MODELLING TMP FIBRE MORPHOLOGY AND PULP PROPERTIES FROM WOOD AND FOREST DATA: THE EXAMPLE OF NORWAY SPRUCE*

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ABSTRACT

Variations in paper properties can be due to process conditions but also to variations in wood properties. Better knowledge about the relationships between wood properties and properties of mechanical pulp could lead to a more efficient use of wood resources. AFOCEL has used its thermo-mechanical pulping (TMP) laboratory pilot refiner to pulp small wood samples and determine the influence wood fibre properties have on pulp fibres. This two-stage laboratory procedure was used within the EU project EuroFiber, which aims at the definition of wood assortments better adapted to the end-product qualities of different European paper mills with TMP plants.

Picea abies (L.) H. Karst. (Norway spruce) trees were sampled in four European countries (Estonia, France, Norway, and Sweden). Samples were taken at different tree heights and split into juvenile, transition, and mature woods, resulting in a total of 450 samples. Wood samples were mechanically pulped after a two-stage refining procedure. Each pulp was characterised by its physical and optical properties, fibre morphology, and specific energy consumption. Data on forest, wood, and pulp properties were compiled and statistically analysed.

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Principal Component Analysis revealed a correlation between pulp properties and fibre properties (light-scattering coefficient, fibre length, fines, freeness, brightness, energy consumption).

Five classes of wood were created based on tracheid length and wood density to identify the influence these parameters may have on pulp production (energy consumption, light-scattering coefficient, and tear index).

Finally, a modelling approach enabled us to detect and quantify wood properties and process effects on measured pulp properties. Some categorical data were also tested: wood age (juvenile, transition, and mature wood), country where the tree was grown, and the previous five classes of wood. Part of variances explained by the models was quite low, but showed a general relationship with the specific energy applied during refining and, to a lesser extent, some tendencies with wood properties. With a process that preserved fibre properties well, this work allowed the identification of some wood properties that may be investigated to produce tailor-made pulp.

Keywords: mechanical pulping; fibre morphology; forest data; *Picea abies*.

INTRODUCTION

Mechanical refining is now well characterised by the model developed by Miles & May (May 1998). Their mathematical description of the refining process provided a good understanding of the influence that process parameters have on the result. However, incoming wood material properties were not taken into account in the process performance and that is still not clearly understood.

In recent years, models have been developed to predict variations within and between trees of different species and the influence of growth conditions: *Pinus sylvestris* L. (Scots pine), Norway spruce (Wilhelmsson *et al.* 1999; Lundqvist *et al*. 2002), and *Pinus pinaster* Aiton (maritime pine) (Chantre *et al*. 2000). At the same time, the influence of Norway spruce wood properties on TMP quality has been studied (Tyrväinen 1995; Braaten 1997; Kure 1997; Wang & Braaten 1997; Bergander & Salmén 1998). The scope of these latter studies, however, did not include developing prediction models.

TMP refining may be studied at different structural levels. Hence, it has been shown that wood behaviour is different from chemical to fibre level and moreover to macroscopic level (Bergander 2001). As fibre morphology is known to influence mechanical pulp properties, most of the studies concern the fibre level. For example, Corson found that both wood density and tracheid length have some effects (Corson 1991): long tracheid in wood results in high content of long fibre in pulp (fraction measured with Bauer McNett), low sheet density, high tear index, high tensile index, and high burst index. But at the same freeness, large differences in wood density or tracheid length did not result in comparably large differences in tensile index.

In addition, fibre perimeter and wall thickness accounted for much, but not all, of the wood density influence (Corson 1997a). Hence, a decrease in wood basic density leads to an increase in sheet density, air resistance, tensile index, and scattering coefficient while tear index decreases. Tear index increased with fibre wall thickness, accompanied by a decrease in fibre perimeter. These results were confirmed by Jones (1999). He found higher burst, tensile energy, and stiffness indices with longer tracheid and higher cellulose content. Like Braaten (1997), he also found a relationship between fibre wall thickness, opacity, and light-scattering coefficient: light-scattering coefficient decreases with an increase in fibre wall thickness.

However, these trends were not always observed and some studies showed little or no effect of wood tracheid properties on mechanical pulp properties. For wood basic density, no correlation was found with either mechanical pulp quality or specific energy consumption. Fibre length had a strong positive correlation with tear index and a slightly negative or no impact on TMP sheet and optical properties. Hence, tensile index of a dry TMP sheet was controlled mostly by bonding properties of pulp fractions.

The ratio of juvenile wood caused the greatest variation in wood fibre properties within a spruce tree. Juvenile wood produced up to 30% lower tear index and up to 20% lower tensile index than mature wood, at the same freeness. On the other hand, juvenile wood caused pulp brightness to increase by 10%, and light-scattering coefficient to increase by at least 20%. No clear pattern for TMP specific energy consumption at a constant freeness level has been found in relation to juvenile and mature wood (Tyrväinen 1995).

The differences in pulp strength and optical properties cannot be explained only by the proportions of different fractions or fibre sizes. Factors such as the proportions of fines and shives have to be taken into account. Fines especially may affect pulp properties according to their origin — fibre cutting or fibre peeling (Moss & Retulainen 1997).

Some trials have been done to correlate pulp properties (tear index, weighted fibre length, ISO brightness, light-scattering coefficient) and wood properties (basic density, tree age, ring width). Correlation coefficients up to 0.65 have been found (Wang & Braaten 1997). Application of on-line measurements made it possible to find good prediction for tear index (Kortelainen *et al.* 2001).

The aim of the current study was to evaluate relations between wood characteristics and pulp properties for Norway spruce. In order to do this, different wood materials were refined in a 300-mm laboratory refiner. The study was part of the EuroFiber project (Lundqvist *et al.* 2003), which also included substantial measurements of variations in wood and fibre properties, pilot plant trials (Fuglem *et al.* 2003), and full-scale trials in mills (Persson *et al.* 2003). It is well known that it is hard to produce industrial-quality pulp in a small refiner. The idea was to use refining of small-sized samples with well-defined properties to identify which wood parameters may influence pulp production. This is not possible in mills or in a large-scale pilot plant because of the huge quantity of wood needed to perform a test. These trials are limited to testing wood with big differences, otherwise pilot trials can focus on specific wood properties such as age. The sampling strategy was designed to provide European Norway spruce samples which presented a wide variation. Hence, wood samples of different ages from four countries in Europe were refined. Latewood content, tracheid morphology, wood density, and chemical composition were measured, as well as properties of the pulp produced.

MATERIAL AND METHODS

Raw Material

Norway spruce trees were sampled in Estonia, France, Norway, and Sweden. In each country, several stands were selected (for model fitting or validation) and characterised in order to cover a maximum range of growth conditions such as climate, site fertility, and tree age. From each stand, three trees of different status were sampled — one dominant/thick tree, one co-dominant/medium-sized tree, and one suppressed/thin tree.

Samples were taken at different heights from each tree and were split into juvenile, transition, and mature woods, resulting in a total of 450 different samples. The classification was based on the growth ring numbers: juvenile wood from rings 1 to 15, transition wood from 16 to 30, and mature wood from 31 onwards. These wood samples were characterised regarding growth ring widths, latewood and juvenile wood content (Olsson 2000), wood basic density, moisture content, heartwood content (Lindgren & Lundqvist 2000), fibre length, fibre width, and fibre wall thickness (Evans *et al.* 1995; Karlsson & Fransson 1999).

Methods

A two-stage refining procedure has been designed to make possible refining of small samples of wood in a 300-mm refiner, rotating at 3000 rpm. In order to avoid the effect of chip size variations, wood samples were turned into 25 × 25 × 4-mm "standard" chips. Chips were saturated in a desiccator full of cold water under vacuum for 30 minutes. Dry matter content of the chips after saturation was around 32%. This stage ensured uniform concentration between the different wood samples for the primary stage of refining.

Wood chips were put into a stainless steel basket above hot water (100°C) and heated to a temperature of 150°C at a pressure of 5 bars. The procedure was optimised in order to reduce the time under pressure. Final temperature was 150°C. In order to avoid lignin condensation, chips were removed from the reactor as soon as the security valve indicated 5 bars.

The primary stage was performed with constant gap clearance (250 μm) and constant feed screw speed. The same refiner was used for the secondary stage. The feeding screw was replaced by a low consistency pump connected to the refiner door flange. The second stage was carried out at a refining consistency of 3.5%, plate gap adjusted at 100 μm, and constant feed screw speed. More details on the procedure have been given by Fauchon *et al*. (2001). A total of 450 two-stage runs were performed during the project (Fig. 1). Canadian Standard Freeness (CSF) was measured according to TAPPI test method T227. Handsheets were made with white water circulation according to international standard T205, and 10 handsheets were made for each refining. Tappi standards were used for pulp testing. Fibre morphology was measured by using a MorFi analyser.

FIG. 1–The two-stage refining procedure used to refine pulps.

RESULTS

First Analysis: Principal Component Analysis

In the first step, a Principal Component Analysis (PCA) was performed on pulp properties and refining parameters to determine how they correlated. The amount of variability explained by the first 11 principal components is indicated in Fig. 2. The three first axes described 65% of the total variance. Other axes did not improve variance a lot, and so they were not considered. The correlation of the variables investigated to axes 1 to 4 is presented in Fig. 3 and 4.

Axis 1 (Fig. 3) was positively correlated to fibre length and negatively to shives proportion, fines proportion, and light-scattering coefficient. Hence, trends were in agreement with what is commonly observed: the more the fines content, the higher the light-scattering coefficient; the longer the fibre length, the lower the fines proportion. Tear index was positively correlated to fibre length and negatively correlated to fines content and light scattering.

Axis 2 was positively correlated to pulp physical properties — tensile, burst, tear indices — and negatively to CSF and brightness. The higher the freeness and the brightness, the lower the pulp physical properties. On these two axes, light absorption coefficient and opacity were highly correlated with energy consumption

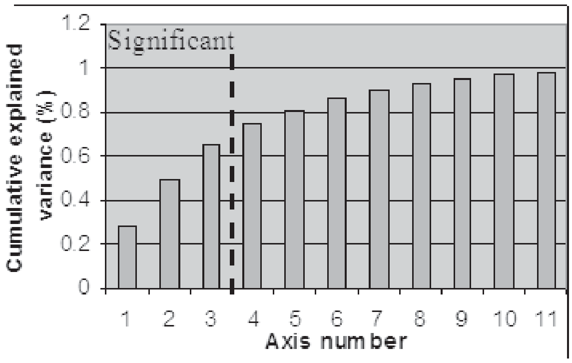

FIG. 2–Explained variance by first 11 principal components. The three first components are significant and account for 65% of the total variance.

FIG. 3–Principal Component Analysis, 1 and 2 axes.

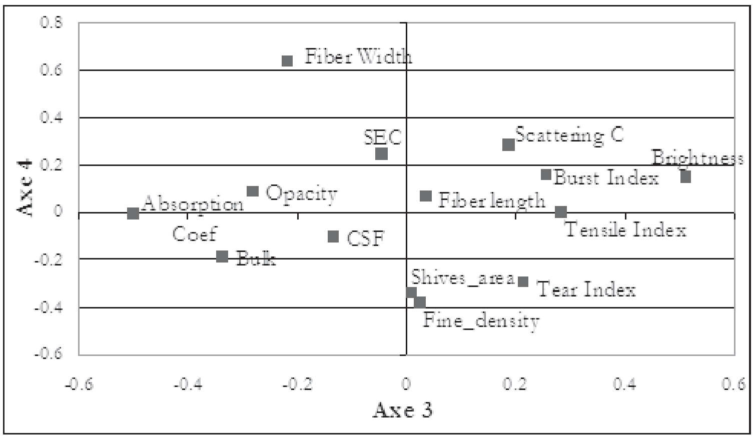

FIG. 4–Principal Component Analysis, 3 and 4 axes.

(SEC), meaning that higher energy consumption was followed by a higher yellowing of the pulp.

Axis 3 (Fig. 4) was correlated with optical properties, positively with brightness and negatively with opacity and absorption coefficient.

For axis 4, explained variance was too low to be significant.

Several variables contributed to all the principal components, but it could be said that axis 1 was strongly correlated to fibre length, axis 2 to the degree of fibre development, and axis 3 to the optical properties.

Adjustment

In order to find the best basis for comparison of the different materials, new refining tests were specially carried out. It was decided to adjust the experimental data for comparison at the same bulk, instead of using comparisons at the same freeness. Adjustments were done to a bulk value of 2.2 cm^3/g. This method had already been used in an earlier study, where tensile index and burst index of paper were both evaluated as a function of apparent sheet density (=1/bulk) (Koran 1994). The same trends were observed concerning evolution of tensile and burst indices. Several statistical tests were performed in order to identify how properties could be adjusted. The most relevant one was the hypothesis of equality of slopes, and so it was applied to all investigated parameters. A common slope was fitted with a mixed model (random intercept). Regression lines were calculated, giving relationships between measured values and bulk. Adjusted values were calculated from experimental data with the following equation:

$$P_{adj} = A\,(2.2 - bulk_{exp}) + P_{exp}$$

where: P_{adj} = value adjusted to bulk 2.2 cm^3/g
A = regression line slope
$bulk_{exp}$ = experimental bulk value
P_{exp} = experimental property value at experimental bulk.

Regression line parameters for each adjusted property are reported in Table 1. A positive coefficient meant that pulp property increased with bulk and vice versa.

Effect of Wood Properties

Wood classification

Due to the large number of samples and refining, it was not possible to study each one as a particular experiment. Therefore, five classes were created based on tracheid length and wood density. This method was also used by Corson (1997b). Selection criteria are listed in Table 2.

TABLE 1–Slope of the regression between pulp properties and bulk

Property	A
Energy consumption (SEC)	–1185
Burst index	–0.476
Tear index	1.311
Tensile index	–22.77
Brightness	2.868
Opacity	–4.111
Absorption Coef.	–2.234
Scattering Coef.	–11.84

TABLE 2–Criteria values in group distinction

Group	Tracheid length (mm)	Wood density (kg/m^3)
A:	<=2.5	<=350
or	<=2.2	<=450
B:	<=2.5	>550
or	<=2.2	>450
C:	>2.5	<=350
or	>2.8	<=450
D:	>2.5	>550
or	>2.8	>450
E:	2.2<=T<2.8	350<=D<550

These criteria defined at least 40 runs within each of the five groups and so a better statistical analysis.

Fibre lengths and wood densities of all the samples, and how they were distributed within the classes, are presented in Fig. 5. The material spans a large area of variation: fibre lengths from 1.5 to 4 mm and wood densities from 300 to 650 kg/m^3. This large variability was created through the splitting of wood into sub-samples of juvenile, transition, and mature wood. Juvenile wood was mostly represented in group A, transition wood in groups A, B, and E, mature wood in groups C, D, and E.

Influence of wood origin on pulp properties

Averages for optical and physical pulp properties, adjusted to the same bulk for each group, are given in Fig. 5 to 10. The properties were compared between the groups. Letters α, β, χ, and δ above the bars of the graphs identify significantly different groups. Method was based on analysis of variance (level 95%). An example is given for energy consumption in Fig. 5. Energy consumption of Group A was significantly different to that of Group C. Groups B, D, and E had similar energy consumption.

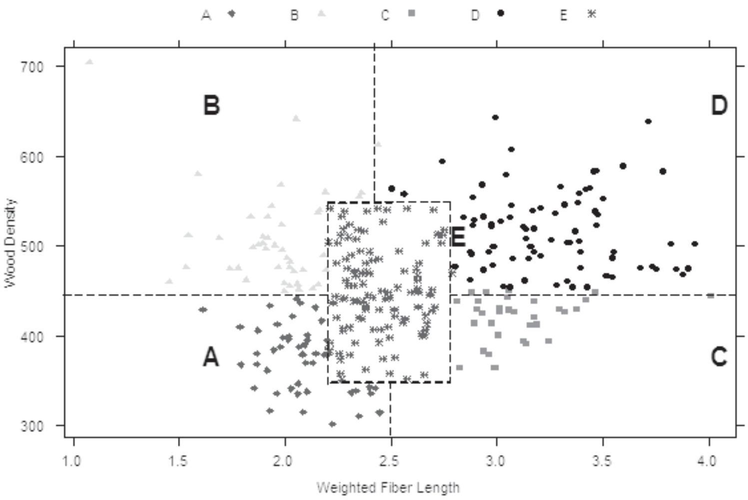

FIG. 5–Division of the material into five groups.

Significant differences between Groups A and C compared to Groups B and D would indicate an effect of density, whereas significant differences between Groups A and B compared to C and D would indicate an effect of tracheid length. Group E would be expected to be intermediate.

Comparing groups, it was possible to point out some differences depending on the property considered. Energy consumption was sensitive to wood density (Fig. 6): low density wood had the highest energy consumption. A decrease with tracheid length was noticed at low wood density but not at high density. Light-scattering coefficient (Fig. 7) increased with wood density for long tracheid wood. Some inconsistency was observed for short tracheid and low density wood (Group A) as the light-scattering coefficient was higher. Parameters other than density and tracheid length may have an influence. Tear index (Fig. 8) was higher with long tracheid wood but did not relate consistently to wood density. For tensile index

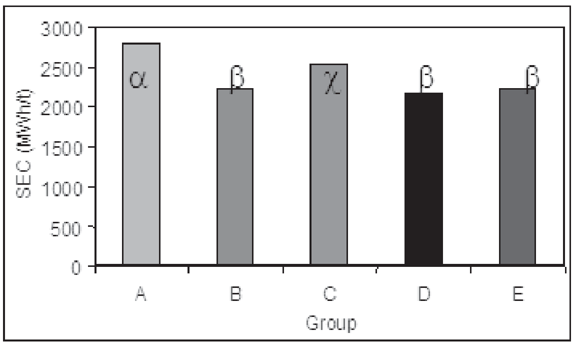

FIG. 6–Energy consumption (SEC) for the different wood groups.

(Fig. 9) and burst index (Fig. 10) no significant differences between the groups could be seen, the differences were not high enough. These two properties may be highly influenced by refining as they are well influenced by fibre development.

Studied parameters and influences from wood density and tracheid length observed in this study are summarised in Table 3.

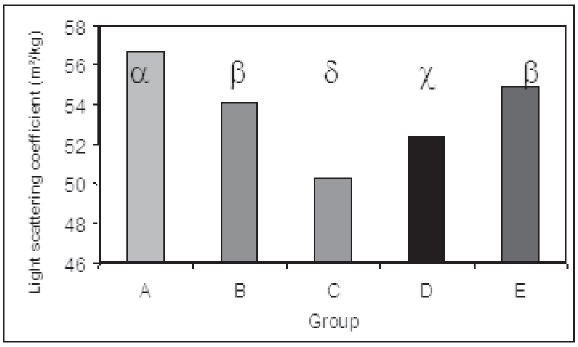

FIG. 7–Light-scattering coefficient for the different wood groups.

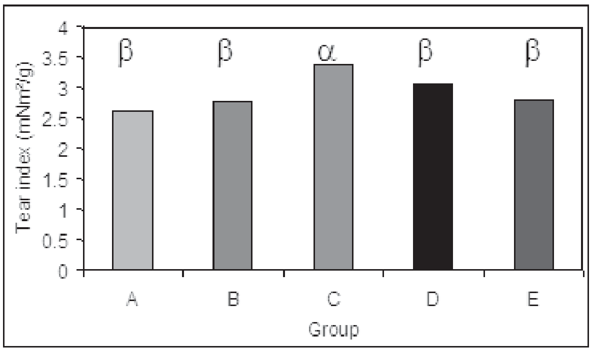

FIG. 8–Tear index for the different wood groups.

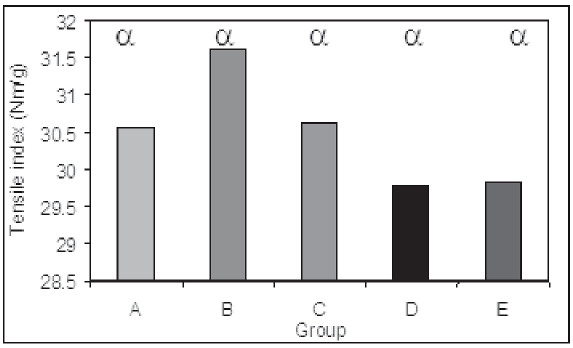

FIG. 9–Tensile index for the different wood groups.

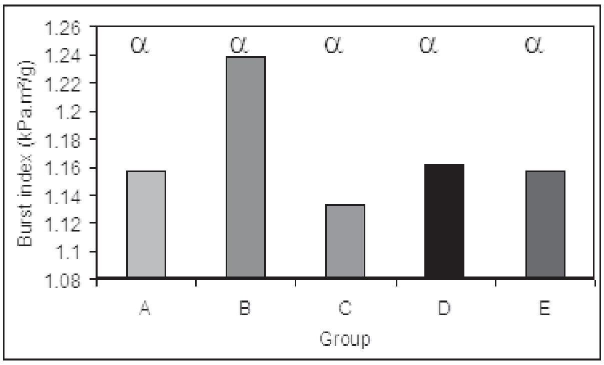

FIG. 10–Burst index for the different wood groups.

TABLE 3–Significant differences pointed out as a function of tracheid length and wood density.

Property	Tracheid length influence	Wood density influence
Energy consumption (SEC)	Yes *at low density*	Yes
Scattering coefficient	Yes	Yes
Tear index	Yes	Yes *at high tracheid length*
Tensile index	No	No
Burst index	No	No

With reference to the selection of wood for industrial application, especially thinning wood *versus* sawmill chips, the results fitted very well with what was observed in the pilot plant (Fuglem *et al*. 2003) and the mill (Persson *et al*. 2003) of the EuroFiber project, as well as in other investigations. Pulpwood from thinning would normally belong to Group A and sawmill chips to Group D. The results showed that pulpwood had a higher energy consumption and will provide a pulp with higher light-scattering coefficient and lower tear index.

Modelling

Pulp properties were modelled as a function of wood characteristics. Half of the samples were used to fit the models and the rest were used to validate the models. Different types of models were tried. A multiplicative model structure was found to be the best one, confirmed by an earlier study (Roux *et al*. 2002). The models were estimated by linear regressions on logarithm transformations of the variables.

An equation enabling the calculation of properties may be as follows:

$$Ln(\text{Opacity}) = \boldsymbol{a} + \boldsymbol{b} * Ln(\text{SEC}) + \boldsymbol{c} * Ln(\text{Tracheid width}) + \boldsymbol{d} * Ln(\text{Tracheid wall thickness})$$

where *a, b, c,* and *d* are the coefficients calculated and presented in the Table 4.

TABLE 4–Retained explanatory variables and associated coefficients (all variables with logarithm transformation).

			Process parameters	Wood properties				Group					Age			Country			
Var	Variability explained	Constant	SEC	Tracheid Length	Tracheid Width	Wood Density	Tracheid Wall thick	A	B	C	D	E	JUV	MAT	TR	Estonia	France	Norway	Sweden
Brightness	20,69%	5,0432	-0,1218				-0,1568												
Opacity	29,02%	4,426	0,0325		-0,0313		0,0153												
Absorp	36,81%		0,6508			0,3508		-5,703	-5,5586	-5,8057	-5,716	-5,7527							
Scatt	30,54%		0,0617			0,2884	-0,4124									2,102	2,0886	2,0941	2,0656
Tear	14,29%	2,1161	-0,1988	0,4698															
Tens	28,88%	-1,9917	0,4043	-0,1198		0,3843													
Burst	27,78%		0,3304			0,3774							0,0446	-0,0443	-0,0004	-4,6695	-4,8155	-4,7063	-4,6501

As this model should be used to predict pulp properties from wood data and process parameters, the following data were used as explanatory variables: energy consumption to express the process conditions, and tracheid morphology (weighted tracheid length, tracheid width, tracheid wall thickness), and wood density. A stepwise regression was used to select the more significant descriptors for each property.

Two trials were done. Firstly, non-adjusted properties were predicted, keeping freeness as an additional explanatory variable on non-adjusted properties. A second test was performed on adjusted properties calculated as described above. As these two models were equivalent in terms of variance explained, it was decided to use only adjusted values without freeness as the explanatory variable.

Some categorical variables were tested to see if they could improve the models. These were wood age (juvenile, transition, and mature wood), country where the tree was grown, and group (A–E) in addition to wood density. A positive sign meant an increase in property with the explanatory variable (Table 4). None of the tree characteristics (number of growth rings, mean ring width, latewood content) influenced pulp properties strongly enough to be kept as explanatory variables in the final model. It could be said age and density were influenced by these two parameters.

Validity of these models was assessed on the validation sample; residual standard errors and bias were calculated for each property (Table 5).

As an application, opacity and scattering coefficient may be calculated as shown.

*Ln(*Opacity*)* = ***4.426*** + ***0.0325*** * *Ln(*SEC*)* – ***0.0313*** * *Ln(*Tracheid Width*)*+ ***0.0153*** **Ln(*Tracheid Wall Thickness*)*

*Ln(*Scattering*)* = [***2.102 * (if Estonia)*** + ***2.0886 * (if France)*** + ***2.0941 * (if Norway)*** + ***2.0656 * (if Sweden)***] + **0.0617** * *Ln*(SEC) + ***0.2884*** * *Ln(Wood Density)* – ***0.4124*** * *Ln(*Tracheid Wall Thickness*)*

TABLE 5–Results for the validation sample

Property	Fitting		Validation		
	n	Residual standard error	n	Bias	Residual standard error
Brightness	155	0.0619	160	–0.0117	0.0725
Opacity	154	0.0128	158	0.0012	0.0141
Absorption	155	0.2304	159	0.0487	0.2658
Scattering	155	0.0646	159	–0.0013	0.0730
Tear	165	0.3115	177	–0.0072	0.2982
Tensile	156	0.1658	162	0.0188	0.1945
Burst	159	0.1997	165	–0.0029	0.2129

As shown in Table 4, 14% to 36% of the variances were explained by the models depending on the property. Even if explained variances were not high, it was interesting to look at what parameters were retained in the models.

Specific energy applied during refining was of great importance. It had an influence on all the pulp properties. For brightness and tear index, it had a negative influence, confirming darkening of pulp and shortening of fibres when refining with higher energy.

Fibre morphology played different roles depending on which characteristic was considered.

Tracheid length had an effect only on tensile and tear indices. Tear index increased with tracheid length; the contrary for tensile index. Higher energy consumption improved tensile index, contrary to tear index.

Tracheid width had a negative influence on opacity; the larger the fibre wall thickness, the lower the opacity.

Tracheid wall thickness had a negative influence on brightness and scattering. Decreasing wall thickness, and collapsibility was better, increasing specific surface area.

Wood density played a positive role in absorption and light-scattering coefficients. This may be due to interaction of wood with refining.

The category contributed significantly for only a few pulp properties: Groups A to E had an influence only for absorption coefficient.

Wood age was found to influence only burst index: juvenile wood presented higher values, decreasing with transition to mature wood.

Country influenced burst index and scattering coefficient. Coefficients of these categories were quite similar, pointing out a small effect between one country, age, or group and another.

Models summed up how wood properties were related to pulp properties and pointed out the large influence tracheid properties can have on pulp. However, a higher influence of tracheid morphology on pulp properties could have been expected, especially tracheid width and wall thickness as observed by Jones (1999). These properties had an influence but it was much lower than those kept in the model — for example, energy consumption, tracheid length, and wood density for tensile index. Moreover, as the models developed a lot of parameters were taken into account at the same time, which could explain why tendencies were different. As a consequence, models presented here were the simplest, with a minimum of explanatory variables. A ranking of explanatory variable impact could then be performed. The high influence of energy consumption could be observed, indicating the importance of the process on pulp properties. With a high energy-consuming process, fibres will be so modified that only a low relationship with tracheids from wood would be expected. In this situation, process alone will give pulp its properties.

CONCLUSION

A Principal Component Analysis (PCA) was performed on mechanical pulp properties. This statistical treatment revealled the correlation between pulp properties. The more the fines content, the higher the light-scattering coefficient; and the longer the fibre length, the lower the fines content. The higher the freeness and the brightness, the lower the pulp physical properties, meaning that higher energy consumption was followed by greater yellowing of pulp.

Comparison of wood groups based on wood density and tracheid length highlighted some differences. Useful trends identified enabled the selection of wood raw materials at the woodyard entrance: wood from roundwood, especially from thinning, had short fibres and low density, compared to sawmill chips with long fibres and high density. Energy consumption was influenced by wood density: the low-density wood of juvenile trees had the highest energy consumption. Light-scattering coefficient decreased with wood density for short tracheid wood (juvenile wood); long fibres (mature wood) gave pulp with lower light-scattering coefficient, but it increased with density. Tear index was higher with long tracheids but did not relate consistently to wood density. For tensile index and burst index no significant differences between the groups could be seen; both properties may be more influenced by the way refining is carried out.

Models presenting pulp properties as a function of wood properties and SEC summed up how these were correlated and showed the large influence firstly of energy consumption, secondly of tracheid properties. The parts of the variances explained by the models were, however, not high enough to use the models for prediction of pulp properties, though they did present tendencies.

Tracheid length had a negative effect on tensile index and a positive one on tear index. Tracheid width had a negative influence on opacity — the larger the fibre wall thickness, the lower the opacity. Tracheid wall thickness had a negative influence on brightness and scattering, and a positive one on opacity. Wood density played a positive role in absorption, light-scattering coefficients, tensile index, and burst index.

Specific energy applied during refining was of great importance. It had an influence on all pulp properties. For brightness and tear index, it had a negative influence, confirming darkening of pulp and shortening of fibres when refining with higher energy. Processing will give pulp its properties, in addition to wood quality. With a process consuming a lot of energy, fibres will be modified in such a way that they will no longer have a relationship with the tracheids in wood. With a process that preserves fibre properties well, this work allowed some properties to be identified that may be investigated for producing tailor-made pulp. However, it was not possible to consider all relevant parameters; among them process would be of importance.

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