sites, and SilviScan and wood chip data agree relatively well for spruce and pine (except for pine at site 2). For fir, however, the chip density is lower than the SilviScan data for wood cores, particularly at site 1 and 2. As a result, wood chip density of spruce is higher than for fir, while from the wood core data relatively similar numbers were expected.

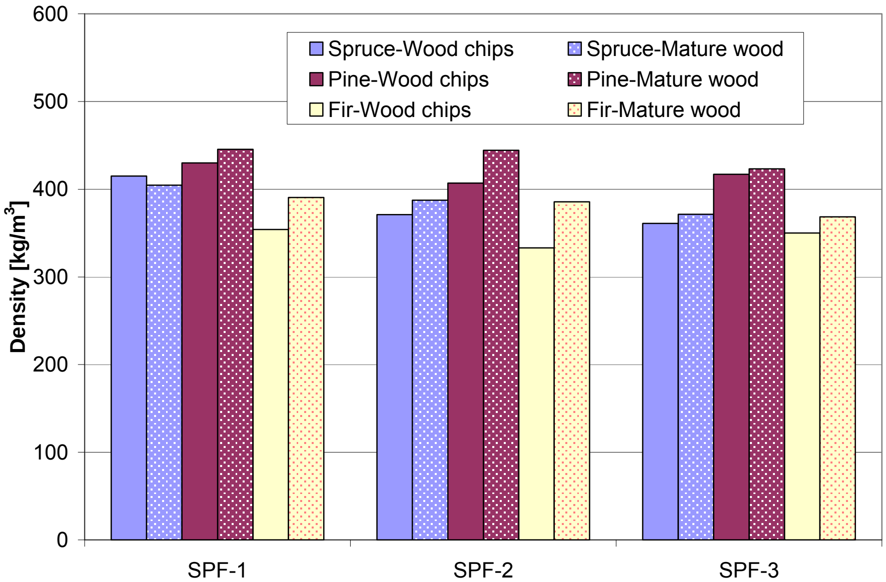

Figure 20. Wood chip density (PAPTAC method A.8P) compared to SilviScan data for mature wood (60 to 80 years)

The chip solids content before chipping is also highest for pine, which could be expected as the pine trees are mountain pine beetle-attacked and research as well as field experience has shown that mountain pine beetle-attacked wood is drier than sound wood. Dry wood can lead to problems during pulping, particularly when mixed with other, non-dry wood, which is a concern that needs to be addressed when a chip mixture contains mountain pine beetle-killed wood. Also, the increase in dryness can cause problems during chipping, resulting in a lower accept ratio.

The lower yield of accept chips of pine obviously can have economic implications. On the other hand, the higher packing density of pine chips is beneficial as it can lead to higher chip throughput at the digesters in kraft cooking.

3.3 Discussion of Modeling Results

The results of the mixing experiments for both kraft and TMP pulping were represented with up to third order model equations. For kraft pulps, the data from PFI mill refining were used as input. The resulting model equations are given in Appendix F. The model equations were used to discuss the influence of different species on the overall property of the pulps, and for predictions of pulp quality changes with the expected increasing pine content in SPF mixtures due to the current mountain pine beetle crisis. Of particular interest were:

- The influence of changing species proportions on each dependent variable at each sample site (thus the discussion should focus on species influence on pulp mixture behaviour, but also on site influence)
- Any common trends that were seen for the same property at different sites (Is there a correlation between origin of the wood and pulp mixture behaviour and if so, can this be defined using site index as another independent variable?)
- Differences in species influence between kraft and thermomechanical pulping
- Which properties are most affected by changing chip composition
- Implications for the expected pulp quality of future SPF mixtures

3.3.1 Model Significance and Correlation

Before discussing mixture behaviour based on the model equations that were found, an evaluation of the adequacy and reliability of models should be done. Modeling was not always successful, and the model equations that were found are of different degrees of significance. If a model has a lower significance, a larger uncertainty in the accuracy of the predictions is accepted, which is important when discussing any expected changes in SPF composition. Particularly when predicted changes are small and model uncertainty is substantial, the validity of any conclusions can be questioned. Thus, a discussion of model significance is important in order to be able to judge the reliability of predicted changes.

Model significance and correlation for all cases is given in Tables 10 and 11. For TMP only the modeling for properties interpolated to a constant CSF of 100 ml are included. The models are divided into four groups based on their degree of significance (as represented by the p-value). Group 1 with a p-value of ≤ 0.001 is deemed highly significant. Correlation values are high and the predictions from model equations can be seen as very reliable. Group 2 are models with a p-value of ≤ 0.05, but >0.001. These models are still significant, but correlation coefficients are in general lower. Choosing a p-value of 0.05 means accepting a probability of 5% that the relationship we have found is not a valid relationship, but solely based on a chance finding. In other words, if we would repeat our experiment 20 times and there is no relationship between the variables, we would still find an apparent relationship in 1 out of 20 cases. Group 3 are called borderline significant models with $0.05<p\leq 0.1$. We thus accept a 10% probability that the model equations we found are not true, which is quite high. Thus, we do not use these model equations to predict any changes. However, they still are an indication of what kind of model and what trends can be expected if chip mixture composition changes. For group 4, $p>0.1$ and thus no acceptable model was found and no statements about behaviour of the properties in question with changing chip composition are possible.

Within each group, the models are then ranked by the degree of correlation as measured by the adjusted R^2-value (which takes the degree of freedom into account). While the level of significance only tells us if we should believe the model equations or not, the R^2-value is a measure of the strength of the relationship we found. It is a measure of the total variability of the predicted properties that can be accounted for by the independent variables (which in our case are the relative proportions of spruce, pine and fir). If only a small portion of the overall variance can be explained from the independent variables, then a large portion of the variance is due to other influences on the predicted property and thus the error of the predicted variable if compared to the actual value could be high (a large confidence interval). Thus, if the models predict only small changes with changing chip composition, and our correlation coefficient is low, then the possible variance in the actual value can be large compared to the predicted change, and the predicted change might not have much meaning.

The pulp properties that were measured and then modeled can also be divided into four groups:

- Pulping variables: These are pulp yield, kappa number, average length weighted fibre length (LWL) and coarseness for kraft pulping, and specific refining energy (SRE), LWL, fines content and long fibre fraction for TMP pulping.
- Strength properties: These are tensile index, tear index, burst index and zero span breaking length (the latter only for kraft pulps).
- Optical properties: Scattering coefficient, opacity and brightness (the latter for TMP only)
- Sheet structure properties: Sheet density, Sheffield roughness and Gurley air resistance (the latter for kraft pulp only).

Table 10. Ranking of model significance and correlation for kraft pulps

Property	Site	p-value	R^2adjusted
I. Highly significant models, p<=0.001			
Pulp Yield	3	0	0.98
Pulp Yield	1	0	0.96
Coarseness	2	0	0.95
Length weighted fibre length	2	0	0.95
Length weighted fibre length	3	0	0.94
Kappa number	1	0	0.92
Pulp Yield	2	0.000001	0.91
Length weighted fibre length	1	0	0.89
Air resistance	1	0	0.87
Opacity	1	0.0001	0.83
Air resistance	3	0.00004	0.81
Kappa number	2	0.0001	0.77
Coarseness	3	0.0001	0.77
Scattering coefficient	3	0.0002	0.75
Kappa number	3	0.001	0.66
Coarseness	1	0.001	0.64
II. Significant models 0.001<p<=0.05			
Burst index	3	0.009	0.63
Tear index 4-ply	2	0.002	0.61
Tear index 1-ply	2	0.003	0.59
Scattering coefficient	2	0.003	0.58
Sheet density	2	0.004	0.57
Zero span breaking length	3	0.012	0.55
Tensile index	1	0.011	0.48
Opacity	3	0.006	0.54
Sheffield roughness	1	0.006	0.53
Opacity	2	0.007	0.52
Air resistance	2	0.022	0.52
Sheffield roughness	2	0.017	0.51
Sheffield roughness	3	0.0099	0.49
Zero span breaking length	1	0.039	0.42
Sheet density	3	0.038	0.41
III. Borderline significant models 0.05<p<=0.1			
Zero span breaking length	2	0.053	0.48
Burst index	1	0.09	0.3
IV. No significant model			
Sheet density	1		
Burst index	2		
Tensile index	2		
Tensile index	3		
Tear index (1-ply and 4-ply)	1		
Tear index (1-ply and 4-ply)	3		
Scattering coefficient	1		

Table 11. Ranking of model significance and correlation for TMP pulps

Property	Site	p-value	R^2adjusted
I. Highly significant models, p<=0.001			
Sheet density	3	0.00004	0.81
SRE	3	0.0002	0.81
Scattering coefficient	2	0.00005	0.8
Fines content	1	0.001	0.79
Fines content	3	0.00009	0.78
Sheet density	1	0.0002	0.76
Opacity	3	0.0002	0.75
Burst index	1	0.0002	0.75
Burst index	3	0.0004	0.71
Opacity	2	0.0005	0.7
Brightness	3	0.001	0.65
II. Significant models 0.001<p<=0.05			
Tear index	1	0.003	0.72
Tensile index	1	0.002	0.63
Sheffield roughness	1	0.002	0.61
Long fibre fraction	2	0.004	0.61
Sheffield roughness	3	0.003	0.59
Burst index	2	0.024	0.54
Scattering coefficient	3	0.004	0.57
Length weighted fibre length	1	0.01	0.56
Tensile index	3	0.01	0.49
Opacity	1	0.02	0.48
Tensile index	2	0.018	0.47
Scattering coefficient	1	0.014	0.45
Length weighted fibre length	2	0.016	0.45
Long fibre fraction	3	0.016	0.45
Length weighted fibre length	3	0.03	0.45
SRE	1	0.037	0.42
Long fibre fraction	1	0.035	0.36
Sheet density	2	0.049	0.32
III. Borderline significant models 0.05<p<=0.1			
Tear index	2	0.068	0.57
Tear index	3	0.068	0.33
Sheffield roughness	2	0.1	0.28
Fines content	2	0.1	0.24
IV. No significant model			
SRE	2		
Brightness	1		
Brightness	2		

Table 10 shows that for kraft pulping, all the pulping properties are represented by highly significant models with mostly very high correlation coefficients. Most optical properties and sheet structure properties still have significant models, but correlation coefficients are lower. Strength properties, on the other hand, are very difficult to model, and in most cases no significant model was found. Only zero span resulted in models that can be considered relevant for all three sites. Most models for kraft pulp show a linear behaviour.

For highly significant models with correlation coefficients of >0.7, the predicted values can be assumed quite close to the actual values that will be seen. For models with correlation coefficients <0.7, variation in data can be large and thus the prediction and actual value can differ much more. This can be illustrated by listing a few predicted values and compare them to the measured data for the validation points that were used (Table 12). The lower the R^2 value, the larger the differences between predicted and measured properties. Thus, in cases where predicted changes in pulp properties are small, the variation due to data scatter can be much larger than the predicted change. In these cases, predicted changes in SPF properties in pulp mills will be seen only if large sample sizes are considered. Differences in SPF quality when only few samples are considered (e.g., when samples from only a short time period are considered) will be more due to data scatter.

Table 12. Comparison of predicted data to the validation points for selected properties of kraft pulp from site SPF-3

	Point 1 (30/65/5)		Point 2 (10/90/0)	
	Predicted	Measured	Predicted	Measured
Pulp yield [%]	45.7	45.8	44.7	44.9
Coarseness [mg/m]	0.173	0.17	0.168	0.164
Burst index [kPa·m^2/g]	11.2	10.8	10.8	11.1
ISO Opacity [%]	89.4	90.1	89.8	92.8

There are a few different possibilities why, in some cases, no significant model can be found. If differences in properties for different mixtures are small and data scatter (experimental error) is large, no meaningful prediction of differences is possible. Another possibility is that the differences between different mixtures are indeed only random and the mixture behaviour could be described by an average value. Lastly, handsheet properties could be influenced by some other independent effects besides the relative content of species and thus it is not possible to find good models.

In the first two cases, including more data points in the mixture design would result in more significant models. We, therefore, tried to include the two validation points in the data that is used for model fitting, and the model fit improved significantly. This shows that the problems with modeling likely are caused by too few data points and future work in this area should consider a different distribution of model points or the inclusion of a few additional points. Unfortunately, keeping the two validation points within the model data was not an option here as these two points were required for validation.

One specific cause for handsheet properties resulting in less significant models than pulping properties could be related to the interpolation or extrapolation that is done to calculate values for a constant CSF of 300 ml for data from different levels of treatment in the PFI mill. The interpolation can introduce an additional error leading to even larger data scatter.

For TMP (Table 11), only very few properties could not be modeled. Also, there is no pattern to see for properties of a certain group being easier or more difficult to model. The majority of models are significant, but not as many models are highly significant and not to the same degree as the pulping properties in kraft pulping are. At site 2 more properties could not be modeled well enough than at site 1 or 3. Overall, the correlation coefficients of TMP models are lower than what was seen in kraft pulping, but TMP pulping is known for higher variances in the results. For the estimation of handsheet properties at a CSF of 100 ml, interpolation is also necessary for the TMP pulps.

Many models in TMP pulping are also linear, but there are a few more that contain interaction terms. If any and what interaction terms are included is not consistent for one property if different sites are compared, and thus interaction also seems to depend on the sample site (wood origin).

Despite the obvious differences between sites, we also tried to combine all data and find a global, site-independent model. Except for kraft pulping properties (pulp yield and kappa number) this did not result in any significant models. Obviously, site-specific factors need to be included if a global model is to be formulated.

When discussing the implications of model predictions in the next section, the above lists of correlation factors should be kept in mind in order to decide if any predicted change might be important or if the change is insignificant compared to the expected possible error in prediction.

3.3.2 Modeling Results for Thermomechanical Pulps

For TMP pulps, modeling was done for properties interpolated to a constant CSF as well as to a constant SRE, but only the models for properties interpolated to a constant CSF of 100 ml are discussed (except the model for CSF itself which is for a constant SRE). Models for properties at constant SRE in general showed the same trends and therefore, are mentioned only if they contributed additional information.

3.3.2.1 General Observations

Pulping variables

The form of the models for the required SRE to reach a certain CSF, or for the expected CSF if SRE is held constant, is not consistent for all sites and some of the correlation coefficients are low. Thus, the predicted values should be taken cautiously. Some interaction between the different species is predicted resulting in non-linear models. The difference in required SRE to pulp to 100 ml CSF for spruce and pine is not large, although pine requires somewhat more energy to pulp to the same SRE. The required SRE for fir can be much lower. The absolute differences in required SRE for the pure species depend on the sample site and thus on growing conditions. If the pine content increases, a small increase in required SRE might be seen, however as differences between spruce and pine are small, this increase will also be small. Fir does have a larger influence on the required SRE, but due to the low content of fir this is not noticeable. An example of the behaviour of SRE with changing mixture composition is illustrated in Figure 21.

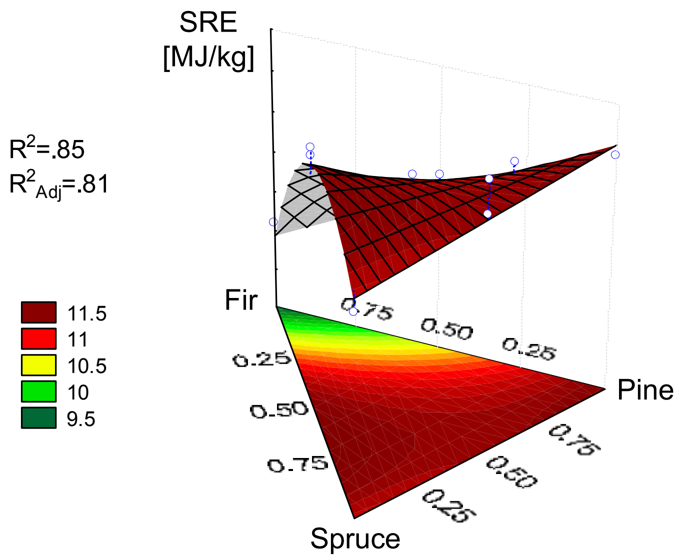

Figure 21. SRE as a function of mixture composition at site SPF-3 (TMP pulping)

In agreement with the findings for required SRE, the models for CSF values that will be reached for a constant SRE also show non-linear behaviour. The CSF of spruce and pine is not that different at site 3 but differs more at site 1 (by about 30 ml), with spruce resulting in a lower CSF. The CSF for fir is lower than for pine or spruce which also agrees with the results from models for SRE. A change in mixture composition can lead to noticeable changes in CSF with increasing pine content. Note that for site 2 it was not possible to model SRE or CSF.

Modeling the mixture behaviour of the average fibre length (given as length weighted fibre length measured with the FQA instrument) also results in some higher order models. At all three sites included in this study the fibre length of spruce exceeds the one of pine, and thus an increase in pine content can lead to a small decrease in fibre length. However, the magnitude of this drop really depends on the input fibre length, and in cases where pine fibre length would exceed spruce fibre length, an increase might be expected with higher pine content. Thus, the only general conclusion from fibre length modeling is that a slight change in average fibre length can be expected with changing mixture composition, and that the mixture fibre length does not necessarily depend linearly on pure species fibre lengths. Also, as long as the content of fir in the mixture is very low, the average length of fir will not influence the overall fibre length much, even if it is noticeably shorter than for spruce or pine (site 2).

The fines content of the single species differ, but for the three sites there is no common trend regarding whether any species results in a higher or lower fines content than another. Fines content as a function of mixture composition at two sites is linear, but at site 1 there are some interaction terms in the model. Differences in long fibre fractions are also small for the three species and do not seem to follow the same trends at different sites. All models for long fibre fraction are linear. Pine at all sites lies at the lower end of long fibre fraction and higher end for fines fraction seen for the three species. With increasing pine content, a small increase in fines content of the mixture and a small decrease of the long fibre fraction is possible, however whether this is the case and the magnitude of change will depend on the origin of chips.

Handsheet variables: Strength properties

At all sites, the tensile index of spruce exceeds the one of pine and also fir. The models describing tensile behaviour of mixtures are all linear. The range and magnitude of predicted tensile strength for varying mixture composition depends somewhat on the site, with the values for pure species at different sites varying by up to 10%. A small but noticeable drop in tensile with increasing pine content is predicted.

Burst index is known to be related to tensile index in an empirical way. The models for burst index at the three sites should reflect this. At site 1 and 3, the linear models indeed show the same trends as was seen for tensile, but at site 2 the model shows some non-linear interaction terms, illustrated in Figure 22. For comparison, Figure 23 shows burst index at site 1 (and the shape of the response surface for burst index at site 3 as well as for tensile index at all three sites would be relatively similar). Figure 22 thus illustrates that unexpected variability can exist. Overall, burst index is, however, always highest for spruce as was the case for tensile index, and with increasing pine content a drop in burst of about the same relative magnitude as for tensile index can be expected.

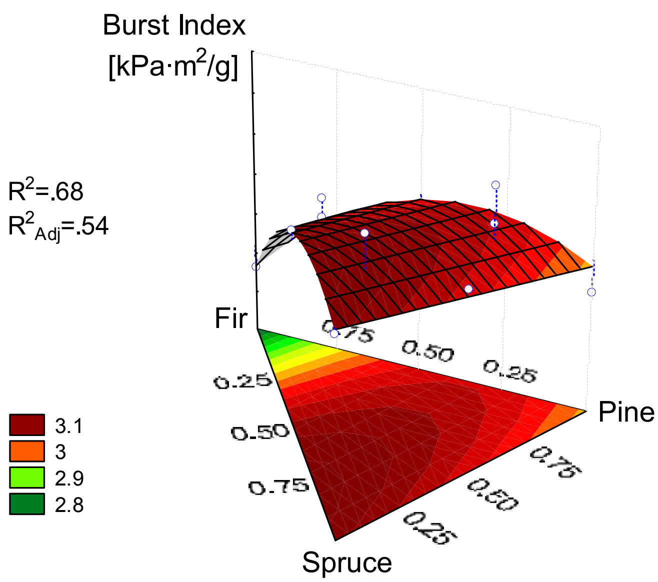

Figure 22. Burst index of TMP pulp as a function of mixture composition at site SPF-2

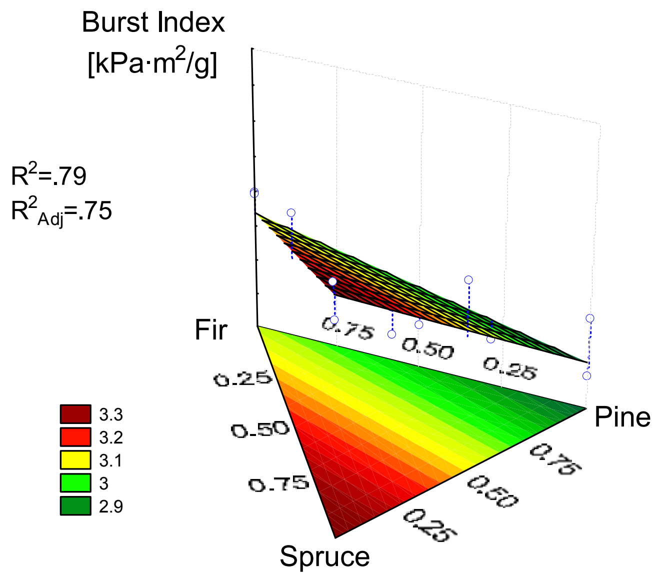

Figure 23. Burst index of TMP pulp as a function of mixture composition at site SPF-1

Modeling of tear did not always result in acceptable models and the models that were found are not all very reliable. They show very different behaviour of the response surfaces for different sites. Some of the models have interaction terms, which is not unexpected for tear which is known to behave non-linearly in mixtures. Possibly a small drop in tear will be seen with increasing pine content, but the models are not reliable enough to use them for actual predictions of ranges or magnitudes of changes.

Handsheet variables: Sheet structure

Good models are found for sheet density at site 1 and 3, and a less significant one for site 2. All models show a linear interaction between the pulp components. Sheet density of spruce is highest and a small drop in sheet density is predicted with increasing pine content in some cases. Whether a decrease in sheet density will be seen and how much it will be, however, again differs for the three sites included in this study.

Sheffield roughness shows linear behaviour with mixture composition at site 1 and 3. The model for site 2 was deemed unreliable. Roughness is lowest for spruce and highest for pine, leading to an increase in roughness with increasing pine.

Handsheet variables: Optical properties

For TMP pulp, which is often used in mechanical printing papers, optical properties are very important and particularly a drop in brightness would be of concern.

Opacity differs between species as well as between sites. Opacity is always lowest for spruce. At site 1 and 3, it is highest for pine, while at site 2 the opacity of fir exceeds the opacity of pine. The models to describe opacity as a function of mixture composition are all linear. As spruce has the lowest opacity, an increase in pine content and thus decreasing content of spruce will lead to a slight increase in opacity.

Scattering coefficient shows the same trends as opacity with the scattering coefficient being lowest for spruce at all sites. The linear models predict a possible small increase in scattering coefficient with increasing pine content.

Brightness could be modeled only at site 3, where increasing pine content would indeed lead to a small drop in brightness (linear model). At the other two sites, no significant model was found. This either means that data scatter is too large and thus, at least based on the few chosen data points, it is not possible to predict the expected change in mixtures, or the differences in brightness between different sites are random and thus no change would be expected. Examining the data for these two sites closer, the difference between brightness of pine and spruce is not large (1% respectively 2%), and at site 2 the brightness of pine pulp is actually larger than of spruce pulp. Thus, the drop in brightness with increasing pine content predicted for site 3 cannot be generalized. Also, scatter even at site 3 is quite large as shown in Figure 24.

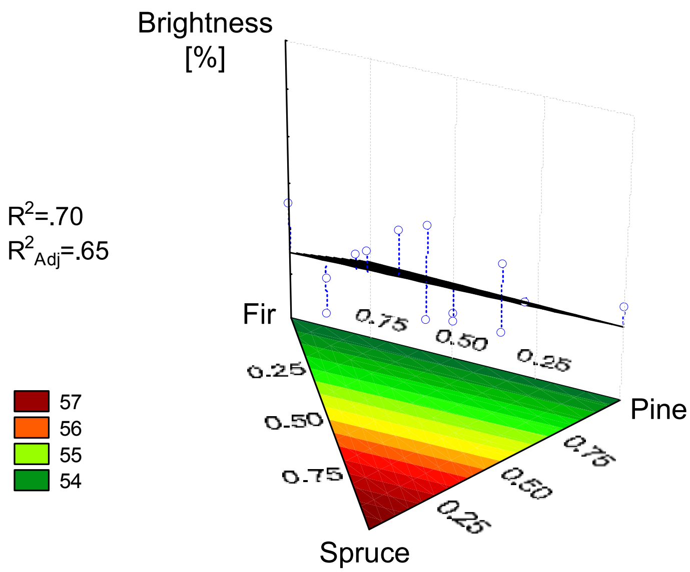

Figure 24. Brightness of TMP pulp as a function of mixture composition at site SPF-3

In summary, the behaviour of pulp and handsheet properties with species composition for SPF mixtures of TMP pulp does not show any surprising results. The overall picture is relatively consistent, with the spruce fibres making a smoother sheet with higher density, good strength properties, but lower opacity compared to the other fibres. Pine gives a sheet of lower density, higher roughness, lower strength but higher opacity. Properties for fir can lie anywhere in between, but as long as the fir content in SPF mixtures is low, it is not of much influence in mixture behaviour. The handsheet properties of mixtures mostly follow linear relationships, thus an increase in pine content is detrimental for sheet structure and strength, but will increase opacity. The differences with changing mixture composition depend on wood origin but are mostly very small (as the differences between pure species already are smaller than was expected).

Pulping properties like necessary SRE and fibre length and fines content generally do not follow linear relationships. The interaction between species for SRE are negative, meaning that the necessary SRE to reach a certain CSF for a mixture is lower than would be expected from a linear relationship between the pure species. This leads to an increase in SRE when one species becomes dominant in the mixture.

A specific example for changes with increasing pine content will be given in section 3.4.1. The predictions from models for TMP should be taken cautiously, as data spread often is large and thus the correlation between predicted and observed values is not very good.

3.3.2.2 Site influence

The absolute values for pulp and handsheet properties of one species differ for different sites. Also, the relative or absolute differences in properties between the three species differ for the three sites included in this study. The models presented above are thus valid only for the specific site that the model data came from.

More general models that can be used for SPF mixtures independent of sampling site would be more useful. Including the site index as a further variable in these models was seen as one possible solution. For this reason, a general comparison of site indices to model equation coefficients was done, to explore if there was any useful correlation which would enable us to present a general model including site influence.

In order to see if a simple correlation exists, the differences in the linear coefficients of the models (thus basically the values for single species) between different sites were compared to differences in site indices. As many pulp fibre properties are growth-dependent, it is assumed that if site index differences for individual species increase between sites, differences in fibre and pulp properties should also increase. If such a correlation between site index and pulp property cannot be found for the pure species, then it makes little sense to look for an influence of site index on the mixture behaviour.

To compare factors of pulp property models and site indices, linear model coefficients as a function of site and species are plotted and compared to a plot of site indices. When looking for common trends in two such plots, the possibility of inverse correlations needs to be included (e.g., larger property coefficient than at other sites but lower site index). See Figure 25 to Figure 27 for an example. Figure 25 shows the site indices. Figure 26 shows the linear factors for burst index and Figure 27 for opacity. For burst index the linear coefficients for pine and spruce, but not fir, follow the general trend for site indices (for spruce and pine, higher site index and also higher burst index at site 2 than at site 1 and 3). For opacity, there seems to be no such relation between linear model coefficients and site index except maybe for spruce.

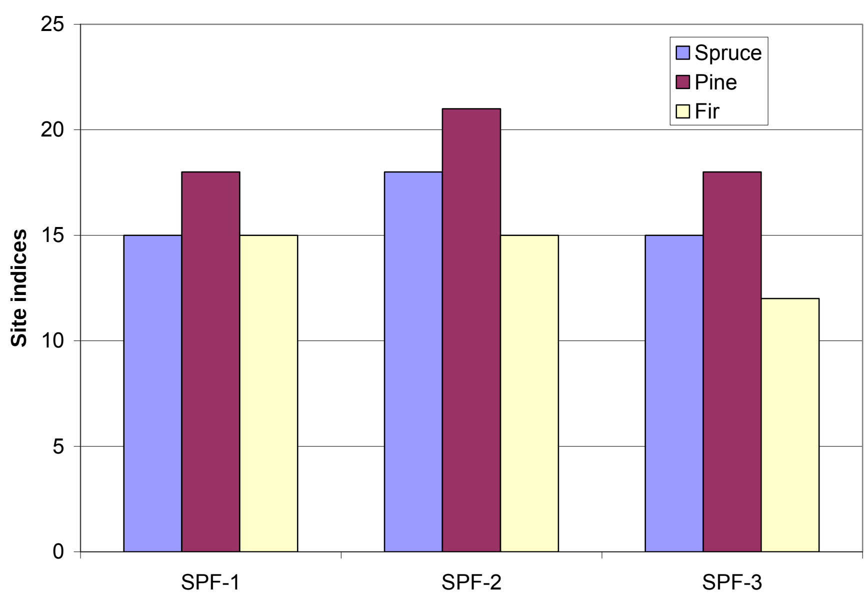

Figure 25. Site indices for all species at the three sample sites

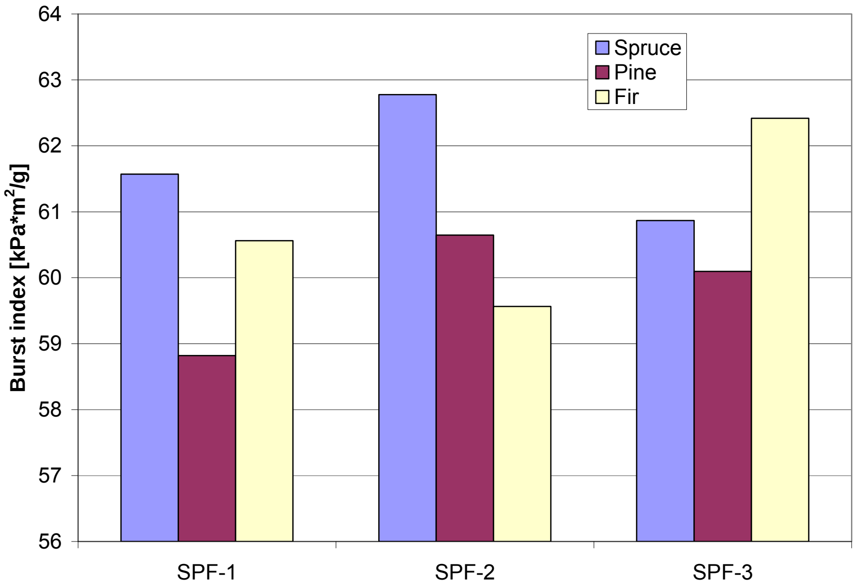

Figure 26. Linear factors of model equations for burst index of TMP pulp (CSF = 100 ml)

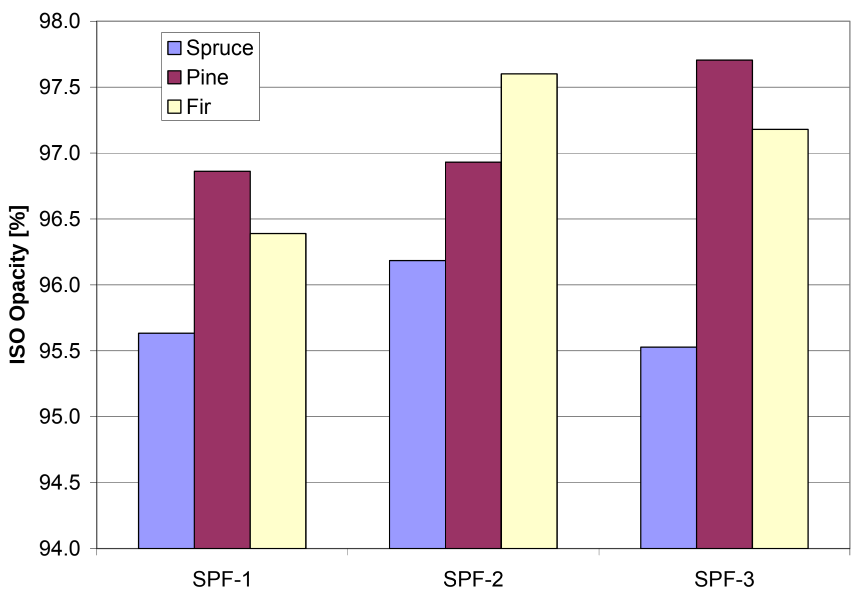

Figure 27. Linear factors of model equations for opacity of TMP pulp (CSF = 100 ml)

For the majority of these comparisons, we did not find any obvious correlation of linear model coefficients and site index, and any findings are not consistent for different species or properties. The few cases where some correlation is found are probably a chance finding. We concluded that, at least from the limited data from the few sites for this study, it is not possible to define global models for SPF pulp mixture behaviour. Most likely, site index is not a good indicator of expected pulp behaviour because the actual physical variables that pulp quality depends on are fibre morphology and wood properties. The correlation of these variables with site index is too low to be useful for predictions, as could be seen in the discussion of fibre and chip properties. Thus, even if the site properties of two different sites result in the same productivity rate for one species (same site index), the fibre properties and wood quality can differ. One should keep in mind though that the sample size (three sites) is very small. In Trent et al. 2006, which includes a comparison of fibre properties to site index for a larger number of sample sites and wider range of site indices, a correlation was found for site index and fibre length, but not for coarseness. In general, better growing conditions that lead to faster growth are expected to result in longer and coarser fibres. More work might be needed in this area to confirm if such a relationship indeed exists for coarseness, and also to look into fibre diameter and wall thickness dependence on growing conditions.

If a general model for SPF fibre mixture behaviour was to be found, it would probably be more appropriate to include fibre morphology variables as additional independent variables instead of site index. Fibre morphology could then be related to site properties (including more than only site index). However, this was beyond the scope of this project.

While it is not possible to predict changes in pulp properties exactly for any SPF mixture, the results from the three different sites can be used to predict the ranges of expected changes. Having chosen three sites with different growing conditions, the differences between pulp properties and model results from the three sites included in this study are probably a good indicator of actual ranges that one can expect to see in pulp mills. However, it will depend on the wood supply if actual changes will be at the upper or lower end within these ranges.

3.3.3 Modeling Results for Kraft Pulps

3.3.3.1 General Observations

Pulping variables

All the pulping variables and fibre properties can be described with highly significant, well correlated models and thus the predictions can be seen as very reliable. Kappa number (at constant H-factor) shows similar behaviour for all sites. The resulting kappa number for fir is much higher than for pine and spruce, while there is no big difference between pine and spruce. The model to describe kappa number as a function of mixture composition is linear and with increasing pine content (and decreasing fir content), the resulting kappa number drops slightly, but not much. There are only small differences between the sites, thus the kappa number is less dependent on the site or origin of the trees than on the species. The kappa number for all mixtures lies within the optimum range of low 20s to mid 30s to achieve best pulp strength properties (McLeod 1988).

Pulp yield also shows a similar response for all sites. Spruce gives the best pulp yield, while pulping pine results in lower pulp yield. Pulp yield of fir lies in between. The model again is linear and thus with increasing pine content a drop in pulp yield can be expected, which is obviously of concern to pulp mills. Pulp yield at site 1 is shown in Figure 28, and response surfaces at the other two sites look quite similar.

Pulp yield and chip basic density (Figure 20) can be combined into a single number for pulpwood productivity *PP* (Cromer et al. 1998):

$$PP = \frac{Basic\ chip\ density\ (kg/m^3) \cdot Pulp\ yield\ (\%)}{100} \qquad \text{(Equ. 5)}$$

Results for pure species are shown in Table 13 (numbers for mixtures can be calculated based on a linear mixing equation as chip density as well as pulp yield follow linear mixing relationships) and show that even though the pulp yield for pine is lower, productivity numbers are in the same range as for spruce, measured in [kg] per [m^3] of pulpwood, due to the higher density of pine. Productivity of fir is lower, based on the low density of fir.

Table 13. Pulpwood productivity of pure species

	Pulpwood Productivity [kg/m^3]		
	Spruce	Pine	Fir
SPF-1	195	187	164
SPF-2	177	185	153
SPF-3	173	183	165

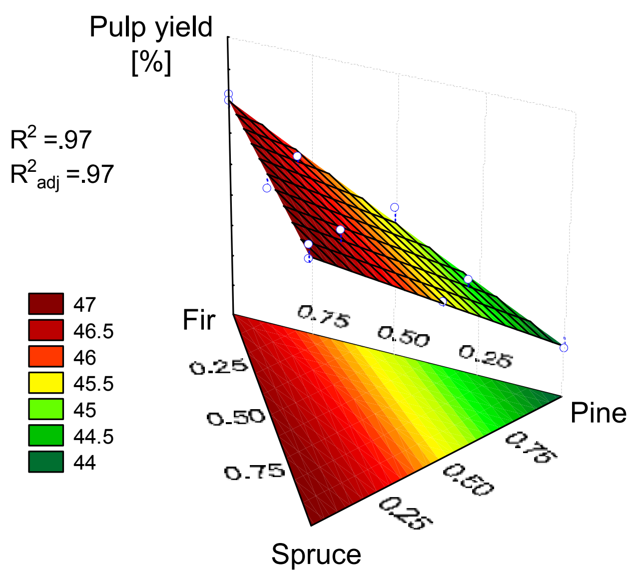

Figure 28. Pulp yield of kraft pulp as a function of mixture composition at site SPF-1 (H-factor = 1420)

Fibre property changes are also modeled with linear models. The average fibre length of fir is lowest at all sites, but either pine or spruce can have the longest fibres. Whether average fibre length decreases or increases with changing mixture composition depends on the origin of the chips and no general statement can be made. Differences in average fibre length overall (between different species as well as different sites) are not more than 0.5 mm. Fibre coarseness is always highest for spruce, which is rather unexpected. In general, pine fibres are expected to be coarsest. However, the finding of higher coarseness for spruce might not be very meaningful, as fibre behaviour in papermaking depends on collapse index and thus on fibre diameter, wall thickness and microfibril angle, as discussed earlier. The average coarseness can be modeled with linear relationships, and thus an increase in pine content can cause a small decrease in coarseness, however the changes might be too small for an effect to be noticed.

Handsheet variables: Strength properties

Spruce pine fir (SPF) kraft pulp is often used as reinforcement pulp and thus strength properties are of great concern. Unfortunately, as noted earlier, modeling the strength properties of SPF mixtures proved to be difficult and in many cases impossible, thus a discussion of expected changes in strength properties with changing mixture composition is limited. Often, modeling was successful for only one site in which case generalization of the result is questionable.

Tensile could be modeled only for one site (site 1, see Figure 29) and in that case the drop in tensile with increasing pine content is too small to be meaningful. The model at that site is linear, and if this is the case in general, whether tensile changes with changing mixture composition would depend on how tensile strengths of the three species compare to each other. For the two sites where no significant model was found, the tensile of spruce is higher than pine at site 3, but lower at site 2 (although differences overall are small). Thus, no general statement is possible whether tensile strength with increasing pine content will drop or not. Any decrease will depend on the difference in tensile strength between pure pulp and on the actual change in pine content. If the difference between species is not large (as indicated by the few data of this study), then the drop in tensile is probably not a significant issue and can be tolerated.

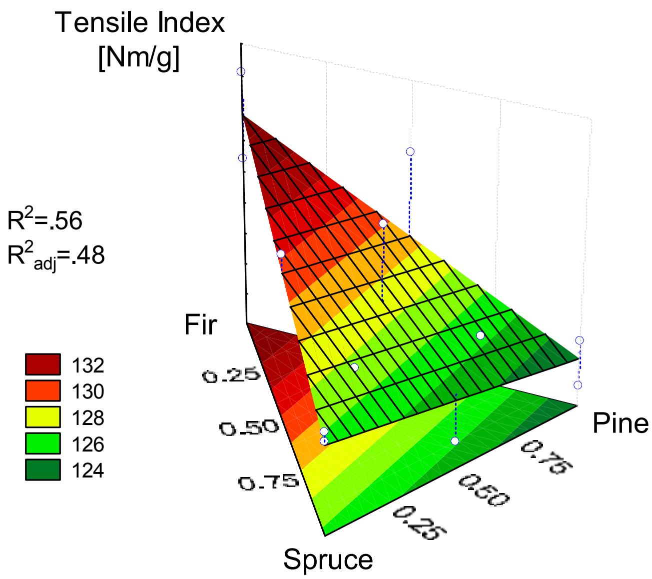

Figure 29. Tensile index of kraft pulp as a function of mixture composition at site SPF-1 (CSF = 300 ml)

Of the two models that were found for burst index, only one is deemed significant enough to be used for predictions. The model for site 3 is linear and predicts a small drop in burst index with increasing pine content.

Tear index could be modeled successfully only for site 2, where the model is linear but no significant change is predicted for changing spruce to pine ratio. At the other two sites the scatter in tear index is large and thus no real change in average tear index with changing mixture composition can be detected.

Zero span breaking length is a test that depends mostly on the individual fibre strength and thus differs from other strength properties which to a large degree also depend on sheet bonding. Of the resulting models, one is linear while the others show some interaction between species, thus not leaving a clear picture of what relationship can be expected. While pine in general shows a slightly larger zero span strength than spruce, an increase in pine content does not necessarily lead to an increase in zero span due to the interaction terms. However, the correlation coefficients for the two models that do show some interaction are low, and predicted changes are very small. Thus, in general not much change in zero span strength is expected, and whether zero span increases or decreases depends on the origin of chips. Zero span behaviour for site 3, which is described by the more reliable linear model, is illustrated in Figure 30.

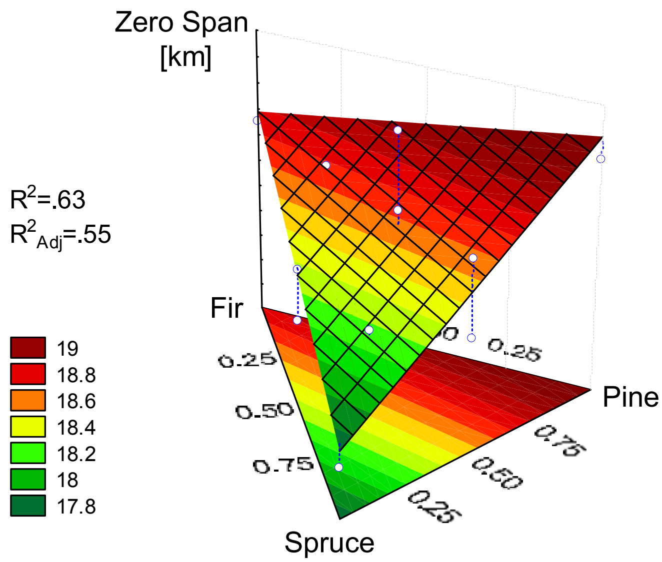

Figure 30. Zero span breaking length of kraft pulp as a function of mixture composition at site SPF-3 (CSF = 300 ml)

<u>Handsheet variables: Sheet structure</u>

No clear picture of the behaviour of sheet density as a function of mixture composition was found. Also, none of the species results in higher sheet density than the other species in general. Only two sites could be modeled. Both models are linear but while at site 2 a small increase in sheet density is predicted, no change is predicted at site 3. At site 3, overall differences between species are not more than 10 kg/m^3, which might be too low to be meaningful. Differences in sheet density overall with changing mixture composition thus probably will not be important.

Interestingly, differences in air resistance, on the other hand, are quite large between different sites, and also can differ substantially for one species. Models for air resistance are linear with the exception of site 2 (but this model is of less significance and results seem questionable). Due to the large differences for air resistance within one species, the prediction for air resistance with increasing pine content can be from no change at all up to a rather large drop.

Sheffield roughness also shows large variations for single species at different sites. There again is no clear picture of one species causing higher or lower roughness in general, but this is really site dependent. As with air resistance, models for site 1 and 3 are linear, but at site 2 some interaction is predicted. However, the differences between absolute values of pure species at that site are quite small, making it more difficult to find a reliable model. Also, correlation coefficients for all models are relatively low. Still, the possibility of such interactions should not be dismissed. For the three sites included in this study, there is either no change or an increase in roughness with increasing pine content predicted, which agrees with air resistance predictions. However, as there are changes in air resistance or roughness, differences in sheet density in general would also be expected, but this is not the case here.

Handsheet variables: Optical properties

Optical properties of unbleached kraft pulp are less important, but scattering coefficient is related to inter-fibre bonding and is thus also an indication of expected sheet strength. Opacity is closely related to scattering coefficient.

For scattering coefficient, a significant model was found only for two sites. At these sites the relationship is linear, and spruce has the lowest scattering coefficient as expected. However, as fir has a higher scattering coefficient than pine, an increase in pine content with a corresponding decrease in fir content does not necessarily lead to an increase in scattering coefficient.

In agreement with scattering coefficient, opacity also shows linear mixing relationships, and at all sites, fir fibres make a more opaque sheet than pine, which in turn is more opaque than spruce. A small increase in opacity with increasing pine content (and small fir content) is predicted at all sites.

In summary, subtle changes can be expected for pulp quality and pulping behaviour for kraft pulps that, however, may often be too small to be detected. Pulp yield most likely will drop slightly, which can be an issue, while kappa number for comparable H-factors will decrease only very little if at all. The model results for the three sites are very similar, thus there seems to be little influence from wood origin (site) on pulping behaviour. Fibre properties, however, depend more on the origin of the wood. The behaviour of fibre length and coarseness with changing mixture composition can be modeled with linear relationships and thus any expected changes depend on the relation of fibre properties of the single species to each other.

Handsheet properties were difficult to model, particularly strength properties. Mostly, there is either no change in strength with increasing pine content or strength properties are slightly deteriorating. However, in some cases a small increase in strength properties was seen as well. While these results should be seen with much caution, they imply that the shift to higher pine contents will not necessarily be detrimental for pulp strength. For sheet structure properties, findings vary. For sheet density no statement can be made whether it is expected to increase or decrease, while air resistance generally decreases or does not change and roughness increases. Variations between different sites and species can be large, particularly for air resistance. Opacity in most cases is predicted to increase slightly.

Overall, the behaviour of kraft pulp with changing mixture composition is different from what was expected. In general, spruce is assumed to be a finer fibre with superior strength properties, which should lead to decreasing pulp quality for increasing pine content. This was not conclusively shown in this study. The accuracy of models to describe handsheet properties might also be a problem; however it seems that in many cases differences between spruce and pine fibres can be very small and in that case not much change in pulp quality is expected.

3.3.3.2 Site influence

As before for TMP pulping, we also looked into a possible correlation of site indices with model behaviour for the kraft pulps by comparing model coefficients with site indices for the different sites.

For kappa number and pulp yield, there is no apparent relationship between site indices and model coefficients; however the differences between sites for the model outcome are very small as noted earlier. Thus, site influence in general seems to have little influence on pulping properties at least for the chosen sites. For fibre properties (average length and coarseness), there is no relation to site index either. While the model coefficients (and thus values for pure species) differ sometimes greatly for different sites, this is not correlated with site index. Other site related factors apart of site index must also be important. This was also observed for fibre properties of TMP pulp.

For handsheet properties, there is no obvious relation between linear model coefficients and site index either. However, as modeling was difficult and only a limited number of models are available, this is not necessarily a meaningful observation.

Neither for TMP nor for kraft models is there an obvious relationship between site index and model coefficients. Still, for most properties there are definite differences in properties and thus in model outcome for different sites, but it is not possible to describe this influence of wood origin by simply adding site index as a further variable to the models. The prediction of fibre properties from site index in general is difficult due to the large variability, and larger sample sizes and site ranges than used in this study would be needed. However, it is still possible to consider the expected ranges of possible changes based on predictions from the three different sites as an estimate of what range of change can be expected in the field. The actual changes that will be seen, however, will not only differ from mill to mill, but will also change within one mill dependent on the origin of fibre supply. Such variations based on fibre supply have been present even before the mountain pine beetle epidemic.

3.4 Changes of pulp quality and pulping properties: A specific scenario

In the following section, a specific example is evaluated where SPF mixture composition is assumed to change from 30:65:5% spruce:pine:fir to a ratio of 10:90:0% (see tables 14 and 15). The first point resembles the SPF mixture composition that mills used to receive, while the second point is the mixture composition that is expected in the coming years when harvest of mountain pine beetle killed pine will be high.

3.4.1 Thermomechanical pulping

Note: The predicted changes are for models at a constant CSF of 100 ml (except the CSF prediction which is at constant SRE).

Table 14. Predicted changes of pulp and handsheet properties for TMP pulp for SPF ratio changing from 30:65:5 to 10:90:0

	Site SPF-1	Site SPF-2	Site SPF-3
SRE [MJ/kg]	11.3 → 11.6	-	11.4 → 11.5
CSF [ml]	132 → 150	-	128 → 129
LWL [mm]	1.86 → 1.85	1.89 → 1.87	2.00 → 1.92
Fines P-200 [%]	No change	-	No change
Long fibres R-48 [%]	60 → 59	No change	No change
Tensile index [Nm/g]	45 → 43	43 → 42	42 → 41
Burst index [kPa·m^2/g]	3.0 → 2.9	No change	3.0 → 2.8
Tear index [mN·m^2/g]	9.0 → 8.6	-	-
Sheet density [kg/m^3]	354 → 347	No change	352 → 346
Sheffield roughness [SU]	209 → 221	-	230 → 242
ISO Opacity [%]	96.5 → 96.7	96.7 → 96.9	97.0 → 97.5
Scattering coefficient [cm^2/g]	598 → 605	599 → 610	607 → 616
Brightness [%]	-	-	54.8 → 54.0

Summarizing for TMP pulping for all three sites, SRE for 100 ml CSF can increase up to 3%, while CSF at constant SRE can increase up to 15%. In both cases it is also possible that no change will be seen. Average fibre length can decrease up to 0.1 mm, which is not significant, and fines and long fibre fraction are not expected to change.

Tensile index decreases between 2% and 5% and burst index decreases from 0 to 7%. For tear, a prediction was possible only for one site (a decrease of about 5%) and thus the result is not representative. Sheet density can drop by up to 2%, while Sheffield roughness can increase up to 6%, however there is not always a change.

Values for ISO opacity slightly increase by an absolute value of 0.2% to 0.5%, while a relative increase in scattering coefficient of 1%-2% is predicted, which again is very small. The brightness drop of 0.8% at site 3 cannot be considered general. Extent of bluestain of the pine chips will have a large influence on brightness.

Comparing relative changes for the three sites, the changes in optical properties are about the same for all sites, but strength properties, sheet density and roughness are more impacted at site 1 and 3, less at site 2. Pulping properties are differently affected at site 1 and 3, with site 3 experiencing no change in SRE and CSF, while at site 1 an impact can be seen. The earlier discussion of fibre properties (length and length distribution) showed the largest differences between species (particularly spruce and pine) at site 1 and 2, while differences at site 3 are lower. Thus, the difference in fibre length and distribution alone also cannot explain the differences in pulp quality changes for wood from different sites. Further knowledge about fibre properties would be necessary to discuss possible fibre property influence on changes in TMP SPF mixtures.

3.4.2 Kraft pulping

Note: The models are for prediction of pulp properties after kraft pulping with subsequent PFI mill treatment to a CSF of 300 ml. Also, one should keep in mind that model correlation for kraft pulp for strength properties and to a lesser degree for other handsheet properties is not good.

Table 15. Predicted changes of pulp and handsheet properties for kraft pulp for SPF ratio changing from 30:65:5 to 10:90:0

	Site SPF-1	Site SPF-2	Site SPF-3
Kappa	31.6 → 31.2	30.7 → 30.3	No change
Pulp yield [%]	45.0 → 44.2	46.4 → 45.9	45.7 → 44.7
LWL [mm]	2.69 → 2.71	2.88 → 2.84	3.00 → 2.95
Coarseness [mg/m]	0.149 → 0.147	0.156 → 0.152	0.173 → 0.168
Tensile index [Nm/g]	124 → 123	-	-
Burst index [kPa·m^2/g]	-	-	11.1 → 10.8
Tear index (1-ply) [mN·m^2/g]	-	12.0 → 11.8	-
Zero span break length [km]	17.5 → 17.2	-	18.7 → 19.0
Sheet density [kg/m^3]	-	No change	No change
Sheffield roughness [SU]	97 → 98	No change	81 → 86
Air resistance [s/100 ml]	No change	123 → 130	96 → 78
ISO Opacity [%]	89.9 → 90.2	89.3 → 89.7	89.4 → 89.8
Scattering coefficient [cm^2/g]	-	No change	143 → 147

In summary, for kraft pulping including all three sites, the expected range of change in pulping properties is about 0-0.5 points in kappa, and 0.5% to 1% absolute decrease in pulp yield. Changes in average fibre length are too small to be significant. Coarseness is predicted to decrease between 0.02 and 0.05 mg/m, or up to 3%.

Statements for strength properties are difficult to generalize as strength properties could not be modeled for all sites. The only tensile model predicts an insignificant decrease of 1% but this could be different for other sites. Burst index is also predicted for only one site and decreases by about 3%. Zero span breaking length is also predicted for two sites and changes by ±2%. The only model for tear does not predict a meaningful change.

No change for sheet density is predicted, and for Sheffield roughness the increase is between 0-6%. Air resistance increases by 6% for one site, which is unexpected but the model is not good. At the other site that was modeled, it decreases by 20%. Thus, larger changes for air resistance can be expected.

The increase in opacity is predicted as about 0.5% point (absolute change) at all sites. Scattering coefficient (modeled only for two sites) increases by 0-3%.

Comparing the three sites, changes are largest for site 1 and 3 for pulp yield. Changes in opacity are about the same in all sites. Air resistance and roughness increase most for site 3. Strength properties can only be compared for site 1 and 3, and not for tensile, which is probably the most important strength property. Tensile was modeled only for site 1 where the decrease is not significant. Burst index increases slightly more at site 3. Zero span experiences similar relative changes at both site 1 and 3, but at site 3 it actually increases. Average fibre length and coarseness changes are small at all sites, but smallest at site 1. Overall, site 3 probably shows the biggest impact from the changing mixture composition.

If the difference in fibre properties between species at one site would be an indicator for the magnitude of expected change in pulp quality for different mixture compositions, then changes indeed would be expected larger at site 3, where differences in collapse index and fibre length between spruce and pine are larger than at site 1. At site 2, larger changes in pulp quality than at site 1, however, would be expected as well, but this cannot be verified due to the missing models for strength properties at that site. To rigorously quantify the extent of influence of fibre properties on pulping and handsheet properties, a statistical analysis would be necessary. In other mixed pulping experiments, Wang and McKimmy (1977) have shown that fibre morphological factors account for 54% to 97% of the variations in handsheet properties in single species pulping.

3.5 Low consistency refining behaviour

Results from Escher-Wyss refining are used to discuss the possible influence of changing SPF mixture composition on low consistency refining behaviour. Only a few samples were refined and results thus are preliminary.

As SPF kraft pulps are commonly used as reinforcement pulps, tensile strength improvement is one of the main targets of low consistency refining. This is achieved through internal and external fibrillation which increases collapsibility and bonding potential of the fibres. Other effects are a decrease in freeness, both due to increased fibrillation as well as generation of fines material, and an increase in sheet density due to improving sheet consolidation. While tensile strength increases, tear strength, which depends more on individual fibre strength and length, decreases due to fibre shortening and weakening of fibres. Opacity and scattering will decrease even though more fines material is generated, as the decrease in free surface area due to better bonding outweighs the effect of fines generation.

All these effects are seen for the samples refined in the Escher-Wyss in this study (see Appendix G). However, differences in refining response for pulps from pure species as well as for different refining settings (particularly different refining intensity) are apparent. Pure pine and spruce pulps refine relatively similarly. At the high intensity of SEL = 2.5 J/m, both pulps develop a maximum strength at around 150 kWh/t (Figure 31). If refined further, the tensile index drops, thus at high energy and intensity some fibre damage and shortening obviously takes place. This is supported by comparing BauerMcNett fractions that show a definite increase in fines and a sharp drop in long fibre fractions at 2.5 J/m for spruce and pine. Interestingly, both mixture pulps also refine very similarly, independent of the ratio, but their refining behaviour noticeably differs from that of spruce and pine at 2.5 J/m SEL. They do not develop a local maximum within the used energy range, and do not reach as high tensile strength as pine and spruce do. The refining response of fir is relatively similar to the mixture pulps.

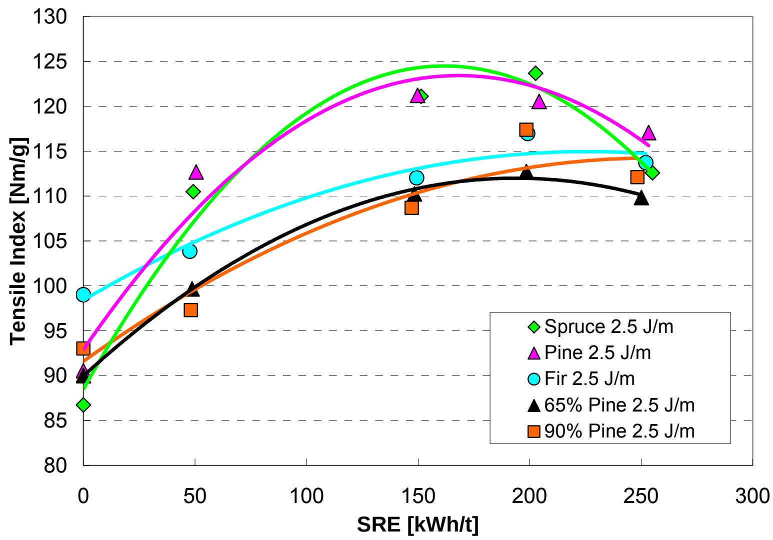

Figure 31. Tensile strength development with Escher-Wyss refining at SEL = 2.5 J/m

At the lower SEL value of 1 J/m however (Figure 32), refining response of all pulps is relatively similar. Only spruce seems to go through a local maximum with increasing energy. Mixture pulps still are at a slightly lower level of tensile than spruce or pine.

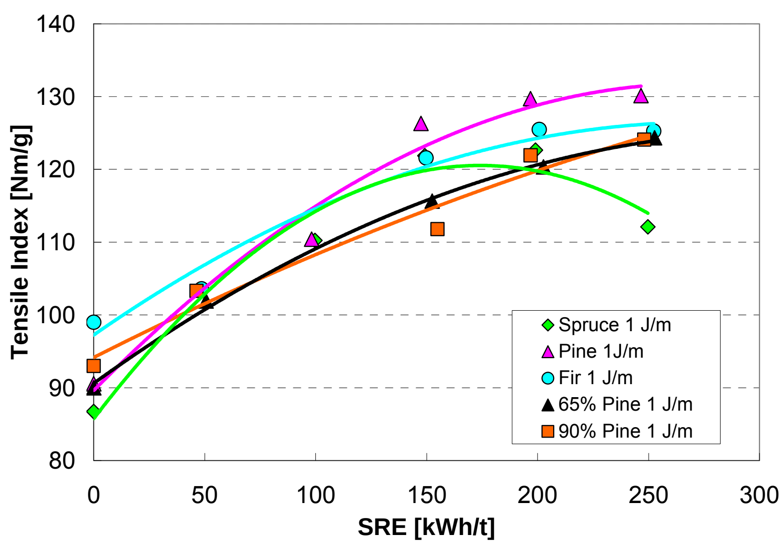

Figure 32. Tensile strength development with Escher-Wyss refining at SEL = 1 J/m

It is also interesting to note that, when comparing the influence of the two different SEL's, spruce and pine show a faster increase in tensile when refined at the higher SEL of 2.5 J/m, while fir and the mixtures reach a higher tensile at a given energy at the lower value for SEL of 1 J/m. The latter is the more commonly known behaviour. Based on these results, it may appear that mixtures should rather be refined at a lower intensity but higher energy, while refining of spruce or pine can be done at either high or low intensity with medium refining energies. Also, it should be pointed out that surprisingly, the low consistency refining response of mixtures does not seem to depend much on the mixture ratio within the ranges used for the study. This should be confirmed with further trials.

The freeness drop is more pronounced for the mixtures than for spruce and pine, with fir in between (Figure 33). Differences in freeness at a given energy are larger at SEL = 2.5 J/m. Freeness drop is generally closely related to the generation of fines. However, comparing the fines fraction (P-200 of BauerMcNett classification, available only for SRE = 250 kWh/t, Figure 34) does not confirm these results: The mixture pulps have a lower fines fraction than the pine or spruce pulps, thus freeness would be expected higher for the mixtures. Therefore, fibre development must be more pronounced for the mixture pulps at a given energy, thus producing a denser pulp pad during dewatering that holds back also more fines and thus lowers the freeness, while the pure species may produce a more open pored pulp pad.

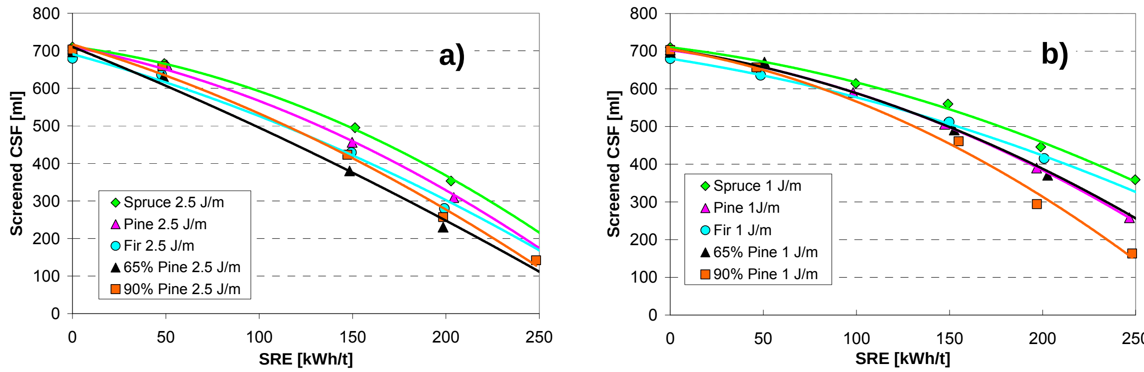

Figure 33. CFS decrease with LC Escher-Wyss refining at a) 2.5 J/m and b) 1.0 J/m

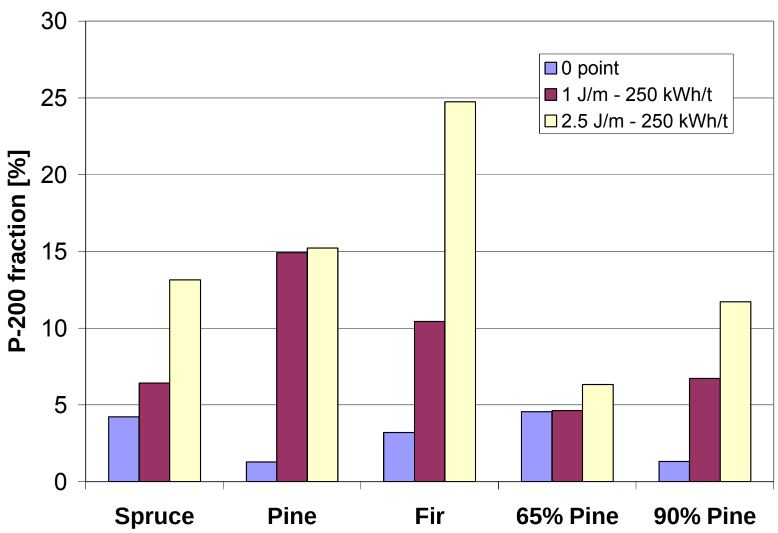

Figure 34. Fines generation with low consistency Escher-Wyss refining

Fibre length distributions were determined by BauerMcNett (Appendix G) and with the FQA fibre analyzer (at 0, 100 and 250 kWh/t). Results confirm that for the high intensity at high energy refining (2.5 J/m, 250 kWh/t), fibre cutting takes place as distributions are markedly shifted to lower fibre lengths. At the lower refining intensity (SEL = 1 J/m), less fibre cutting takes place. It should be noted that for the two mixture pulps, distributions at 250 kWh/t and 1 J/m are shifted further to the left than for spruce or pine (see Figure 35, remaining fibre distributions are shown in Appendix G), thus suggesting that more fibre cutting takes place. Still, the tensile development at SEL = 1 J/m is relatively similar for all pulps and mixture tensile indices are higher than for spruce at the highest energy. This illustrates that fibre development (fibrillation) is similarly important for tensile.

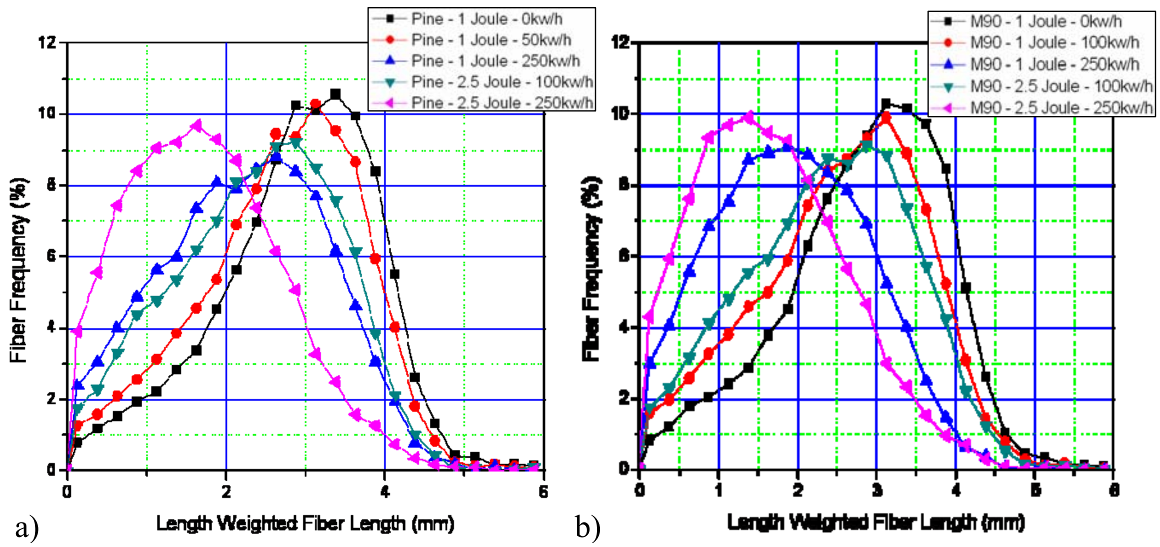

Figure 35. Fibre length distributions of a) pure pine pulp and b) 90% pine mixture

Other handsheet properties were also tested. Sheet density between samples as well as between different SEL's does not differ significantly at a given freeness. Opacity and scattering coefficient, when compared against freeness, are lowest for spruce and highest for fir. They depend on fines content as well as sheet bonding. The high numbers for fir are likely related to the high fines content of fir.

Particularly the results for tensile strength suggest that the pine and spruce pulps may consist of stronger fibres that are less prone to fibre damage and cutting than fir pulps and mixture pulps, and therefore can be refined at higher intensity. However, as the mixture pulps have been made from the same chips as the pure pulps, such a result could only be explained with possible differences in how the pulping process influences fibre chemistry and morphology when pulped as pure or mixture chip blends. As neither the previously discussed differences in fibre properties, nor results from FQA and BauerMcNett measurements for the LC-refined pulps could offer an obvious explanation of such differences, results from these preliminary LC trials should be seen cautiously. While they do suggest that differences in refining behaviour for pulps made from pure species or chip mixtures exist, more extensive trials and fibre analysis would be necessary to confirm these results and offer explanations for the mechanism that causes these differences. Particularly, low consistency refining trials of bleached samples would be required to establish the influence of bleaching on any existing differences in fibre chemistry. An important finding in the context of this study is that increasing pine content seems to have little influence on low consistency refining response for mixtures. However, the results also illustrate that refining response in Escher-Wyss refining and PFI mill refining can be different, as the latter resulted mostly in linear models describing the influence of chip mixture ratio changes, which is not the case for the limited data set of the Escher-Wyss refining. Thus, the behaviour of mixture pulps in industrial LC refining may show differences from what was seen for PFI mill refining.

4 Conclusions

The influence of increasing pine content in SPF mixtures on pulp quality and pulping behaviour was investigated. It was found that some changes can be expected, however they are mostly small. Whether pulp and pulping properties change depends on the origin of the wood chips and is most likely related to the extent of differences in fibre and wood properties of the three species.

The most important changes that were found are:

- A likely decrease in pulp yield for kraft pulping.
- The possibility for higher energy requirements in TMP pulping.
- A possible small drop in strength properties (kraft and TMP).
- A small increase in air resistance and sheet roughness.
- A small improvement in opacity and scattering coefficient.

The first two points obviously will have an economic impact on pulp mills. The technical implications of these changes for the pulping process are mainly slight adjustments that need to be done regarding target SRE for TMP pulp. For kraft pulping, in some cases kappa number can also change with changing pine content, but the changes seen in this study are small and thus likely would not make an adjustment of target H-factor necessary. Also, increasing extractives content due to increasing pine content can lead to problems such as foaming, which might need process adjustments.

Changes in pulp strength also can have an economic impact if they are large enough so that the pulp quality is not satisfactory to the customer. However, in most cases the pulp strength decrease (if any) will probably be small enough to be tolerated. A calculation of collapse index, which is closely linked to sheet strength, showed a smaller collapse index for pine than for spruce, but differences are small when compared to collapse index numbers for competitor pulps, indicating that the increasing pine content does not threaten the market advantage of B.C. pulps. Also, as the magnitude of decrease in pulp strength is not constant, but depends on wood origin, it will differ for each individual case how much increase in pine content can be tolerated. Good chip management might help to lessen the variation in impact of increasing pine content.

In this study, it was also shown that while wood origin is important, site index (site productivity) is not a good indicator for expected changes. This is possible considering that pulp fibre properties ultimately control the pulp quality that can be achieved. Fibre properties also depend on the wood origin and variations between different sites were found, but they are not correlated with site index either. The differences between different sites can be as large or larger than differences between species. On the other hand, it is possible that if a larger number of sample sites would be included, some correlation between fibre (or pulp) properties and site index could be found (see Trent et al. 2006). In any case, due to the dependence of fibre properties on site, it will be important to monitor the incoming chip quality. The outcome of other research, as in Hsieh et al. 2006, which explores options for rapid assessment tools for wood quality based on near-infrared technology, might help with this task.

One possibly important finding is that, for the chosen sites, the variation in fibre length and to a lesser degree width distribution between different sites is lower for pine and also fir than for spruce. If this holds true in general, there is a possibility that with increasing pine content, the pulp mills will see an overall more uniform pulp, as differences that are caused by wood origin should somewhat diminish. However, SilviScan measurements of wood cores showed that for some properties, the variation for pine fibres was relatively small for sites 1, 2 and 3, but larger when sites 4 and 6 were considered as well, and if this is the case for pulp fibres, the actual variation in pine fibre properties for wood of different origin might be larger than what combined results from site 1 to 3 imply.

Overall, changes in SPF processing and pulp quality are expected to be small. However, they are somewhat dependent on wood origin, thus incoming wood and fibre quality in pulp mills should be monitored closely. Results from preliminary Escher-Wyss low consistency refining trials also showed that the mixture response to increasing pine content may differ qualitatively depending on refining conditions. These findings would need to be confirmed with further trials, particularly including bleached samples.

The site specific differences in fibre properties and resulting differences in pulping behaviour and pulp quality, as well as the large variations of wood and fibre properties for each species within one site show the importance of undertaking such detailed trials rather than basing any conclusions on single species (tree) samples of unknown origin. Clearly, more pulping samples would aid in confirming the findings presented in this study.

5 Acknowledgements

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8 Appendices

Appendix A: Fibre properties of trees from five possible sample sites

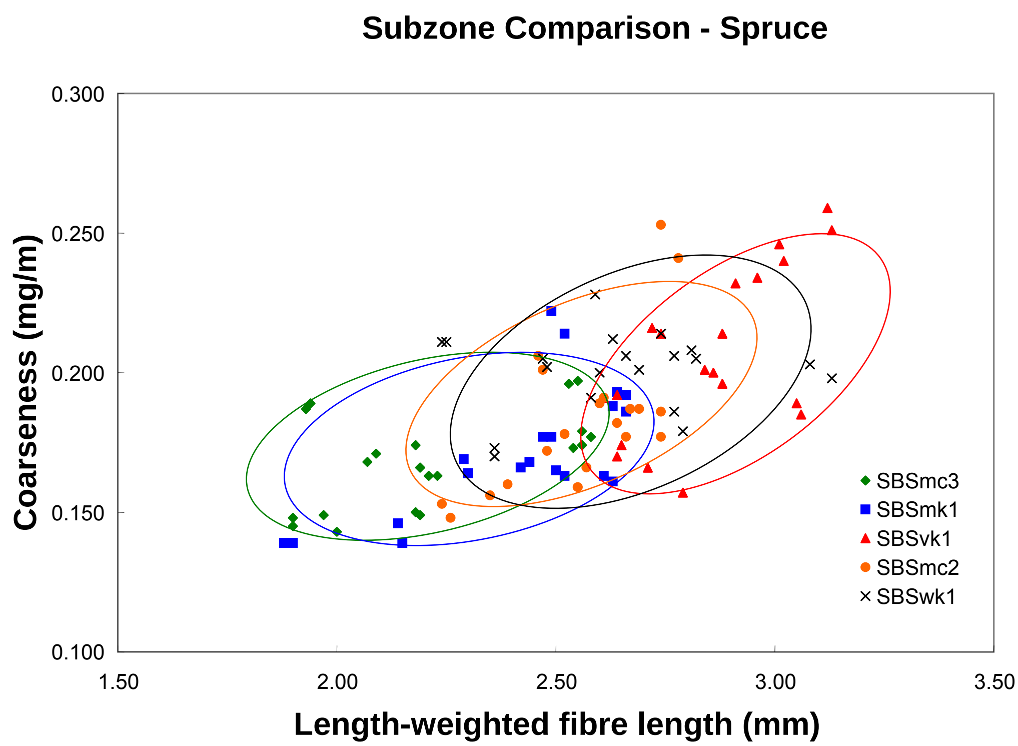

Figure A-36. Fibre coarseness versus length-weighted fibre length from five sites for white hybrid spruce for age class 60-80 years.

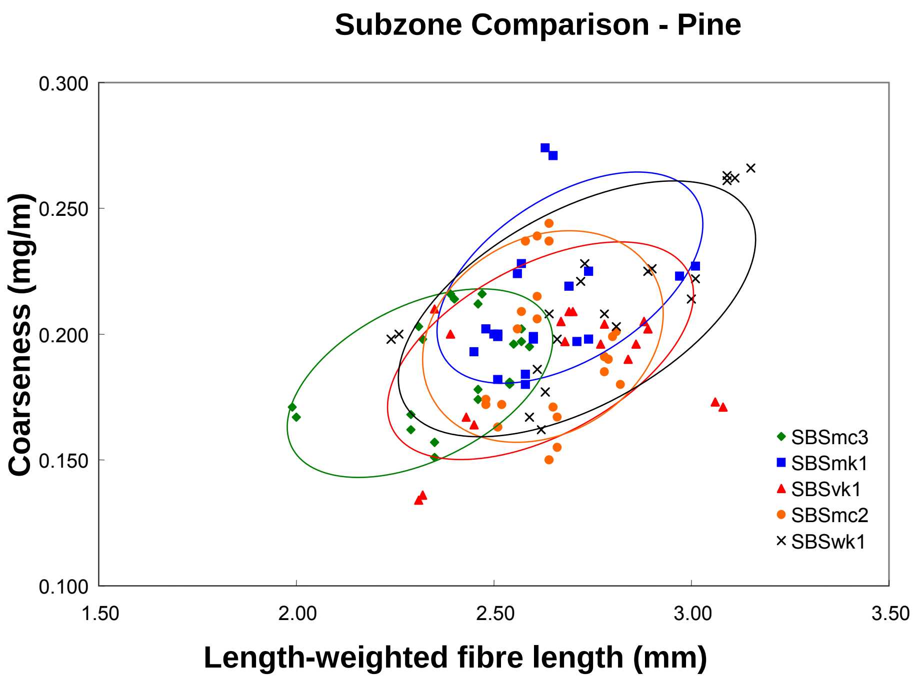

Figure A-37. Fibre coarseness versus length-weighted fibre length from five sites for lodgepole pine for age class 60-80 years.

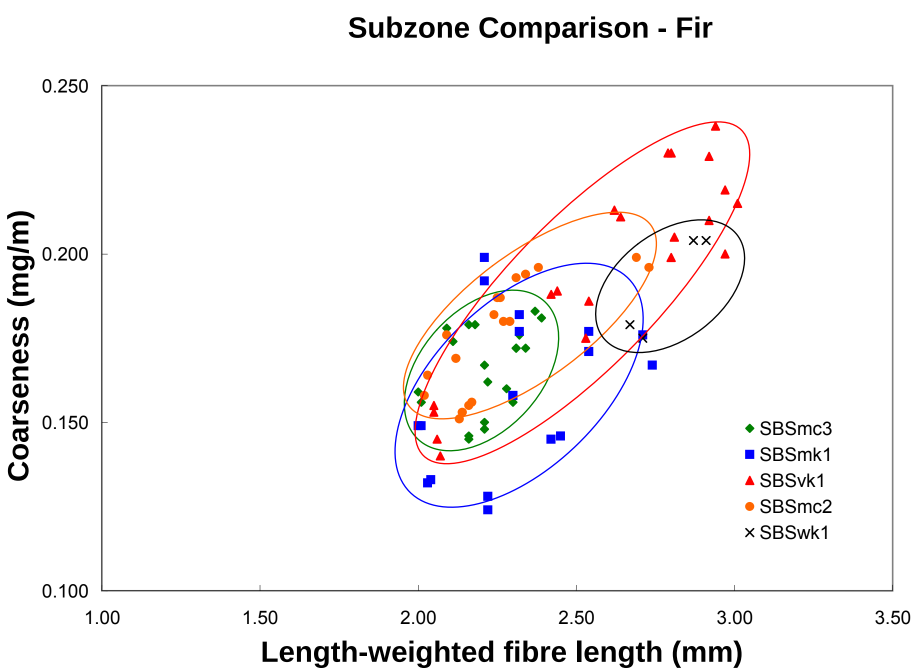

Figure A-38. Fibre coarseness versus length-weighted fibre length from five sites for subalpine fir for age class 60-80 years.

Appendix B: Chip quality data

Table B-16. Chip quality data

SPF - Mature Wood			
Sample	SPF 1		
	Spruce	Pine	Fir
45 mm round hole (overlarge), %	1.0	1.0	0.7
10 mm slot (overthick), %	5.9	9.3	6.0
7 mm round hole (accept), %	88.8	87.3	90.6
3 mm round hole (pins), %	3.4	1.9	2.5
Pan (fines), %	0.9	0.4	0.3
Chip Packing Density, kg/m^3	203	219	180
Chip Basic Density, kg/m^3	415	430	354
Chip solid content when logs were chipped, %	64.6	73.4	55.1
Standard Deviation			
Sample	SPF 1		
	Spruce	Pine	Fir
45 mm round hole (overlarge), %	0.9	0.0	1.0
10 mm slot (overthick), %	1.6	1.3	1.9
7 mm round hole (accept), %	2.0	0.8	1.3
3 mm round hole (pins), %	0.5	0.8	0.6
Pan (fines), %	0.4	0.4	0.2

SPF - Mature Wood			
Sample	SPF 2		
	Spruce	Pine	Fir
45 mm round hole (overlarge), %	0.5	1.3	0.6
10 mm slot (overthick), %	3.5	7.9	6.8
7 mm round hole (accept), %	90.2	86.5	88.5
3 mm round hole (pins), %	4.9	3.8	3.7
Pan (fines), %	1.0	0.5	0.3
Chip Packing Density, kg/m^3	177	190	157
Chip Basic Density, kg/m^3	371	407	333
Chip solid content when logs were chipped, %	52.7	73.0	51.3
Standard Deviation			
Sample	SPF 2		
	Spruce	Pine	Fir
45 mm round hole (overlarge), %	0.1	0.3	0.2
10 mm slot (overthick), %	1.0	0.6	1.0
7 mm round hole (accept), %	0.7	0.7	1.3
3 mm round hole (pins), %	0.4	0.8	0.4
Pan (fines), %	0.1	0.1	0.1

SPF - Mature Wood			
Sample	SPF 3		
	Spruce	Pine	Fir
45 mm round hole (overlarge), %	0.1	0.5	0.0
10 mm slot (overthick), %	4.4	9.3	3.0
7 mm round hole (accept), %	91.6	85.5	88.8
3 mm round hole (pins), %	3.6	4.1	7.2
Pan (fines), %	0.3	0.7	0.9
Chip Packing Density, kg/m^3	172	222	179
Chip Basic Density, kg/m^3	361	417	350
Chip solid content when logs were chipped, %	48.9	67.3	51.1

Standard Deviation			
Sample	SPF 3		
	Spruce	Pine	Fir
45 mm round hole (overlarge), %	0.1	0.5	0.1
10 mm slot (overthick), %	0.8	1.3	1.2
7 mm round hole (accept), %	0.6	1.4	1.9
3 mm round hole (pins), %	0.4	2.1	0.6
Pan (fines), %	0.0	0.4	0.2

Appendix C: Pulping and handsheet physical testing properties of kraft and thermomechanical pulps

Table C-17. Properties of Thermomechanical Pulps from SPF Chip Mixtures at 100 mL CSF (Site 1)

	Mixture Composition S (%)	P (%)	F (%)	Specific Refining Energy (MJ/kg)	R-48 Fraction (%)	Fines (P-200) (%)	L. Weighted Fibre Length (mm)	Apparent Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Tensile Index (N·m/g)	Tear Index (mN·m2/g)	Sheffield Roughness (SU)	Brightness (%)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
1	100	0	0	11.3	61.5		1.97	382	3.4	50	8.6	180	54	96.5	567
2	0	100	0	11.8	58.1	28.0	1.81	348	2.8	43	8.3	239	53	97.1	618
3	0	0	100	11.2	60.7	25.6	2.00	346	3.1	44	9.2	190	56	96.7	617
4	50	50	0	11.2	61.3	26.6	1.93	362	3.2	48	9.0	198	55	96.7	599
5	50	0	50	11.8	61.8	25.3	1.90	364	3.3	48	8.9	182	56	96.4	587
6	0	50	50	11.4	61.7	24.4	1.73	337	2.8	41	9.2	208	56	96.4	599
7	33.3	33.3	33.3	11.3	60.2	27.0	1.80	343	3.0	45	9.1	215	56	96.2	608
8	66.7	16.7	16.7	11.6	60.8	26.4	1.91	363	3.2	45	9.0	197	57	95.9	601
9	16.7	66.7	16.7	11.4	57.9	27.7	1.86	355	2.9	44	8.9	203	57	96.3	614
10	16.7	16.7	66.7	11.1	60.7	26.1	1.96	346	3.0	41	9.3	213	56	96.1	602
11	100	0.0	0.0	11.6	61.4	25.7	1.97	374	3.3	48	8.6	172	57	95.4	563
12	0	100	0.0	12.0	59.4	27.5	1.85	343	3.0	43	8.7	215	56	96.2	585
13	0	0	100	11.1	59.5	26.6	1.89	354	3.1	43	8.9	184	56	96.3	596
14	33.3	33.3	33.3	11.0	59.4	27.2	1.86	360	3.0	43	9.0	181	57	96.0	600
15	10	90	0	11.9	59.9	27.9	1.92	358	3.0	45	9.1	211	56	96.7	620
16	30	65	5	11.6	59.9	27.9	1.89	364	3.0	44	8.6	207	56	96.5	603

Table C-18. Properties of Thermomechanical Pulps from SPF Chip Mixtures at 100 mL CSF (Site 2)

	Mixture Composition S (%)	P (%)	F (%)	Specific Refining Energy (MJ/kg)	R-48 Fraction (%)	Fines (P-200) (%)	L. Weighted Fibre Length (mm)	Apparent Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Tensile Index (N·m/g)	Tear Index (mN·m2/g)	Sheffield Roughness (SU)	Brightness (%)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
1	100	0	0	10.6	63.2	23.8	2.02	356	3.1	47	8.7	237	54	96.1	554
2	0	100	0	11.2	60.4	26.6	1.89	351	2.9	41	8.6	239	56	96.9	625
3	0	0	100	10.5	60.0	25.8	1.81	338	2.8	41	8.9	228	55	97.7	637
4	50	50	0	10.7	60.7	25.8	1.88	346	3.1	44	9.0	232	56	96.7	608
5	50	0	50	10.5	60.9	25.0	1.90	353	3.1	46	8.4	201	54	97.1	593
6	0	50	50	10.6	61.0	25.2	1.87	348	3.0	44	9.0	211	54	97.4	615
7	33.3	33.3	33.3	10.6	60.1	26.1	1.85	347	3.0	43	8.4	210	55	96.8	605
8	66.7	16.7	16.7	11.0	62.2	24.9	1.99	358	3.0	45	8.7	196	54	96.6	573
9	16.7	66.7	16.7	11.1	61.3	25.5	1.82	355	3.1	42	8.4	234	55	96.7	596
10	16.7	16.7	66.7	10.6	59.9	25.8	1.72	350	3.0	44	8.0	216	55	97.0	615
11	33.3	33.3	33.3	11.1	63.1	22.6	1.80	358	3.1	42	8.2	205	52	97.5	602
12	66.7	16.7	16.7	11.3	62.4	25.2	1.85	362	3.2	43	8.7	224	54	96.5	578
13	16.7	66.7	16.7	11.8	61.3	27.4	1.89	364	3.2	46	8.7	206	54	97.0	597
14	16.7	16.7	66.7	11.2	59.6	28.6	1.77	340	3.0	44	8.7	218	54	97.2	623
15	10	90	0	11.5	59.8	29.1	1.75	361	3.1	43	8.5	203	55	96.9	608
16	30	65	5	11.5	60.9	28.2	1.80	354	3.0	44	8.7	220	55	96.7	596

Table C-19. Properties of Thermomechanical Pulps from SPF Chip Mixtures at 100 mL CSF (Site 3)

	Mixture Composition S (%)	P (%)	F (%)	Specific Refining Energy (MJ/kg)	R-48 Fraction (%)	Fines (P-200) (%)	L. Weighted Fibre Length (mm)	Apparent Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Tensile Index (N·m/g)	Tear Index (mN·m2/g)	Sheffield Roughness (SU)	Brightness (%)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
1	100	0	0	11.0	59.9	27.6	1.93	382	3.4	49	9.0	180	58	94.9	574
2	0	100	0	11.4	59.1	28.0	1.89	344	2.7	42	8.5	263	54	97.6	627
3	0	0	100	9.6	62.4	22.9	2.02	328	2.8	42	9.2	240	55	96.9	604
4	50	50	0	11.8	60.4	27.3	2.01	361	3.1	43	8.7	192	56	96.6	607
5	50	0	50	11.6	61.2	25.9	2.01	348	3.2	43	9.3	227	54	96.6	586
6	0	50	50	10.1	60.9	25.3	1.91	327	2.8	41	9.3	232	53	97.1	605
7	33.3	33.3	33.3	10.9	61.4	25.3	2.00	352	3.0	42	9.3	229	56	96.8	585
8	66.7	16.7	16.7	11.2	61.7	25.7	2.05	351	3.0	42	9.5	226	57	96.5	602
9	16.7	66.7	16.7	11.4	61.0	27.0	2.02	349	3.1	40	9.3	238	54	97.1	606
10	16.7	16.7	66.7	10.4	61.7	24.5	1.96	343	3.0	41	9.2	230	54	96.9	597
11	50	50	0.0	11.4	61.6	26.1	2.05	354	3.1	42	9.1	228	55	96.9	602
12	50	0	50	11.7	61.7	25.6	2.07	354	3.2	42	9.1	218	55	96.6	588
13	0	50	50	10.7	61.6	24.5	1.88	341	2.8	41	8.7	239	53	97.6	595
14	33.3	33.3	33.3	11.3	61.2	25.5	1.98	346	3.1	43	9.0	219	54	97.3	604
15	10	90	0	11.1	57.8	29.5	1.84	351	2.7	41	8.9	239	54	97.6	642
16	30	65	5	11.3	60.8	26.7	2.00	345	2.9	40	9.3	261	55	97.4	637

Table C-20. Properties of Thermomechanical Pulps from SPF Chip Mixtures at a Specific Energy of 10.0 MJ/kg (Site 1)

	Mixture Composition									
	S (%)	P (%)	F (%)	Unscreened CSF (mL)	Length Weighted Fibre Length (mm)	Apparent Sheet Density (kg/m3)	Tensile Index (N•m/g)	Tear Index (mN•m2/g)	Sheffield Roughness (SU)	Scattering Coefficient (cm2/g)
1	100	0	0	126	2.01	354	45	9.4	204	546
2	0	100	0	142	1.83	314	36	9.3	280	599
3	0	0	100	134	2.02	326	40	9.8	206	589
4	50	50	0	125	1.94	338	42	9.7	229	592
5	50	0	50	147	1.91	345	43	9.4	205	566
6	0	50	50	132	1.78	305	36	9.3	250	589
7	33.3	33.3	33.3	129	1.82	317	40	9.7	250	584
8	66.7	16.7	16.7	142	1.92	325	39	10.0	245	577
9	16.7	66.7	16.7	135	1.89	332	37	9.6	242	606
10	16.7	16.7	66.7	128	1.97	318	39	9.6	241	593
11	100	0.0	0.0	142	2.00	351	43	9.3	184	548
12	0	100	0.0	160	1.88	330	39	9.4	241	570
13	0	0	100	127	1.98	335	39	9.1	221	568
14	33.3	33.3	33.3	122	1.88	338	39	9.3	209	581
15	10	90	0	150	1.94	331	37	9.6	242	577
16	30	65	5	146	1.92	336	39	9.4	232	587

Table C-21. Properties of Thermomechanical Pulps from SPF Chip Mixtures at a Specific Energy of 10.0 MJ/kg (Site 2)

	Mixture Composition			Unscreened CSF	Length Weighted Fibre Length	Apparent Sheet Density	Tensile Index	Tear Index	Sheffield Roughness	Scattering Coefficient
	S (%)	P (%)	F (%)	(mL)	(mm)	(kg/m3)	(N•m/g)	(mN•m2/g)	(SU)	(cm2/g)
1	100	0	0	114	2.03	347	44	9.0	242	551
2	0	100	0	124	1.90	330	38	9.2	258	592
3	0	0	100	115	1.81	328	40	9.0	241	631
4	50	50	0	116	1.90	337	42	9.2	244	596
5	50	0	50	116	1.93	339	43	9.0	215	568
6	0	50	50	112	1.89	340	42	9.1	218	610
7	33.3	33.3	33.3	115	1.86	338	42	8.9	224	600
8	66.7	16.7	16.7	119	2.00	341	43	9.2	200	558
9	16.7	66.7	16.7	120	1.86	336	39	9.1	250	579
10	16.7	16.7	66.7	112	1.73	338	41	8.5	225	606
11	33.3	33.3	33.3	125	1.85	337	40	8.9	226	576
12	66.7	16.7	16.7	125	1.87	343	41	9.1	240	568
13	16.7	66.7	16.7	155	1.95	344	41	9.3	228	574
14	16.7	16.7	66.7	132	1.78	317	41	8.8	240	607
15	10	90	0	145	1.83	326	40	9.4	250	603
16	30	65	5	132	1.85	330	41	9.2	246	581

Table C-22. Properties of Thermomechanical Pulps from SPF Chip Mixtures at a Specific Energy of 10.0 MJ/kg (Site 3)

	Mixture Composition									
	S (%)	P (%)	F (%)	Unscreened CSF (mL)	Length Weighted Fibre Length (mm)	Apparent Sheet Density (kg/m3)	Tensile Index (N•m/g)	Tear Index (mN•m2/g)	Sheffield Roughness (SU)	Scattering Coefficient (cm2/g)
1	100	0	0	125	1.95	356	45	9.8	197	560
2	0	100	0	125	1.91	326	37	9.2	282	607
3	0	0	100	91	2.01	336	43	9.1	237	612
4	50	50	0	135	2.05	328	37	9.4	233	602
5	50	0	50	139	2.02	317	40	10.0	258	578
6	0	50	50	100	1.93	320	41	9.4	235	601
7	33.3	33.3	33.3	118	2.02	337	39	9.6	245	572
8	66.7	16.7	16.7	119	2.08	338	39	10.3	238	595
9	16.7	66.7	16.7	135	2.03	332	36	9.8	250	592
10	16.7	16.7	66.7	107	1.96	338	39	9.3	232	594
11	50	50	0.0	130	2.05	333	39	9.8	254	592
12	50	0	50	137	2.10	326	40	9.9	234	569
13	0	50	50	115	1.93	330	38	9.1	246	594
14	33.3	33.3	33.3	129	2.00	309	40	10.0	246	580
15	10	90	0	116	1.87	335	38	9.1	240	635
16	30	65	5	132	2.03	321	38	9.5	275	616

Table C-23. Kappa Number and Pulp Yield of Kraft Pulps from SPF Chip Mixtures after Pulping at H-factor=1420

	Site SPF-1					Site SPF-2					Site SPF-3				
	Mixture Composition			Kappa	Pulp	Mixture Composition			Kappa	Pulp	Mixture Composition			Kappa	Pulp
	S (%)	P (%)	F (%)	Number	Yield (%)	S (%)	P (%)	F (%)	Number	Yield (%)	S (%)	P (%)	F (%)	Number	Yield (%)
1	100	0	0	31.9	47.1	100	0	0	31.2	48.0	100	0	0	29.5	48.2
2	0	100	0	31.2	43.8	0	100	0	30.8	45.6	0	100	0	30.3	44.3
3	0	0	100	37.8	46.6	0	0	100	35.8	46.0	0	0	100	34.4	47.3
4	50	50	0	32.0	45.5	50	50	0	30.2	47.0	50	50	0	30.7	46.3
5	50	0	50	34.2	46.6	50	0	50	32.6	46.8	50	0	50	32.6	48.1
6	0	50	50	34.0	45.4	0	50	50	32.3	45.6	0	50	50	33.0	45.9
7	33.3	33.3	33.3	33.6	45.6	33.3	33.3	33.3	31.6	47.0	33.3	33.3	33.3	34.3	46.8
8	66.7	16.7	16.7	32.1	46.7	66.7	16.7	16.7	33.1	47.4	66.7	16.7	16.7	31.6	47.4
9	16.7	66.7	16.7	31.4	45.0	16.7	66.7	16.7	32.2	46.2	16.7	66.7	16.7	32.1	45.4
10	16.7	16.7	66.7	34.4	46.3	16.7	16.7	66.7	34.7	46.3	16.7	16.7	66.7	33.6	46.8
11	100	0.0	0.0	31.7	47.3	33.3	33.3	33.3	31.6	46.8	50	50	0.0	29.7	46.3
12	0	100	0.0	31.0	43.8	66.7	16.7	16.7	31.6	47.2	50	0	50	32.3	48.0
13	0	0	100	36.4	46.5	16.7	66.7	16.7	30.2	46.1	0	50	50	32.9	46.0
14	33.3	33.3	33.3	34.2	45.4	16.7	16.7	66.7	34.6	46.6	33.3	33.3	33.3	33.5	46.6
15	10	90	0	31.7	43.9	10	90	0	29.7	45.6	10	90	0	32.7	44.9
16	30	65	5	32.3	44.7	30	65	5	29.6	46.1	30	65	5	32.1	45.8

Table C-24. Handsheet Properties of Kraft Pulps from SPF Chip Mixtures at a CSF of 300 ml (Site 1)

	Mixture Composition S (%)	Mixture Composition P (%)	Mixture Composition F (%)	PFI Mill Revs.	Apparent Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Break Length (km)	Tensile Index (N·m/g)	Stretch (%)	Tear Index 1-ply (mN·m2/g)	Tear Index 4-ply (mN·m2/g)	Zero Span Break Length (km)	Gurley Air Resist. (s/100ml)	Sheffield Roughness (SU)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
1	100	0	0	12573	703	11.3	12.8	126	3.56	11.3	11.1	15.6	57.9	104	89.0	145
2	0	100	0	13093	712	11.6	12.4	121	3.08	10.4	10.1	16.3	64.4	86	90.7	145
3	0	0	100	13756	690	11.9	13.3	131	3.63	11.8	11.6	17.4	118.5	76	91.7	147
4	50	50	0	13697	712	12.3	12.4	122	3.29	11.7	11.1	17.8	54.8	100	89.2	131
5	50	0	50	13054	705	11.7	13.3	131	3.43	12.0	11.2	18.6	94.7	82	90.3	141
6	0	50	50	12863	705	11.9	12.6	124	3.53	11.8	11.5	19.8	97.0	83	91.0	143
7	33.3	33.3	33.3	13826	706	12.7	13.3	130	3.33	11.1	10.4	19.2	84.5	75	92.0	144
8	66.7	16.7	16.7	13507	684	11.7	12.9	127	3.18	11.0	10.6	17.7	62.0	99	89.6	147
9	16.7	66.7	16.7	13686	690	11.6	12.7	125	3.58	10.9	10.2	17.9	54.6	106	89.5	145
10	16.7	16.7	66.7	13435	693	11.7	12.8	126	3.49	10.7	10.5	17.9	94.0	80	90.9	146
11	100	0.0	0.0	13139	694	11.5	12.9	126	3.58	11.6	11.2	16.9	68.3	100	88.8	149
12	0	100	0.0	13405	703	12.1	12.7	124	3.85	11.1	10.8	17.8	62.4	110	90.5	145
13	0	0	100	13968	695	12.0	13.9	136	4.06	10.3	9.9	18.5	133.4	76	90.8	143
14	33.3	33.3	33.3	13923	696	12.3	13.5	132	3.74	11.9	11.5	19.4	66.2	81	90.0	143
15	10	90	0	13514	701	12.6	12.7	125	3.66	10.6	10.4	18.5	58.4	105	90.0	147
16	30	65	5	13990	705	12.5	13.4	131	3.88	9.9	9.6	19.3	60.3	97	89.4	143

Table C-25. Handsheet Properties of Kraft Pulps from SPF Chip Mixtures at a CSF of 300 ml (Site 2)

	Mixture Composition S (%)	P (%)	F (%)	PFI Mill Revs.	Apparent Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Break Length (km)	Tensile Index (N·m/g)	Stretch (%)	Tear Index 1-ply (mN·m2/g)	Tear Index 4-ply (mN·m2/g)	Zero Span Break Length (km)	Gurley Air Resist. (s/100ml)	Sheffield Roughness (SU)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
1	100	0	0	11265	685	11.7	12.8	125	3.06	11.8	11.2	17.7	157.1	76	87.4	138
2	0	100	0	12194	702	11.9	13.1	128	3.42	11.7	11.6	19.4	121.0	71	90.1	141
3	0	0	100	11802	715	11.3	12.9	127	3.40	13.8	13.6	18.8	142.6	71	90.0	147
4	50	50	0	11469	700	11.7	13.0	127	3.40	11.4	10.9	19.4	134.2	77	88.4	138
5	50	0	50	11302	709	11.9	13.2	130	3.37	13.2	12.7	20.0	143.4	70	89.9	147
6	0	50	50	12201	708	11.7	13.0	127	3.13	12.9	12.6	19.5	128.0	59	90.7	147
7	33.3	33.3	33.3	11416	706	11.3	12.5	123	2.97	13.1	12.7	18.2	118.8	74	88.8	147
8	66.7	16.7	16.7	11506	697	12.1	13.0	128	3.10	12.4	12.1	18.6	116.1	76	89.5	141
9	16.7	66.7	16.7	12284	711	12.1	13.2	130	3.47	12.6	12.6	16.7	117.3	63	90.3	141
10	16.7	16.7	66.7	11875	714	12.0	12.6	123	2.96	12.4	12.3	17.8	97.7	62	89.9	146
11	33.3	33.3	33.3	11373	693	11.8	12.9	127	3.32	12.5	12.5	18.0	106.6	73	88.3	140
12	66.7	16.7	16.7	11975	705	12.0	13.4	132	3.45	12.8	12.4	19.1	100.4	72	88.5	141
13	16.7	66.7	16.7	11880	701	12.1	12.8	126	3.23	11.9	11.8	18.4	125.2	70	89.3	146
14	16.7	16.7	66.7	11773	711	11.6	13.0	128	3.55	12.8	12.6	18.0	102.0	70	91.1	149
15	10	90	0	12516	697	11.9	12.9	127	3.27	11.7	11.4	18.9	121.1	76	87.9	138
16	30	65	5	12100	713	11.0	12.7	124	3.37	12.2	12.2	17.8	104.3	86	89.6	143

Table C-26. Handsheet Properties of Kraft Pulps from SPF Chip Mixtures at a CSF of 300 ml (Site 3)

	Mixture Composition S (%)	P (%)	F (%)	PFI Mill Revs.	Apparent Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Break Length (km)	Tensile Index (N·m/g)	Stretch (%)	Tear Index 1-ply (mN·m2/g)	Tear Index 4-ply (mN·m2/g)	Zero Span Break Length (km)	Gurley Air Resist. (s/100ml)	Sheffield Roughness (SU)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
1	100	0	0	12895	694	11.2	12.6	124	3.44	13.1	12.1	17.6	142.1	72	86.7	129
2	0	100	0	13615	690	10.7	12.2	119	3.37	12.9	12.7	19.0	69.6	91	89.6	147
3	0	0	100	12197	682	11.2	12.4	122	2.81	12.4	12.1	18.7	160.8	85	92.0	144
4	50	50	0	13195	692	11.5	12.6	123	3.49	12.9	12.1	18.7	80.7	82	90.3	143
5	50	0	50	12612	683	11.7	13.0	127	3.58	12.5	12.7	18.3	157.4	73	90.4	142
6	0	50	50	12190	687	11.8	12.7	125	3.49	13.0	12.7	18.8	138.1	76	89.1	151
7	33.3	33.3	33.3	12329	683	11.7	12.3	120	3.33	12.9	13.2	19.3	130.0	74	89.8	138
8	66.7	16.7	16.7	12382	677	11.7	12.8	126	3.24	12.3	12.8	18.2	141.1	67	88.4	136
9	16.7	66.7	16.7	12821	681	11.3	12.4	122	3.49	13.1	13.4	17.5	120.7	87	91.4	148
10	16.7	16.7	66.7	11955	700	11.9	12.7	124	3.23	13.1	13.1	18.7	161.2	83	92.9	148
11	50	50	0.0	13324	691	10.9	12.3	120	3.33	13.2	13.4	18.1	97.0	76	87.7	136
12	50	0	50	12490	687	11.7	12.3	120	3.15	13.1	13.3	17.9	160.3	69	90.1	137
13	0	50	50	12423	686	11.5	12.7	125	3.19	13.0	12.9	17.0	112.1	80	92.3	147
14	33.3	33.3	33.3	12261	688	11.7	12.7	124	3.25	13.0	13.1	18.7	122.1	73	89.7	139
15	10	90	0	13621	703	11.2	12.4	122	3.04	12.5	13.7	18.2	100.1	73	92.8	146
16	30	65	5	12353	697	10.8	12.7	125	3.00	12.6	12.6	18.1	105.7	76	90.1	146

Appendix D: Model Fitting and Assessing Model Fit

Choosing and validating a model

To describe the influence of chip composition on pulping and handsheet properties, models of increasing complexity were fitted to the data. The three models that were included are a linear, a quadratic and a special cubic model, using the Scheffé mixture polynomials. Mixture experiments are characterized by the constraint that the fractions of all components add up to unity:

Spruce (S) + Lodgepole Pine (P) + Subalpine Fir (F) =1

With this restriction the general cubic equations can be re-parameterized and certain terms can be eliminated. The resulting equations (with *a,b,c,d,e,f,g* the model coefficients) are:

Linear model: $Y = a \cdot S + b \cdot P + c \cdot F$

Quadratic model: $Y = a \cdot S + b \cdot P + c \cdot F + d \cdot S \cdot P + e \cdot S \cdot F + f \cdot P \cdot F$

Special cubic model: $Y = a \cdot S + b \cdot P + c \cdot F + d \cdot S \cdot P + e \cdot S \cdot F + f \cdot P \cdot F + g \cdot S \cdot P \cdot F$

To decide which of the increasingly complex models provides a sufficient fit, the models are compared in a stepwise fashion with the help of ANOVA. The STATISTICA software was used to produce the ANOVA analysis and also for subsequent model evaluation. Consider the following example of fitting the model equations to the observed data for tear after thermomechanical pulping of site 1 trees. The ANOVA analysis returns the following result (**Table D-27**):

Table D-27. Example tear (TMP site 1): ANOVA-table

	ANOVA; Var.:Tear Index(mN·m2/g) (MPB SPF Site 1 TMP) 3 Factor mixture design; Mixture total=100., 14 Runs Sequential fit of models of increasing complexity									
Model	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p	R-Sqr	R-Sqr Adjusted
Linear	0.397103	2	0.198551	0.711447	11	0.064677	3.069893	0.087223	0.358218	0.241531
Quadratic	0.513070	3	0.171023	0.198376	8	0.024797	6.896932	0.013107	0.821049	0.709204
Special Cubic	0.007415	1	0.007415	0.190961	7	0.027280	0.271828	0.618192	0.827738	0.680085
Total Adjusted	1.108549	13	0.085273							

Choosing an alpha (α) level of significance of 0.05 for all statistical tests, we can use the p-values to evaluate model significance. In the above example, the linear equations with a p-value >0.05 do not provide a statistically significant model. Adding second order parameters does significantly improve the model fit (p<0.05 for quadratic model, compared to linear model), but adding third order terms does not further improve the model significantly (p>0.05). Thus, we consider a quadratic model. Also from the ANOVA table we can read the R^2 value as an estimate of the goodness of fit. Next we look at a list of the calculated model factors and their significance, to check whether the model could be simplified by excluding terms that are not significant (Table D-28).

Table D-28. Example tear (TMP site 1): Estimated model coefficients for a quadratic model

Factor	Coeff.	Std.Err.	t(8)	p	-95.% Cnf.Limt	+95.% Cnf.Limt
	Coeffs (recoded comps); Var.:Tear Index(mN·m2/g); R-sqr=.821; Adj:.7092 (MPB SPF Site 1 TMP) 3 Factor mixture design; Mixture total=100., 14 Runs DV: Tear Index(mN·m2/g); MS Residual=.024797					
(A)S (%)	8.602339	0.109144	78.81670	0.000000	8.350654	8.854025
(B)P (%)	8.474862	0.109144	77.64872	0.000000	8.223176	8.726547
(C)F (%)	9.068764	0.109144	83.09019	0.000000	8.817078	9.320450
AB	1.747177	0.614836	2.84169	0.021755	0.329362	3.164992
AC	0.470608	0.614836	0.76542	0.466001	-0.947208	1.888423
BC	1.718597	0.614836	2.79521	0.023370	0.300782	3.136412

Only the linear parameters as well as the interaction parameters between AB (spruce and pine) and BC (pine and fir) are of significance, thus we omit the interaction term AC (spruce and fir) from the model equations and fit this reduced quadratic model to the data. We then check with a new ANOVA analysis if the model is still a significant improvement over lower order models. Also, we need to confirm that the model in itself is significant and there is no lack of fit of the model. A lack of fit is given if the residual variability (sum of squares of residuals) significantly exceeds the pure error variability (sum of squares of pure error) that is calculated from the replicate runs. Lack of fit of the model indicates that there are other major effects on mixture behaviour that are not accounted for in the model. Lack of fit and model significance can be checked in the table assessing overall model fit (**Table D-29**).

Table D-29. Example tear (TMP site 1): Overall fit of quadratic model (factor AC excluded)

Source	SS	df	MS	F	p
	Overall Fit of Model; Var.: Tear Index(mN·m 2/g) (MPB SPF Site 1 TM 3 Factor mixture design; Mixture total=100., 14 Runs (Some terms were excluded from the respective full models)				
Model	0.895645	4	0.223911	9.465307	0.002764
Total Error	0.212904	9	0.023656		
Lack of Fit	0.058647	5	0.011729	0.304151	0.888039
Pure Error	0.154257	4	0.038564		
Total Adjusted	1.108549	13	0.085273		

For our example, the reduced quadratic model is significant ($p_{model}<0.05$), and there is no significant lack of fit ($p_{lack\_of\_fit}>0.05$). We thus decide to use this reduced quadratic model, pending further validation of the model.

In multiple regression, it is assumed that the residuals are distributed normally around zero with constant variance. Thus, residuals should be carefully examined for outliers and the validity of these assumptions. Also, the general data should be reviewed for obvious outliers. The following plots were thus reviewed:

- The scatterplot of predicted versus residual value. This should show a random distribution, as the model should capture all significant effects.
- The normal probability plot of the residuals. Given the assumption of normal residual distribution, all residuals should fall on or close to the line. Any apparent trend in

deviation from the straight line needs to be further considered. Sometimes, it is possible to alleviate such a problem by considering data transformation; however this did not prove successful for cases with non-normal residual distribution in this study. The histogram of residual distribution can also be used to validate the normality assumption.

- The scatterplot of observed versus predicted values, together with a table of observed, predicted and residual values, to identify possible outliers. The normal probability plot also helps revealing possible outliers.

The plots for the example from before are shown below (**Figure D-39** to **Figure D-42**). Obviously, the residuals are reasonably normally distributed, are randomly distributed compared to predicted values, and there are no apparent outliers in the data.

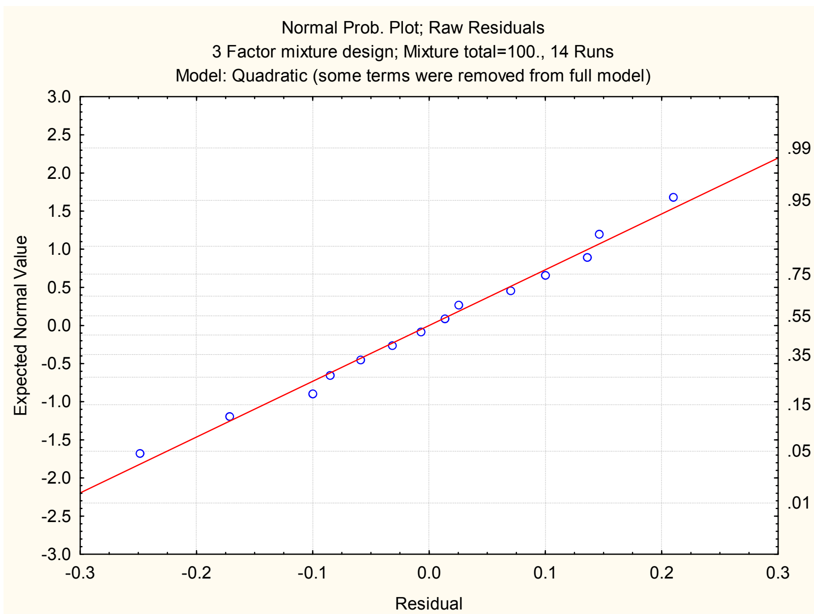

Figure D-39. Example tear (TMP site 1): Normal probability plot of residuals

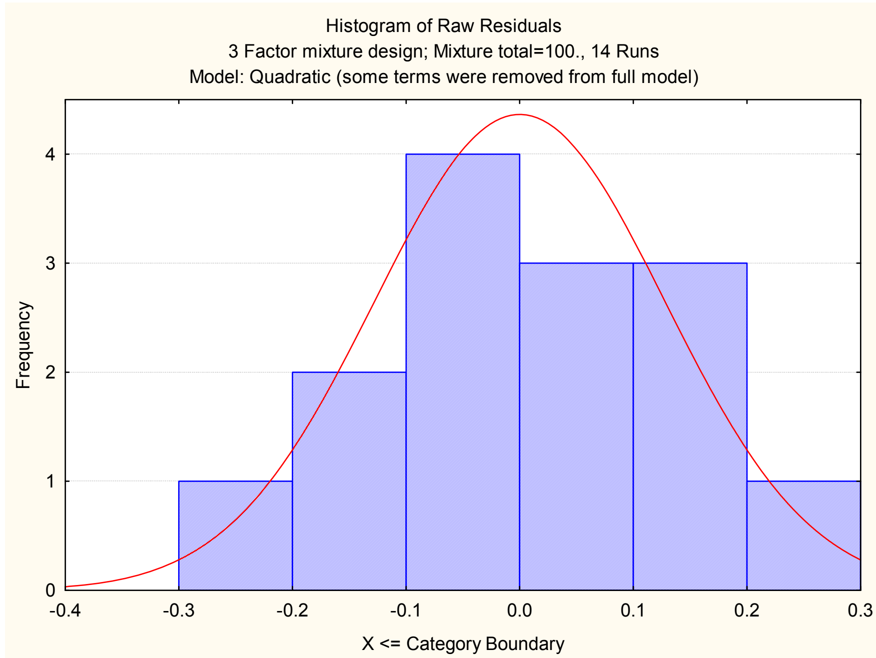

Figure D-40. Example tear (TMP site 1): Histogram of residuals

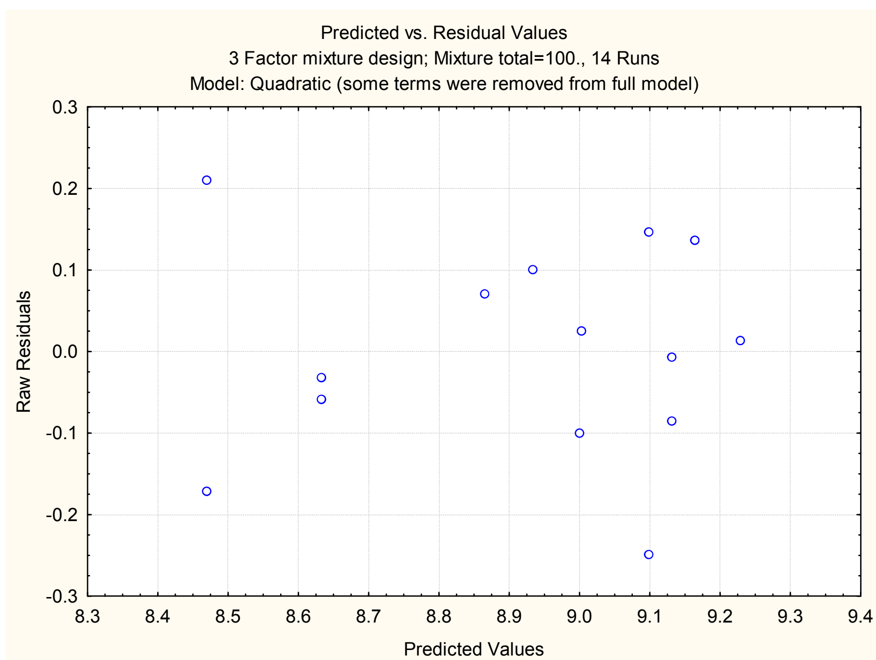

Figure D-41. Example tear (TMP site 1): Predicted versus residual values

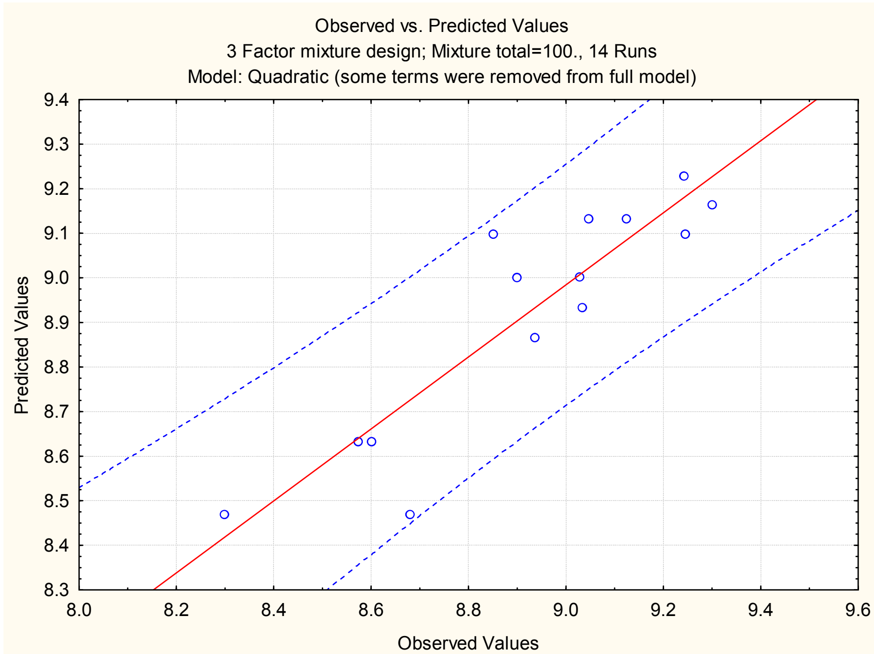

Figure D-42. Example tear (TMP site 1): Observed versus predicted values

Procedure for possible outliers

In general, no data points were found that were obviously outliers. However, some data points were in a range where they could be outliers, but did not necessarily have to be. The following was done to decide if they are outliers and should be omitted, or if they are valid data points.

First, the model fitting was repeated without these outliers. In some cases, this did not improve the data fit and in these cases the data points were kept in the data set. If omitting the data point improved the model fit significantly (while at the same time not influencing the calculated model parameters too much), the data point was reviewed in light of the overall data set before deciding to finally exclude it from the data set. For example, if the data point in question was a single species point which showed a much higher value for a certain property than the rest of the data set, but the species in question is known to produce high values for this property, one cannot justify to exclude the data point. However, if it is a mixture of two species that returns a very high value, while both the single species return a much lower value for the given property, then the data point is likely bad data that should be omitted. (This arguing holds only if not much interaction is seen between the different species. However, this was the case for most properties that were investigated. There are only very few properties that show considerable interactions between two species.)

Further validation using the validation points

Two experimental runs were done with mixtures where the results were not included in the data set for fitting a model. These data points were used to verify that the chosen model adequately predicts mixture properties. To check this, predicted values for all properties using the model equations were compared to the measured ones. It was confirmed that the measured points fall within the 95% confidence interval of the predicted values, using the scatterplot of predicted versus observed as shown above (**Figure D-42**). Also, it was checked that the residuals of the predicted validation points lie within the same range as the model residuals. If the validation point were not predicted according to these criteria, the model was considered unsatisfactory, and attempts were made to improve the model (by including higher order terms). If this was not possible, it was concluded that no suitable model could be found based on the given information.

If the model is considered satisfactory, the model results can be visualized by using a contour (2-d) or surface (3-d) plot. The 3-d surface plot is shown below (**Figure 1**).

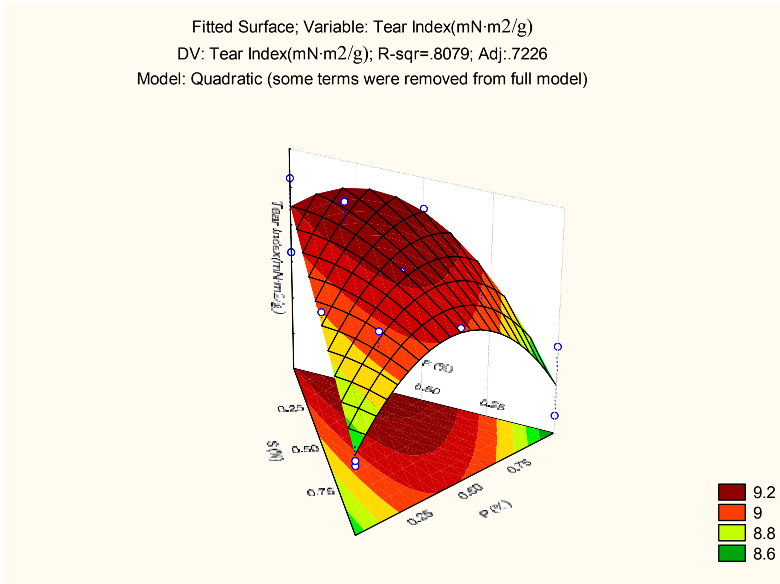

Figure D-43. Example tear (TMP site 1): Surface plot of predicted response surface, and comparison with observed values

A note about choosing the model: As described earlier, the ANOVA table was used to choose the model equations. In some cases, a lower order model predicted the response sufficiently, but higher order models would significantly improve the model. Even though, in general the lower order model was used pending further validation. The higher order model was only considered if the validation showed possible problems with the model. However, in a few cases where the model improvement was very significant (e.g., doubling of R^2 value or similar), or where the specific response was believed to include interaction terms (as would be the case for tear strength, according to experience from other literature), the higher order model was chosen over a linear model, even if the linear model was sufficient.

Appendix E: Fibre length and width distribution profiles (kraft pulp)

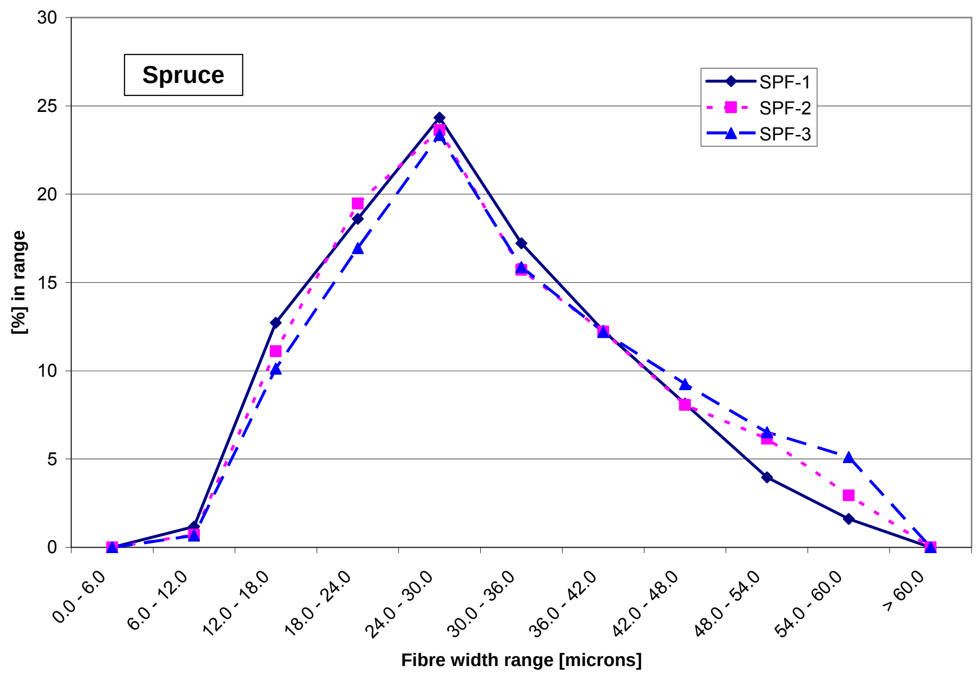

Figure E-44. Fibre width distribution of spruce kraft pulp fibres

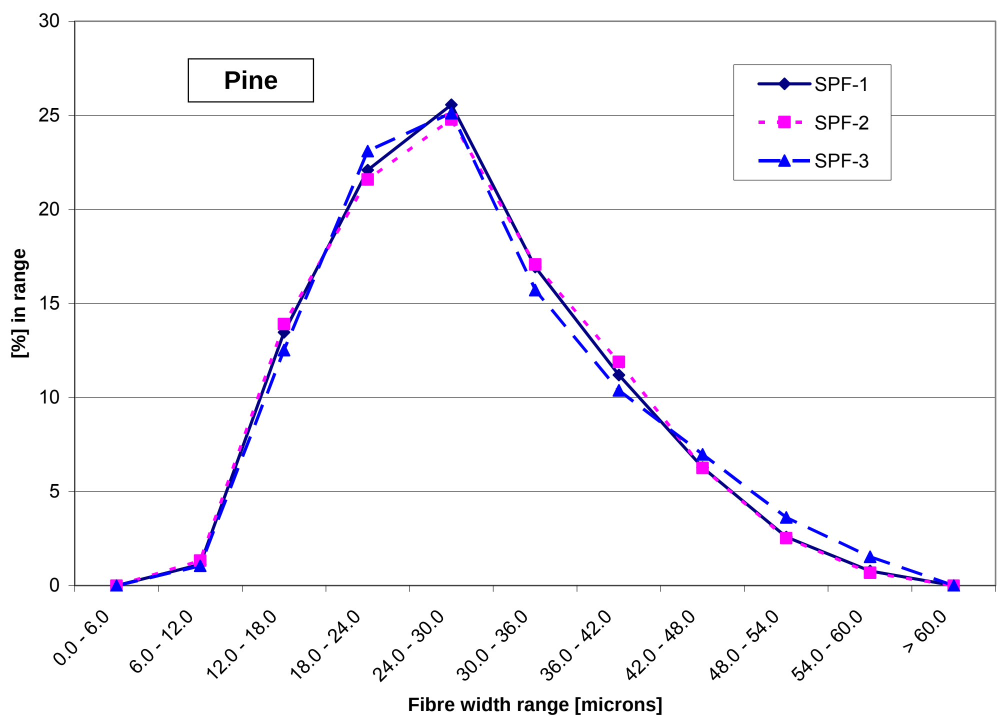

Figure E-45. Fibre width distribution of pine kraft pulp fibres

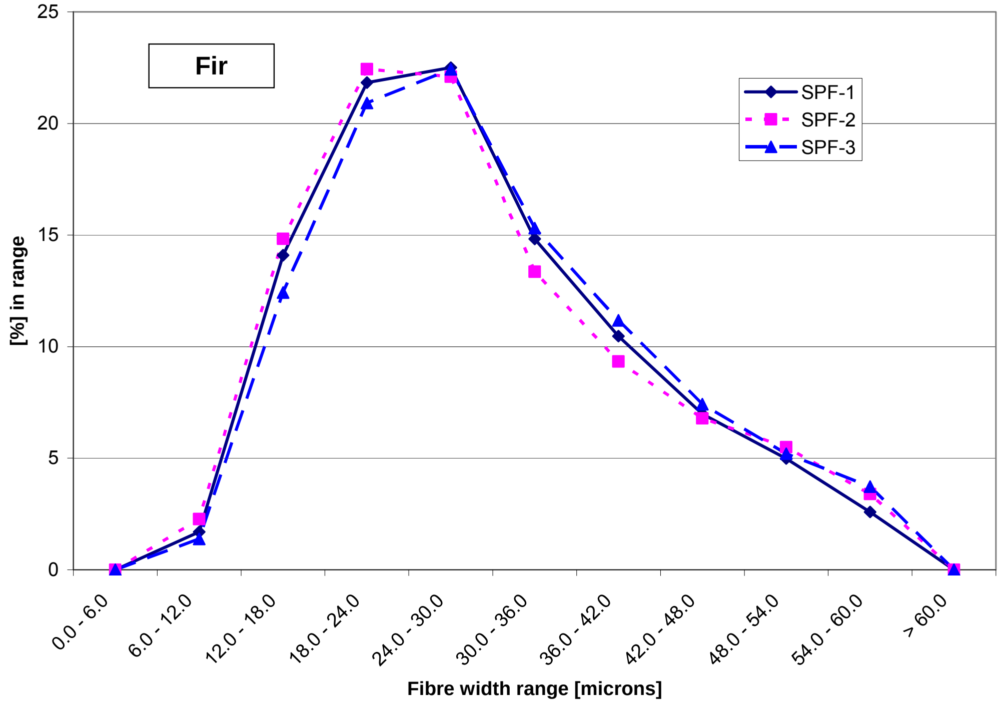

Figure E-46. Fibre width distribution of fir kraft pulp fibres

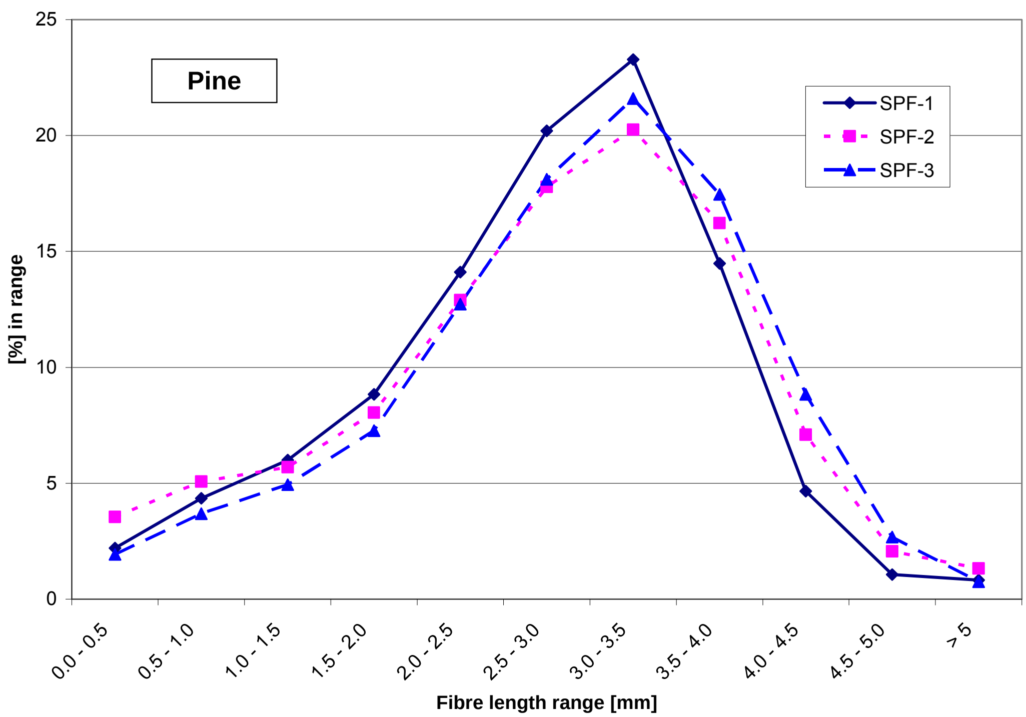

Figure E-47. Fibre length distribution of pine kraft pulp fibres

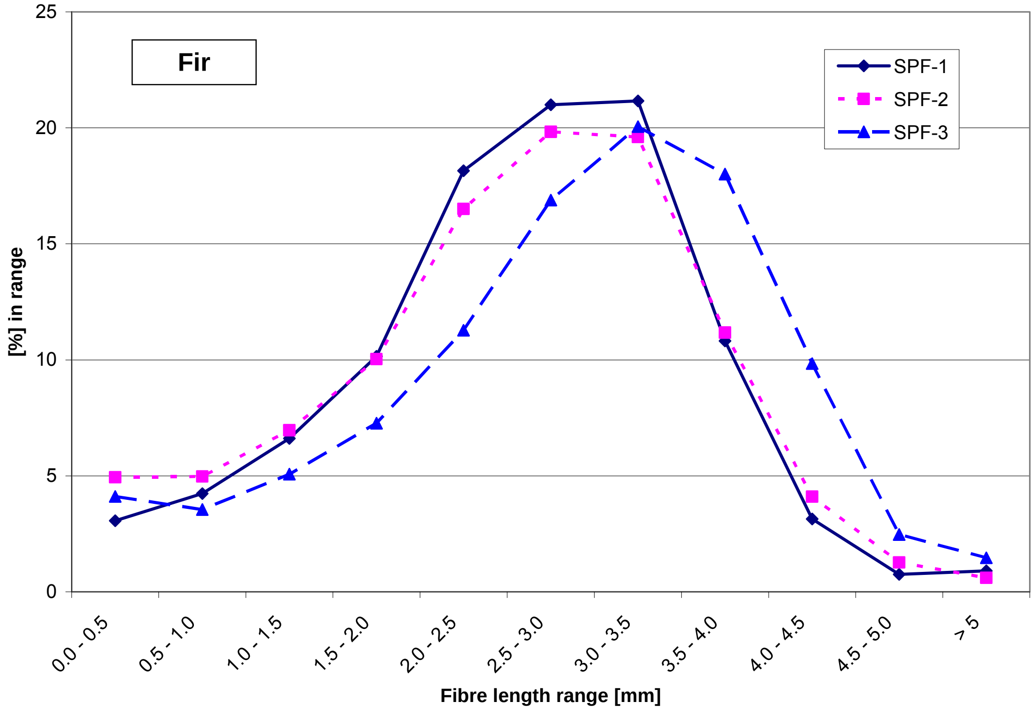

Figure E-48. Fibre length distribution of fir kraft pulp fibres

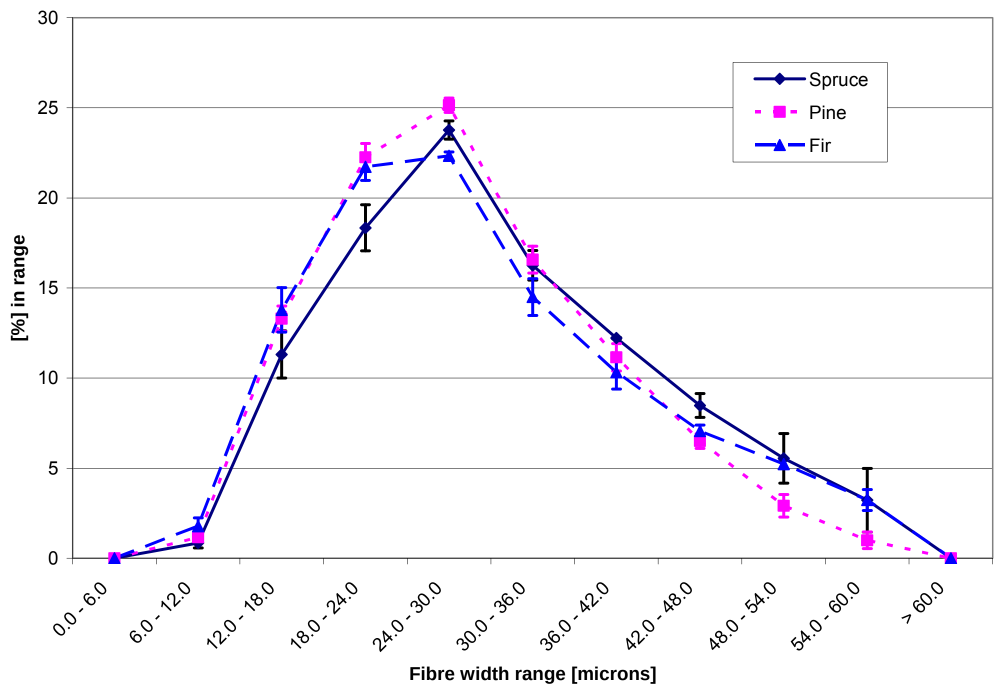

Figure E-49. Fibre width distribution of spruce, pine and fir kraft pulp averaged over three sample sites. Error bars denote the standard deviation.

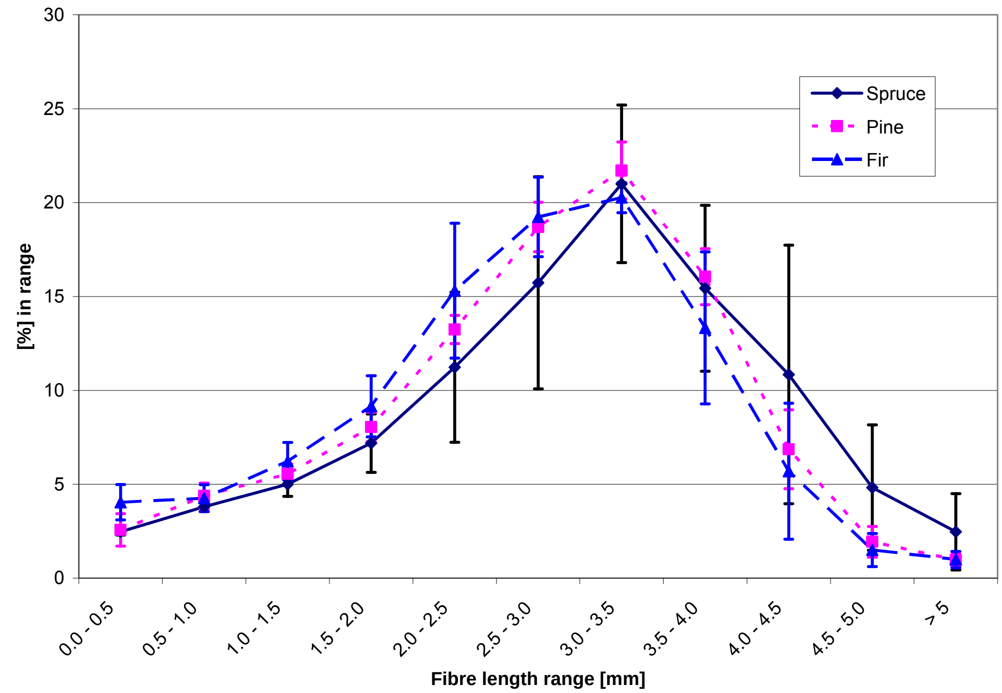

Figure E-50. Fibre length distribution of spruce, pine and fir kraft pulp averaged over three sample sites. Error bars denote the standard deviation.

Appendix F: Model Equations

Table F-30. Model equations for kraft pulp after PFI refining (CSF = 300 ml)

Pulp Property	Site	Model equation
Kappa Number	SPF-1	31.8**S* + 31.1**P* + 36.9**F*
	SPF-2	31.1**S* + 30.2**P* + 35.7**F*
	SPF-3	30.2**S* + 31.1**P* + 35.2**F*
Pulp yield [%]	SPF-1	47.1**S* + 43.8**P* + 46.5**F*
	SPF-2	48.1**S* + 45.7**P* + 46.1**F*
	SPF-3	48.3**S* + 44.3**P* + 47.4**F*
Length weighted fibre length [mm]	SPF-1	2.66**S* + 2.72**P* + 2.60**F*
	SPF-2	3.08**S* + 2.82**P* + 2.60**F*
	SPF-3	3.19**S* + 2.92**P* + 2.94**F*
Coarseness [mg/m]	SPF-1	0.153**S* + 0.147**P* + 0.146**F*
	SPF-2	0.172**S* + 0.150**P* + 0.136**F*
	SPF-3	0.187**S* + 0.166**P* + 0.168**F*
Sheet density [kg/m^3]	SPF-1	N/A
	SPF-2	691**S* + 704**P* + 717**F*
	SPF-3	692**S* + 688**P* + 681**F*
Burst index [kPa·m^2/g]	SPF-1	11.4**S* + 11.8**P* + 12.8**F* + 3.08**S***P*
	SPF-2	N/A
	SPF-3	11.4**S* + 10.8**P* + 11.2**F* + 2.78**P***F* + 1.81**S***F*
Tensile index [N·m/g]	SPF-1	125.7**S* + 123.1**P* + 133.6**F*
	SPF-2	N/A
	SPF-3	N/A
Tear index 1-ply [mN·m^2/g]	SPF-1	N/A
	SPF-2	12.1**S* + 11.8**P* + 13.7**F*
	SPF-3	N/A
Tear index 4-ply [mN·m^2/g]	SPF-1	N/A
	SPF-2	11.6**S* + 11.7**P* + 13.5**F*
	SPF-3	N/A
Gurley air resistance [s/100ml]	SPF-1	58.0**S* + 57.3**P* + 123.2**F*
	SPF-2	146.3**S* + 128.7**P* + 131.5**F* -1144**S***P***F*
	SPF-3	137.9**S* + 71.3**P* + 175.1**F*
Sheffield roughness [SU]	SPF-1	99.7**S* + 98.1**P* + 71.7**F*
	SPF-2	77.5**S* + 71.8**P* + 69.6**F* - 39.0**P***F*
	SPF-3	67.0**S* + 87.6**P* + 78.5**F*
ISO Opacity [%]	SPF-1	88.8**S* + 90.3**P* + 91.3**F*
	SPF-2	87.7**S* + 89.9**P* + 90.7**F*
	SPF-3	87.3**S* + 90.1**P* + 92.6**F*
Scattering coefficient [cm^2/g]	SPF-1	N/A
	SPF-2	138.6**S* + 141.8**P* + 150.1**F*
	SPF-3	129.6**S* + 148.7**P* + 147.0**F*
Zero span breaking length [km]	SPF-1	16.9**S* + 17.3**P* + 18.1**F* + 9.10**P***F*
	SPF-2	18.3**S* + 19.7**P* + 18.4**F* + 6.17**S***F* - 42.7* *S***P***F*
	SPF-3	17.7**S* + 19.2**P* + 18.8**F*

Note: *S*,*P*,*F* are fractions of Spruce, Pine and Fir in the mixture
Highlighted model equations are for models where the p-level of significance was low (0.1>p>0.05) and thus should not be used to predict pulp or handsheet properties

Table F-31. Model equations for TMP pulp (CSF = 100 ml)

Pulp Property	Site	Model equation
SRE [MJ/kg]	SPF-1	11.6*S + 11.8*P + 11.1*F - 2.07*S*P
	SPF-2	N/A
	SPF-3	11.1*S + 11.5*P + 9.4*F + 4.83*S*F
Length weighted fibre length [mm]	SPF-1	1.96*S + 1.84*P + 1.94*F - 0.520*P*F
	SPF-2	1.98*S + 1.85*P + 1.75*F
	SPF-3	1.98*S + 1.87*P + 2.01*F + 0.476*S*P
Fines fraction (P-200) [%]	SPF-1	25.7*S + 27.8*P + 25.9*F - 9.07*P*F - 47.0*S*P*F
	SPF-2	24.3*S + 26.7*P + 26.4*F
	SPF-3	27.1*S + 27.2*P + 23.1*F
Long fibre fraction (R-48) [%]	SPF-1	61.6*S + 58.8*P + 60.6*F
	SPF-2	62.8*S + 60.6*P + 59.6*F
	SPF-3	60.9*S + 60.1*P + 62.4*F
Sheet density [kg/m^3]	SPF-1	377*S + 344*P + 346*F
	SPF-2	360*S + 355*P + 341*F
	SPF-3	374*S + 343*P + 328*F
Burst index [$kPa \cdot m^2/g$]	SPF-1	3.37*S + 2.83*P + 3.04*F
	SPF-2	3.11*S + 2.97*P + 2.77*F + 0.608*S*F + 0.667*P*F
	SPF-3	3.39*S + 2.77*P + 2.89*F
Tensile index [N·m/g]	SPF-1	49.0*S + 42.7*P + 42.5*F
	SPF-2	46.1*S + 41.4*P + 42.9*F
	SPF-3	45.7*S + 40.5*P + 40.8*F
Tear index [$mN \cdot m^2/g$]	SPF-1	8.63*S + 8.47*P + 9.10*F + 1.81*S*P + 1.78*P*F
	SPF-2	8.80*S + 8.54*P + 8.90*F + 1.42*S*P + 1.12*P*F - 1.39*S*F - 13.77*S*P*F
	SPF-3	9.11*S + 8.66*P + 9.30*F
Sheffield roughness [SU]	SPF-1	178*S + 225*P + 192*F
	SPF-2	231*S + 226*P + 225*F - 130*S*F
	SPF-3	190*S + 248*P + 240*F
Brightness [%]	SPF-1	N/A
	SPF-2	N/A
	SPF-3	57.5*S + 53.6*P + 53.5*F
ISO Opacity [%]	SPF-1	95.6*S + 96.9*P + 96.4*F
	SPF-2	96.2*S + 96.9*P + 97.6*F
	SPF-3	95.5*S + 97.7*P + 97.2*F
Scattering coefficient [cm^2/g]	SPF-1	574*S + 609*P + 608*F
	SPF-2	557*S + 616*P + 631*F
	SPF-3	582*S + 620*P + 594*F

Note: *S,P,F* are fractions of Spruce, Pine and Fir in the mixture
Highlighted model equations are for models where the p-level of significance was low ($0.1>p>0.05$) and thus should not be used to predict pulp or handsheet properties

Table F-32. Model equations for TMP pulp (SRE = 10 MJ/kg)

Pulp Property	Site	Model equation
CSF [ml]	SPF-1	136*S + 160*P + 130*F - 92*S*P - 69*P*F + 52*S*F
	SPF-2	N/A
	SPF-3	125*S + 130*P + 88*F - 107*S*F
Length weighted fibre length [mm]	SPF-1	1.98*S + 1.86*P + 1.99*F - 0.520*P*F
	SPF-2	1.98*S + 1.89*P + 1.76*F
	SPF-3	1.98*S + 1.90*P + 2.01*F + 0.441*S*P
Sheet density [kg/m^3]	SPF-1	350*S + 318*P + 324*F
	SPF-2	346*S + 335*P + 333*F
	SPF-3	351*S + 322*P + 337*F - 172.6*S*F
Tensile index [N·m/g]	SPF-1	43.8*S + 36.5*P + 39.0*F
	SPF-2	43.7*S + 39.0*P + 41.0*F
	SPF-3	41.2*S + 35.8*P + 41.4*F
Tear index [$mN{\cdot}m^2/g$]	SPF-1	N/A
	SPF-2	9.07*S + 9.20*P + 8.74*F
	SPF-3	9.94*S + 9.43*P + 9.02*F + 2.19*S*F
Sheffield roughness [SU]	SPF-1	202*S + 264*P + 221*F
	SPF-2	234*S + 257*P + 235*F - 106*P*F
	SPF-3	219*S + 268*P + 239*F
Scattering coefficient [cm^2/g]	SPF-1	556*S + 597*P + 584*F
	SPF-2	548*S + 591*P + 622*F
	SPF-3	566*S + 606*P + 596*F

Note: S,P,F are fractions of Spruce, Pine and Fir in the mixture
Highlighted model equations are for models where the p-level of significance was low (0.1>p>0.05) and thus should not be used to predict pulp or handsheet properties

Appendix G: Escher-Wyss refining results

Table G-33. CSF and handsheet data after Escher-Wyss refining of pure species pulps

Species	SEL (J/m)	Spec. Refining Energy (MJ/kg)	CSF (ml)	App. Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Tensile Index (N·m/g)	Tear Index (1 ply) (mN·m2/g)	Zero Span Breaking Length (km)	Gurley Air Resistance (sec/100ml)	Sheffield Roughness (SU)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
Spruce	1.0	0	710	569	7.3	86.7	16.2	17.1	4.7	242	94.5	227
		99.7	614	635	9.8	110.2	13.5	15.8	20.8	170	92.5	180
		149.2	560	638	10.4	121.9	12.8	16.7	29.5	145	91.2	174
		199	446	658	10.8	122.6	12.7	16.4	67.8	92	90.5	160
		249.7	359	669	10.6	112.1	11.6	16.6	205.8	67	90.0	158
Spruce	2.5	0	710	569	7.3	86.7	16.2	17.1	4.7	242	94.5	227
		49.2	666	601	9.2	110.5	14.0	19.9	9.3	214	93.5	205
		151.3	495	650	9.8	121.1	13.1	19.7	38.7	120	91.2	172
		202.7	353	691	9.8	123.7	11.9	18.3	279.8	52	89.9	154
		255	202	686	9.5	112.6	10.4	18.2	> 1800	51	89.9	150
Pine	1.0	0	703	567	7.3	90.6	13.8	18.1	4.4	235	96.2	254
		98.2	590	644	9.7	110.4	12.2	18.4	18.6	166	94.2	197
		147.4	506	653	10.2	126.3	11.1	17.7	41.2	130	92.3	180
		196.8	390	681	10.1	129.7	10.8	17.6	123.8	75	90.8	160
		246.6	258	692	10.7	130.1	10.3	17.0	639.1	41	90.6	157
Pine	2.5	0	703	567	7.3	90.6	13.8	18.1	4.4	235	96.2	254
		50.5	662	608	8.6	112.7	0.0	18.3	7.1	220	94.6	219
		149.8	456	678	9.6	121.2	0.0	18.0	41.6	101	91.3	168
		204.2	309	700	9.2	120.5	0.0	17.7	398.3	39	91.2	165
		253.3	169	731	9.3	117.1	0.0	17.0	> 1800	39	90.0	146
Fir	1.0	0	680	575	7.7	99.0	14.4	18.8	10.6	175	96.6	269
		48.6	636	632	8.9	103.6	13.1	19.7	24.6	145	96.0	222
		149.8	512	670	10.4	121.6	11.4	19.4	63.9	95	94.4	185
		200.8	415	685	9.8	125.5	11.0	20.3	203.5	50	94.0	179
		252.4	324	712	10.2	125.2	10.5	19.7	911.2	40	93.8	165
Fir	2.5	0	680	575	7.7	99.0	14.4	18.8	10.6	175	96.6	269
		47.7	636	622	9.1	103.8	14.4	19.8	22.4	153	96.2	227
		149.4	429	684	9.4	112.0	11.8	18.6	250.8	73	94.8	186
		199.2	280	708	9.4	117.0	10.3	18.6	1295.2	30	93.5	163
		252.1	175	746	9.1	113.7	9.2	17.5	> 1800	28	92.6	145

Table G-34. CSF and handsheet data after Escher-Wyss refining of mixture pulps

Species Mix	SEL (J/m)	Spec. Refining Energy (MJ/kg)	CSF (ml)	App. Sheet Density (kg/m3)	Burst Index (kPa·m2/g)	Tensile Index (N·m/g)	Tear Index (1 ply) (mN·m2/g)	Zero Span Breaking Length (km)	Gurley Air Resistance (sec/100ml)	Sheffield Roughness (SU)	ISO Opacity (%)	Scattering Coefficient (cm2/g)
M65 (30/65/5 S/P/F)	1.0	0	697	556	7.1	90.0	16.2	21.2	3.1	241	96.2	259
		50.6	671	608	9.0	101.9	13.6	17.7	6.0	209	94.0	209
		152.5	491	661	10.1	115.6	11.5	17.0	57.6	122	91.8	174
		202.7	371	686	10.5	120.3	11.0	17.5	144.3	82	90.6	156
		252.7	256	710	10.7	124.3	10.4	17.3	1224.7	35	90.3	152
M65 (30/65/5 S/P/F)	2.5	0	697	556	7.1	90.0	16.2	21.2	3.1	241	96.2	259
		48.7	631	606	8.6	99.7	14.3	19.1	6.2	223	94.6	216
		148.4	380	668	9.5	110.2	11.3	17.0	39.5	131	92.1	171
		198.5	230	696	9.5	112.7	10.7	17.2	203.1	59	91.3	160
		250.1	124	717	9.3	109.8	10.3	16.4	1626.8	33	90.7	149
M90 (10/90/0 S/P/F)	1.0	0	703	548	7.2	93.0	14.4	21.1	2.3	250	96.5	271
		46.3	657	609	8.8	103.3	14.0	17.6	6.3	216	94.3	209
		154.9	461	667	10.1	111.8	12.4	17.0	58.8	111	91.8	163
		196.9	294	694	10.2	121.9	11.8	18.2	327.9	54	91.1	154
		248.1	163	714	10.6	124.1	10.1	17.0	> 1800	39	89.9	143
M90 (10/90/0 S/P/F)	2.5	0	703	548	7.2	93.0	14.4	21.1	2.3	250	96.5	271
		48.2	659	614	8.8	97.3	13.8	18.4	6.7	212	94.4	212
		147.2	423	677	9.7	108.7	11.3	17.0	67.6	91	92.4	170
		198.5	257	706	9.5	117.4	10.0	18.2	1111.4	37	90.5	154
		248.3	142	731	9.1	112.1	9.6	15.7	> 1800	53	89.8	138

Table G-35. BauerMcNett distributions of pulps before and after Escher-Wyss refining (SRE = 250 kWh/t)

Sample	Mesh Size	Unrefined Fraction (%)	SEL = 1J/m Fraction (%)	SEL = 2.5 J/m Fraction (%)
Spruce	R14	71.41	57.79	38.38
	R28	13.24	15.53	22.36
	R48	8.51	13.87	21.04
	R100	2.13	4.39	1.67
	R200	0.49	2.00	8.18
	P200	4.22	6.42	13.15
Pine	R14	68.40	37.31	19.93
	R28	15.23	22.38	30.73
	R48	11.63	17.85	26.36
	R100	2.68	5.26	0.91
	R200	0.78	2.28	10.34
	P200	1.28	14.92	15.22
Fir	R14	62.65	28.55	6.87
	R28	17.86	29.93	32.32
	R48	12.11	20.77	30.72
	R100	3.10	6.75	10.89
	R200	1.08	3.57	0.45
	P200	3.20	10.43	24.74
M65 (30/65/5 S/P/F)	R14	69.33	42.54	26.31
	R28	14.24	23.59	29.61
	R48	10.40	20.20	25.30
	R100	2.13	5.76	8.31
	R200	1.11	3.28	4.14
	P200	4.56	4.63	6.33
M90 (10/90/0 S/P/F)	R14	70.48	28.07	16.74
	R28	14.87	29.23	30.44
	R48	10.93	24.33	27.52
	R100	0.31	7.45	9.44
	R200	2.09	4.20	4.15
	P200	1.32	6.72	11.72

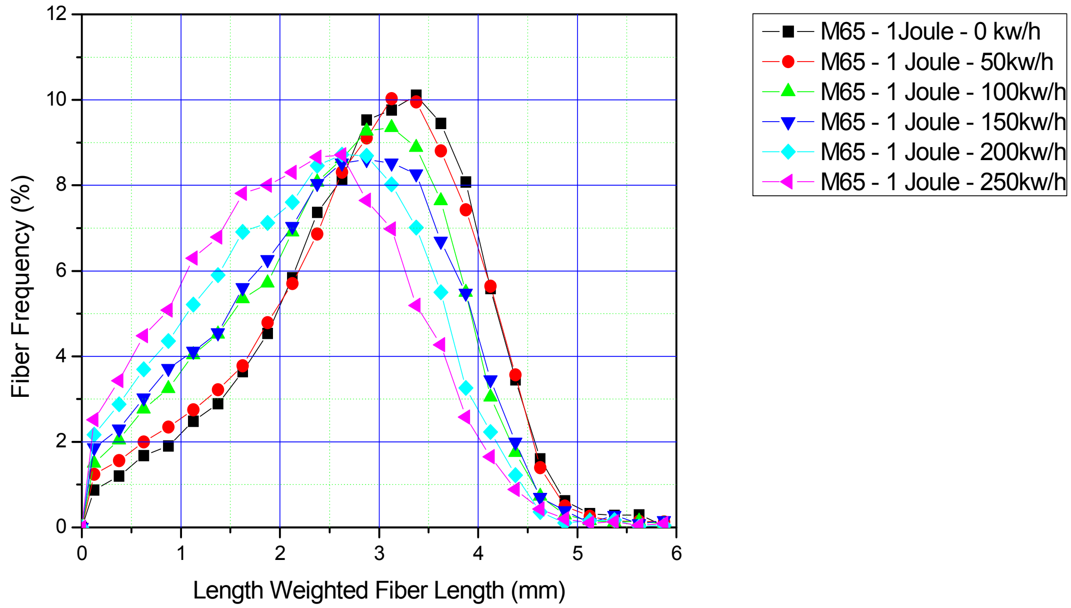

Figure G-51. Change in fibre length distribution with Escher-Wyss refining: S/P/F 30/65/5 mixture, refined at SEL = 1 J/m

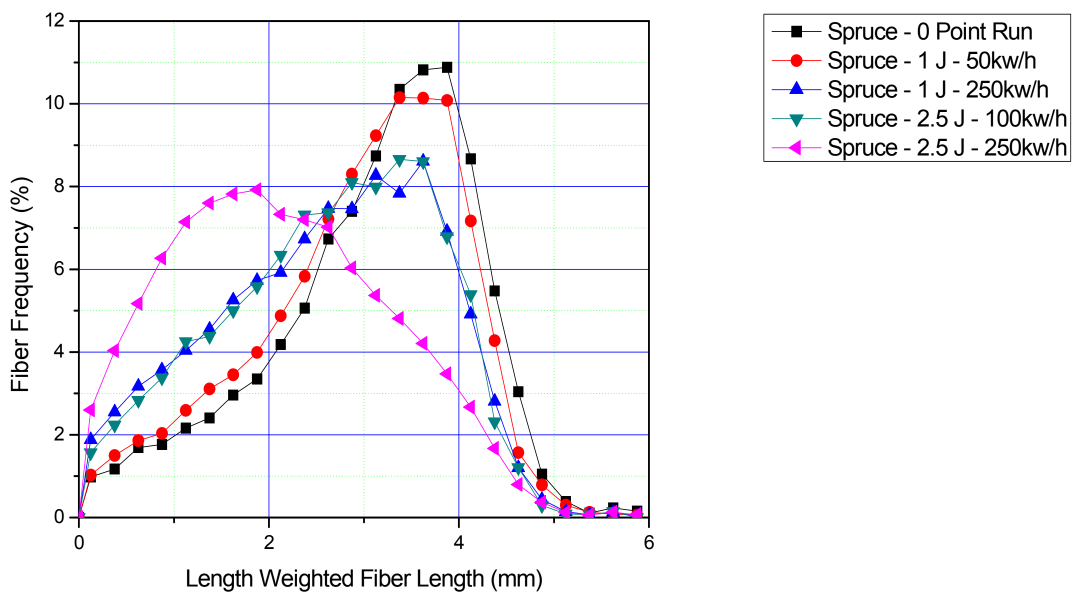

Figure G-52. Change in fibre length distribution with Escher-Wyss refining: Spruce

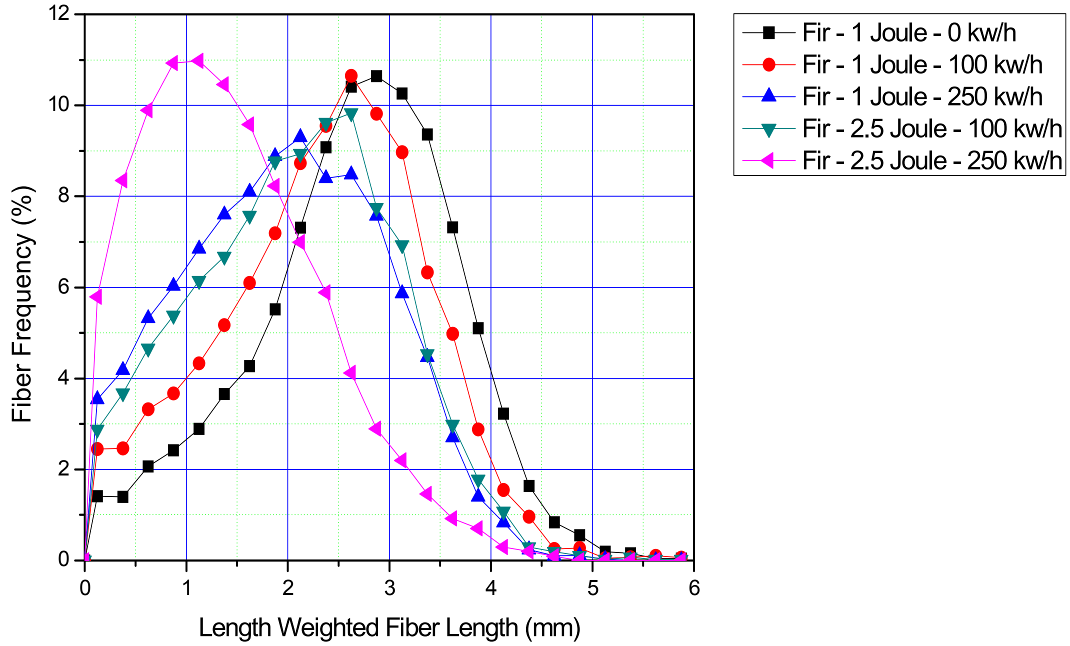

Figure G-53. Change in fibre length distribution with Escher-Wyss refining: Fir.

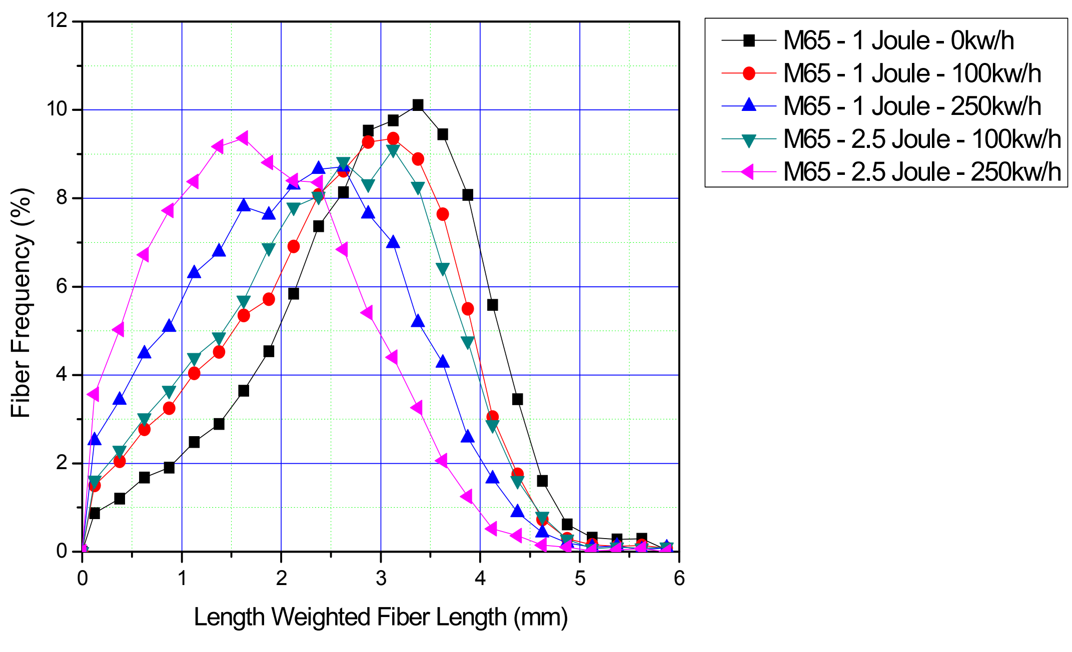

Figure G-54. Change in fibre length distribution with Escher-Wyss refining: S/P/F 30/65/5 mixture