Correlations between fibre properties and paper properties

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Mater thesis in Pulp Technology
Abstract
The understanding of what properties the fibre should have in order to give the right end-product paper properties, along with the type of processing, is a subject for a lot of research and development. Today the ability to measure fibre properties on-line is widely used for pulps. It is often necessary to measure many properties and variables in a process. The data collected is therefore almost always multivariate. It is very hard to analyse process data due to a lot of noises. Correlations between fibre and paper properties are hard to find, but this does not mean that correlations do not exist. Fibre properties, measured by the pulp analyser PulpEye, were investigated and correlations to paper properties were studied. The work was divided into three different studies. Study 1 was an investigation of historical process data, in study 2 pulp samples from the production was analysed and study 3 was a refiner setting trial, were different refiner segments, flows through refiners and intensities were studied. Both the group-plots and MVDA’s based on the historical process data in study 1, showed that the Scott Bond was increased with increased amount of kinks and curl for the unbleached pine pulp (softwood pulp). Coarseness measurements, made in the study of historical data, indicated that the coarseness was varying in such a large extent that it was believable that it had effects in the papermaking process. Another interesting fibre property, investigated in the refiner setting trial, was crill. The amount of crill is said to have strong correlation to paper strength. The analysis showed that the incoming pulp had different amount of crill and that the amount of crill after the refiners also was varying for the different samples. The development of crill at different kappa numbers and for pulps refined with different segments and refiner strategies should be further investigated. In this work it has been difficult to find correlations between fibre properties and paper properties in the refiner setting trial. This could have been due to small variations of the different parameters. This work showed that the normal production can be handled very well and variations are rather small. It can be seen though, that problems do appear when parameters are deviating from the normal case. An efficient way to work is to do measurements when the incoming pulp parameters are deviating. It should also be more investigated how the most common deviating pulp parameters should be handled in the refining process and at the board machine. The communication between the pulp production and the board machines is recommended to be further developed, especially when the pulp production have disturbances that can be affecting the refining and further the board production.
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1 Background

The cellulose fibre is strong and has a very good bonding ability. The pulp is a complex system that can be given different properties and the resulting paper can be used for a broad variety of applications. Every application has its own specific demands. The selection of what properties the fibre should have to give the right paper properties, along with the type of processes used, is optimised by a lot of work and research.

Today mills have to have and also rely on on-line methods to optimise the process. The usage of automatic methods for pulp analysis gives a frequent feedback on the process and therefore the product becomes more uniform, and the raw material and energy use is optimised. Today the ability to measure fibre properties on-line is widely used for pulps.

Korsnäs AB has invested in the on-line fibre analyser PulpEye from Eurocon Analyzer AB. The analyser makes measurements on samples taken from seven different positions in the process after the refining, both on PM 4 and PM 5. PulpEye is analysing freeness/SR, fibre dimensions, shives and pulp concentration. At the present time the data from PulpEye are used in a very limited way.

The objective of this master thesis was to investigate the fibre properties of the incoming pulp and the pulp after refining, the variations in the pulp properties and the correlation with some important paper properties. Most of the work was focused on the unbleached pine pulp in the bottom layer at PM4 at Korsnäs mill in Gävle.

2 Theory

2.1 Pulping process

The aim of the pulping process is to liberate the fibres from the wood matrix. This can mainly be done in two ways, either mechanically or chemically. The mechanical process demands a lot of electric power, but on the other hand it makes use of almost 100 % of the raw material. A modern chemical pulp mill is not requiring any external power. Instead one drawback is that only about 50 % of the wood becomes pulp. To be environmentally and economically the chemical pulp mills have to have an efficient recovery of chemicals.

2.1.1 Mechanical pulping

In the mechanical pulping the fibres are released from the wood logs or wood chips by grinding. Depending on what mechanical pulp process that is used, the pulp yield is from 90 to almost 100 %. It is only some easily dissolved carbon hydrates and extractives that are lost. The mechanically fibres are almost entirely uncollapsed and stiff but the pulp will consist of large amounts of fine material, so called fines. Fines consist of fragments from the fibre wall and broken fibres. The fines are very important and give the mechanical pulps some specific optical properties. If the pulp consists of a higher portion of long fibres, the pulp strength will be enhanced. The groundwood pulp is produced by pressing round wood logs against a rotating cylinder made of sandstone. Refiner pulp is made of wood chips that are fed into the centre of two refiner discs. If the lignin in the middle lamella is softened by increased temperature, the amount of fines can be lowered and the fracture takes place in the secondary or primary wall instead. The chips can be treated with steam, around 120 °C, before
feeding to the refiner. This type of mechanical pulp is called Thermo-Mechanical Pulp, TMP. If the chips are soaked in a sodium sulphite solution, the lignin becomes sulphonated. This will lead to a decrease of the softening temperature of the lignin. In a Chemo-Thermo Mechanical Pulp, the chemical treatment with sodium sulphite solution is followed by a steam pre-treatment.

2.1.2 Chemical pulping

The chemical way to produce pulp is to remove the lignin with chemicals. The lignin works as glue between the fibres and by remove most of the lignin the fibres will be released. The delignification of wood is achieved by degradation of the lignin and the introduction of charged groups. This keeps the lignin fragments in solution and eventually they will be washed away. There is no chemical totally selective towards lignin and some amounts of carbon hydrates will also be degraded and end up in solution. Therefore some amounts of lignin is left in the pulp and is estimated by determine the kappa number. Approximately half of the wood material is dissolved during the chemical pulping process. Kraft cooking is the most common chemical pulping method. The cooking liquor, or the white liquor as it is called, consists of sodium hydroxide and sodium sulphide. The active cooking species are OH\(^-\) and HS\(^-\). The hydrogen sulphide is the main delignifying agent and the hydroxide keeps the lignin in solution. Kraft cooking can also be called sulphate cooking. The name “Kraft cooking” comes from the Swedish and German word for strength. Chemical pulp fibres are more flexible compared to mechanical pulp fibres. The chemical fibres will conform to each other in a better way than mechanical pulp fibres when the paper is formed and therefore the chemical pulp offer good strength properties.

2.2 Hardwood and softwood differences in fibre morphology

The wood used for paper making can be classified in the main groups of hardwoods and softwoods. Softwood fibres are long and strong. The strongest paper products are manufactured from chemical softwood pulp. Hardwood fibres are shorter and thinner than softwood fibres. Therefore hardwood fibres give better formation and are used in products requiring a smooth printing surface and high opacity. Hardwood pulps are easier to bleach because it contains less lignin compared to softwood. Many paper qualities are blends between both softwood and hardwood to fulfil both the demands on the printing surface and the strength. There are not only differences between softwoods and hardwoods, differences due to environment and the climate in which the trees grow up can also be found. There are not only differences in fibre properties between different trees, species and differences depending on the environment. It is also lots of variation within the same tree.

Much of the fibre properties depend on the raw material, but this does not mean that the operations that are made in the pulp and paper processes are unimportant to the final product. All operations in the pulp and paper processes will more or less have impact on the fibres.

2.3 Deformations, damages and defects

In wood, the fibres are normally relatively straight, except for some deformations due to growth stresses. Fibres in the pulp are rarely straight and fibre curl, deformations and damages can originate from several steps in the process, such as chipping, defiberization, medium-consistency unit operations and hitting the turns in pipe lines. This may in the end lead to lower strength of the paper.
The morphological fibre-wall properties are affecting the development of the fibre deformations. Fibre deformations are often occurring simultaneously as damages, but they are not the same phenomena. For some properties the deformations does not have to be bad, opposite from the fibre damages that is usually something to avoid.

2.3.1 Fibre curl and fibre kink
The use of curly fibres will lead to low tensile index, but it may also lead to high tear-index. The curly fibres are also tended to form sheets with low elastic modulus but higher stretch than sheets made from straight fibres. Changes in the axial direction that is sharp such as kinks, angular folds and twist are related to lowered tensile strength and elastic modulus of paper. Figure 1 shows an illustration of fibre curl and fibre kink. Equation 1 is used to calculate the curl index.

\[ \text{Curl index} = \frac{L}{l} - 1 \]

It may be possible to increase the runnability by using deformed fibres. The tensile stiffness, defect resistance, behaviour on moistening and the uniformity of the web are important web properties for a good runnability. The tensile stiffness is often compromised when deformed fibres are used. The structural weak points in paper can both be reinforced or weakened by the use of deformed fibres.

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2 Page et al. (1985)
3 Page et al. (1985)
Tear strength is used to predict the web runnability and the curly fibres gives increased tear strength. The curly fibres do also distribute the damages over a larger area and more bonds are broken.  

### 2.4 Fibre length
Chemical long fibres are used to reinforce paper. Length is one of the most important fibre properties. A long fibre can have more fibre joints and therefore create a stronger network compared to a shorter fibre. It is not always clear though, how the long fibres are affecting the paper strength. This due to the longer fibres tendency to form more or bigger flocs compared to shorter fibres. The flocculation leads to a more uneven sheet, which may affect the paper properties. This can be avoided by lower the fibre concentration for the long fibre stock during forming and by improve the dewatering elements on the wire.

Fibre flocculation is the main reason for bad formation. But it is not only the fibre length that is affecting the formation, also the fibre mass and coarseness is affecting. The effect of the fibre mass on handsheet formation can be noticed if stock concentration is sufficiently low to eliminate flocculation.

### 2.5 Fibre-wall thickness and fibre collapse
The thickness of the fibre-wall plays a crucial part of the paper properties, both in the pulping process and later on in the paper process. A fibre with thinner cell-wall will collapse more easily than a fibre with thicker cell-wall. Therefore the earlywood, with its thin walled fibres, will collapse easily in the process. The latewood fibres, with much thicker fibre-wall, will in much larger extent remain the same shape. Figure 2 shows a schematic picture of the earlywood and the latewood fibres and their ability to collapse. It can also be seen how a network is building up from the different type of fibres.

![Figure 2. Latewood and earlywood and their different ability to collapse and build up networks.](image)

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4 Joutsimo et al. (2005)
2.5.1 Influence of fibre collapse on paper properties

It will have large effect on the paper properties if the fibres are collapsed in a larger or smaller extent. The collapsed fibres will create a network with much higher density and lower bulk. This paper will have a higher tensile strength, compression strength, burst strength, tensile stiffness and elasticity. Collapsed fibres are more flexible and have a higher area available for bonding. The fibres are collapsed in the pulping process, papermaking process or during wet pressing, drying or calendering. In a study the tensile index of different kraft pulp fractions were plotted against the beating degree as can be seen in figure 3. The pulp was fractionated by a hydrocyclone, which separates the fibres by flexibility. The flexibility of the fibres and the fibre joints had a large influence on the tensile strength of the paper. An increased degree of bonding will give a paper with higher tensile strength. The flexibility of the fibres will also affect for example the density, porosity and surface properties, such as light scattering of the paper. In table 1 information about the different fractions in figure 3 can be seen. The uncollapsed fibres will create a network with higher porosity and higher bulk compared with the collapsed ones. Therefore the paper made of uncollapsed fibres will have higher bending stiffness and it will also be easier to dewater. It is believed that a thicker fibre-wall gives high fibre strength and this will in turn give higher tear strength for the paper made of uncollapsed fibres. In table 2 it can be seen how some paper properties are depending on the type of fibres, earlywood or latewood.

![Figure 3. Tensile index for different softwood kraft pulp fractions, fractionated by hydrocyclones in several steps, and the dependency on beating. A stands for accept, R for reject and the number represent from which step the fractionation is.](image)

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5 Nordmark Urban (2000)
7 Paavilainen, L., (1993)
Table 1. Fibre dimensions after fractionation by hydrocyclones in several steps.\(^8\)

<table>
<thead>
<tr>
<th></th>
<th>Origin</th>
<th>Accept I</th>
<th>Reject II</th>
<th>Reject III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latewood [%]</td>
<td>20</td>
<td>6</td>
<td>63</td>
<td>74</td>
</tr>
<tr>
<td>Cell-wall thickness [µm]</td>
<td>5.6</td>
<td>4.7</td>
<td>8.0</td>
<td>9.2</td>
</tr>
<tr>
<td>Fibre width [µm]</td>
<td>43.6</td>
<td>44.0</td>
<td>39.0</td>
<td>36.7</td>
</tr>
</tbody>
</table>

Table 2. How different paper properties are affected by the thickness of the fibre-wall.\(^9\)

<table>
<thead>
<tr>
<th>Property</th>
<th>Latewood</th>
<th>Earlywood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tear strength</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Dewatering</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Bending stiffness</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Tensile strength</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Compression strength</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Burst strength</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Tensile stiffness</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Stretch</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

2.6 Effects of the refining

It is important to know the fibre modifications desirable for the special product produced. The beating can be a help to obtain the required properties. By controlling the beating, wanted properties can hopefully be achieved. The most important effects of beating are:

- Cutting or shortening of fibres.
- Production of fines and complex removal of parts of the fibre wall, creating fragments in the suspension.
- External fibrillation. Partial removal of the fibre wall. The parts are still attached to the fibre.

\(^8\) Paavilainen, L., (1993)

• Internal changes in the wall structure. This is described by delamination, internal fibrillation or swelling.

• Curling/Straightening of fibres.

• Inducing/Removal of kinks, nodes, slip planes and micro compressions in the fibre-wall.

• Dissolving or leaching out colloidal material into the external liquor.

• Redistribution of hemicelluloses from the interior of the fibre to the exterior parts.

• Scrub the surface at the molecular level to produce surface with a gel consistency of the surface.

2.6.1 Creation of fines and crill
When refiners are operating at low concentrations with a minimum distance between, or a high force on the refining surfaces, fibre cutting will take place because of a greater fibre-to-bar contact. The cutting of fibres will increase the formation quality, but in most cases, when high paper strength is desirable, the fibre cutting is not wanted.

The fibrillation is creation of rough fibre surfaces. The refiners are breaking the primary wall and when this happens, the fibrils from the secondary wall will stick out. This will increase the surface area for bonding and therefore increase paper strength. Once the fibrils are detached from the fibre, they are called fines. A refiner filling designed to fibrillate, will give more fibre-to-fibre contact rather than fibre-to-bar contact. Therefore it will work at higher concentration. Results of the internal fibrillation will be partial delamination of the fibre wall and partial separation of fibrils. This will lead to higher swelling and conformability of the wet fibre wall. This leads to improved fibre joints and strength of the paper at the price of optical properties. It is the external fibrillation that will improve the sheet consolidation and increase the strength of fibre joints. External fibrillation only exists in water suspensions and the external fibrils will go back to the fibre surface in the drying process.

The largest fines are the ones that are fragments of the fibre wall and the smallest fines are fibrils or parts of the fibrils. There are two types of fines in the chemical pulps, primary and secondary fines.¹⁰ The primary fines are the ones existing in the unbeaten pulp and they are ray cells, parenchyma cells and middle lamella lignin. Primary fines have a higher lignin content compared with fibres in a kraft pulp.¹¹ The beating creates the secondary fines, these come mostly from the fibre surface and have higher lignin content compared with the fibres, but lower compared with the primary fines.¹² The primary fines are normally less than 2 % of the total amount of fines. The secondary fines have approximately twice as much fibrils compared to the primary fines.¹³ Fines will fill the voids in the

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¹⁰ Brecht et al. (1952)
¹¹ Lindström and Nordmark (1978); Heijnesson (1996); Liitiä et al. (2001); Retulainen et al. (2002); Thalib and Heinesson-Hulten (2006)
¹² Lindström and Nordmark (1978); Htun and de Ruvo (1978); Heijnesson (1996)
¹³ Krogerus et al. (2002)
bonds and especially fibrillar fines can bring fibres into closer contact to each other during the consolidation. Even if the fines content is low, it has a significant influence on the bonds.

The tensile index, TEA index (tensile energy absorption), burst index and stretch-to-break are improved when fines are added, especially when adding secondary fines. Figure 4 illustrates the effects on paper properties in a study when fines were added at two levels, in pulp with two different kappa number, 45 and 90 respectively. The study showed that adding fines will increase the sheet density which results in tensile improvements. No difference between primary and secondary fines could be found in the relationship between tensile index and density. The improved mechanical properties are thought to come from a better consolidation process. The capillary forces are probably higher between the fibre surfaces and the fines, compared with the capillary forces in the absence of fines. Fines will increase the potential of fibre joints when they are bridging between the fibres during the consolidation.14

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14 Bäckström Marie et al. (2008)
The refining process is an energy intensive process that has a significant impact on the properties of many paper products and therefore it is very important to control this process. Today on-line measurements of the drainage resistance of the stock, for example the MSR, and also sometimes the geometrical dimensions of the fibres are mainly used to control the refining process. One very important variable left out is the potential of fibres to bond to each other. The fibrils that are partially or completely loosened from the fibres are called crill. Crill is generated during the refining process. Recently results show an indication of a correlation between crill and paper strength properties. Crill is significantly improving the bonding between fibres and therefore it is crucial to be able to measure crill.

For instance the MSR is difficult to use when the strength potential wants to be predicted. This is due to its strong non-linear development when refining is increased together with the reliance of the measurement on variables that are not significant for the strength. The tensile strength properties are known to be strongly affected by the fibre joints. Measurement results indicate in a convincing way that the crill measurement can be used to evaluate the development of tensile strength potential during the refining process. When the refining energy is increased a linear development of the crill can be seen. The linear dependency increases the reliance that the crill is a variable that significantly affects the strength.

2.6.2 Effect of refining on different pulps
Hardwood and softwood will respond differently to the refining. Softwood pulps are requiring higher refining intensities than hardwoods and minimum amount of refining to keep the fibre length and an optimal tear/tensile stability. Hardwood pulps on the other hand will require gentle refining and more energy to develop strength. In a morphological perspective it is many similarities between the hardwoods, but the fibres from for example birch and eucalyptus are different in their fibre structure, chemical composition density and also their tendency to collapse. It is also differences between earlywood and latewood and their effect on paper properties. Unbeaten latewood fibres are stronger compared to earlywood fibres. Beating of the two types will decrease the difference in strength. How pulps are responding on beating is also very affected by the pulp yield. When the pulp is beaten, the dewatering of the web will be deteriorated and therefore the dewatering capacity will

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15 Bäckström Marie et al. (2008)
16 Pettersson, Thorulf (2010)
17 Pettersson, Thorulf (2010)
be limiting the beating. In the future the refiner systems will treat fibres individual and hopefully someday the treatment will be chemical, biological or sonic instead of mechanical.

2.6.3 How the refining will affect paper properties
The shortening of fibres will give an improved formation. The beating will increase the surface area and flexibility of the fibres. The flexible fibres are more bendable to conform around each other. This, together with the liberation of a lot of fines, will improve the contact between the fibres which in turn leads to an increased strength of the fibre joints and therefore also the strength of paper. The increased flexibility is probably due to an increase of porosity or delamination of the fibre wall.

All the strength properties accept for the tear index will increase during beating. This is because the tear strength depends on the individual strength of the fibres and the other properties rely on the fibre joints. The increase of fibre joints will lead to an increase of the density of the paper and the light scattering coefficient will decrease. The bulk, opacity and porosity are other properties decreased by the refining. Beating influences the elastic breaking strain much more than wet pressing or grammage. The elastic modulus though, has been shown to be insensitive towards different additions of fines.

2.6.4 Refiner settings
The effect of energy differs between different types of fibres. The specific energy means the amount of energy transferred from the motor of the refiner to the fibres see equation 2. The term “no load” means the energy required to just spin the rotor in the pulp slurry.

\[ P_s = (P_t - P_0)/q \]  \[2\]

- \( P_s \) = Specific energy [kWh/ton] or [MJ/kg]
- \( P_t \) = Energy input [kW]
- \( P_0 \) = No load-energy [kW]
- \( q \) = Pulp flow [ton/h]

Specific edge load, SEL, is a term used to define how the energy is applied on the fibres, the refining intensity. The definition of SEL is the amount of energy applied across one meter of refiner plate’s bar edge and transferred to the pulp per second, see equation 3a and 3b. The power, \( P \), for the refiner is the amount of energy that is transferred from the refiner’s motor to the fibres.

\[ SEL = P/L_s \]  \[3a\]

where

\[ L_s = nzrzstl \]  \[3b\]

\( L_s \) is the edge length per second.

\[18\] Lumiainen Jorma (1990)
\[ n = \text{frequency \,[s^{-1}]} \]

\[ z_r = \text{number of rotors} \]

\[ z_{st} = \text{number of stators} \]

\[ l = \text{effective length of one bar}\,[m] \]

### 2.7 Laboratory sheet forming vs. paper machine

Laboratory sheet formers will give isotropic sheets i.e. the fibres are randomly oriented in the paper. In a paper made on a paper machine, the fibres align themselves in the machine direction and this paper will be anisotropic. This results in different properties between the machine direction and in the cross direction for machine made paper. There is also a difference in formation between machine made paper and laboratory sheets (handsheets). In the laboratory sheets the fibres will be evenly distributed and the formation will be almost ideal. On the paper machine, the fibres will catch on to each other and this leads to flocculation. Due to the fact that formation affects the strength properties of the paper, it can be misleading to give judgement on paper strength based on laboratory sheets. Laboratory sheets of softwood fibres will be much higher compared to laboratory sheets made from hardwood. But the tendency of softwood fibres to flocculate on the machine will decrease the differences in strength between hardwood and softwood. The closed system on a paper machine will give a good retention of fines, compared to an open system as in the laboratory, where the fines are lost to a certain degree.

In a paper machine the pressing section differs a lot from the one used in the laboratory. The laboratory wet pressing is accomplished by pressing the sheets in a flat plate pressing machine in one or two quite long steps. In a paper machine the press section consists of two to three sets of pressing rolls which will press the paper web for only a short time each but at much higher load.

The development of the drying stress, in fully restrained drying, depends on the drying process itself. If the temperature is high or the rate is low, drying stress becomes low. If the stress is varied during the drying process, as on a paper machine, the final properties of the paper depend on the increasing drying stress vs. solid content. Stresses applied in the beginning of the drying process, before 60% dryness, have the largest effect on the elastic modulus. Because of the fact that handsheets are dried slower compared to machine-made paper, the properties will be different between the two kinds of paper.\(^\text{19}\)

### 3 Experimental

#### 3.1 The paper and board production at Korsnäs AB in Gävle

Korsnäs AB in Gävle has three paper/board machines, PM2, PM4 and PM5. Together they produce 700 000 tonnage paper and board per year. Three fibre lines provide these machines with pulp. Fibre line 1 and 2 produces unbleached softwood pulp of pine and spruce. Fibre line 3 is alternating and

\(^{19}\) Htun and de Ruvo (1983); Htun (1986)
produces both bleached softwood pulp of pine and spruce and hardwood pulp of mostly birch. One must be aware of the fact that the pulp referred as “pine pulp”, in this work, not only contains pine but also spruce and the pulp referred as birch pulp, not only contains birch but also aspen. So the softwood pulp is referred as pine pulp and the hardwood pulp as birch pulp, because that is what is done at the mill. PM2 produces only one-layered products. The products are bleached and unbleached sack paper with high strain, bleached and unbleached kraft paper, and liquid packaging board. PM4 produces two-layered products. The products are coated and uncoated white top kraft liner (WTL), liquid packaging board and uncoated bleached kraft paper. PM5 produces three-layered products and the products are coated and uncoated liquid packaging board. Important properties for the liquid packaging board are smell and taste neutrality, strength and stiffness, printability, convertability and purity. For the WTL the printability, strength and convertability are the most important properties. The sack paper should have strength, tear strength, convertability, porosity, high strain and good printability. The most important properties for the kraft paper are printability, convertability, stiffness and strength.

When the pulp comes from the fibre lines it passes through the refining process before it can be used in the board and paper production. Different qualities have different demands on the refining process. The different layers in for example a liquid packaging board should have different properties. The unbleached middle layer should contribute to the bulk and z-strength and the top layer consists of bleached pulp and gives a good tensile stiffness and printability.

3.2 The fibre analyser PulpEye

PulpEye is a pulp analyser from Eurocon Analyzer AB. PulpEye can be used to measure the concentration, freeness as CFC, SR, MSR, fibre length, fibre thickness, curl, kinks and coarseness, shive content as number/gram, weight-% and size distribution, brightness, pH and kappa number. It is module based and has for example one module for drainage and one for fibre and shives properties. The measurements can be done either automatically or manually. The analyser is controlled by different PLC-units which are communicating with a PC. Online measurements at Korsnäs AB in Gävle are done at seven different positions in the process. All measurements are done after the refining at both PM4 and PM5. The seven online units can be found in the pulp streams called unbleached pine (softwood), bleached pine (softwood) and bleached birch (hardwood) at PM4 and at unbleached middle layer, bleached birch (hardwood), unbleached bottom layer and bleached birch (hardwood) at PM5. A total analysis of both concentration, freeness, shives and fibres takes about 10 minutes and an analysis of just the freeness and concentration takes about 5 minutes. At Korsnäs AB in Gävle the MSR, Modified Schopper-Riegler number, is used as a measure of the drainage properties. The difference compared to the usual SR is that the steps are smaller between one units of MSR compared to one unit of SR. See the properties measured by PulpEye and the explanations in appendix.

3.3 Method

Analysis of historical process data was made and fibre properties measured by PulpEye investigated and correlated to paper properties. Randomly pulp samples from the daily production were collected, both before and after the refiners. The pulps were manually analysed in PulpEye and
laboratory sheets were made. Three of the random pulp samples were collected after the start up after a longer production break. Two of them were taken out almost right after the start up. A refiner setting trial was also done at PM4. During the trial different refiner settings were tested and pulp were collected at every settings. The effects of different settings and how they affected the fibre properties were investigated. Laboratory sheets were made and paper properties were tested. Pulp samples were also sent to Innventia for crill measurement. To find correlations between fibre properties and sheet properties, group-plotting and MVDA (Multivariate Data Analysis) was used.

3.3.1 Sheet preparation
The laboratory sheets were prepared from a suspension of three gram dry pulp per litre water. The sheets were formed in a Finnish sheet former. When the sheets from a pulp sample had been made, they were pressed in a flat plate pressing machine, all at the same time. It was a static pressure of 0.4 MPa for four minutes. Right after pressing the sheets were dried in a cylinder dryer for 360 seconds. The drying process was made in a cylinder dryer in order to try to obtain a restrained drying of the sheets. The grammage of the sheets were set to be 100 g/m².

3.3.2 Paper properties
The investigated paper properties in the studies are presented in table 3, which also shows the method used, in which unit the properties are presented and some general information about the properties.
Table 3. Measured paper properties and the method used.

<table>
<thead>
<tr>
<th>Paper property</th>
<th>Method/Unit</th>
<th>General information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air resistance</td>
<td>Gurley method, ISO 5636-5: The time, in seconds, it takes for 100 ml of air to pass through the sheet. [s/100 ml] or [Gurley seconds]</td>
<td>An important property for the production of sack paper.</td>
</tr>
<tr>
<td>Air permeability</td>
<td>The ability to let air through the sheet, Air permeability, ISO 5636-3: 128/t, where t is the time it takes for 100 ml of air to pass through the sample (the same as Gurley seconds). [µm/Pa*s]</td>
<td>An important property for the production of sack paper.</td>
</tr>
<tr>
<td>Bending stiffness</td>
<td>ISO 2493 [mNm] in 5°</td>
<td>Mostly controlled by the grammage (which not is the actual structural property determine the bending stiffness). Increased bulk will give increased bending stiffness.</td>
</tr>
<tr>
<td>Burst strength</td>
<td>SCT (Short Span Compression Test), ISO 9895 [kN/m]</td>
<td>Can be difficult to measure due to buckling of a thin sample. This can be prevented by either making the buckling load higher than the compressive strength with a proper geometry for the specimen or as for SCT, make a short span length (0.7 mm) below the one needed for buckling.</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>ISO 534 [kg/m³]</td>
<td>Can be used to predict the bonded area in the sheet. Increased density ability indicates more bonded area.</td>
</tr>
<tr>
<td>Density</td>
<td>z-strength, according to STFI [kPa] Scott Bond, TAPPI T569 pm-00 [J/m²]</td>
<td>Measures the strength in the z-direction. The delamination energy can be measured with a method called Scott Bond. Sometimes the delamination energy is used to measure the inter-fibre bonding energy, but that is not optimal.</td>
</tr>
<tr>
<td>Out-of-plane strength</td>
<td>ISO 1924-3 Tensile Energy Absorption (TEA) index [J/kg], tensile index [kN/kg], stretch at break [%] and tensile stiffness index [MNm/kg]</td>
<td>Gives the tensile strength (greatest longitudinal stress a substance can take before it breaks). The tensile strength will be depended on the strength of the fibre joints and the strength of the fibres. It also gives the stretch at break, tensile energy absorption (TEA) and tensile stiffness.</td>
</tr>
</tbody>
</table>
3.3.3. Fibre properties
How the fibre properties are presented by PulpEye can be seen in table 4. More details about the fibre properties (measured by PulpEye) can be seen in appendix.

**Table 4.** How fibre properties are measured by PulpEye.

<table>
<thead>
<tr>
<th>Fibre property</th>
<th>PulpEye parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre length</td>
<td>Length fractions 1 to 5 (Length fraction 1=0.2 to 0.5 mm, 2=0.5 to 1.0 mm, 3=1.0 to 1.5 mm, 4=2.0 to 2.5 mm and 5=2.5 mm and longer) arithmetic length, length weighted length (the longer fibres are affecting more compared to what they do in the arithmetic fibre length)</td>
</tr>
<tr>
<td>Fibre curl</td>
<td>Curl fractions (Mean value of the curl in each length fraction), arithmetic curl, length weighted curl</td>
</tr>
<tr>
<td>Fibre width</td>
<td>Width fractions (Mean value of the width [μm] in each length fraction), arithmetic width, length weighted width</td>
</tr>
<tr>
<td>Fines</td>
<td>Fines share, fines ≤0.2 mm</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Coarseness [mg/m]</td>
</tr>
<tr>
<td>Kinks</td>
<td>Kinks/fibre, kinks/mm and segmented length (length between kinks)</td>
</tr>
</tbody>
</table>

The flexibility has been measured indirectly as coarseness and the fibrillation has been measured as crill. In the future, a module which measures fibre wall thickness and also a module which measures crill will be available to add to the pulp analyser PulpEye. This is two very interesting fibre properties that most likely have large influence on paper properties.

On-line measurements of crill can now be made by the Innventia OptoPlatform System and this may enable further optimisation of both the quality and the uniformity of the products. Due to the fact that crill is about 0.25 μm wide makes it very difficult to measure crill with methods based on image analysis, especially in the visible range. The weight of the loosened fibrils normally is around 1% of the pulp but in spite of that they have a surface area comparable to that of the fibres. The Innventia OptoPlatform is a portable measurement system that was developed for monitoring rapid changes in the properties of fibres and fillers. The measurements made with the system are based on a theoretical approach where light is scattered, absorbed and transmitted by the pulp and analysed as a stochastic process. The measurements of how the light interacts with the particles in the pulp are made in the two spectral regions viz. UV and NIR. When the methods implemented in the portable system were tested at Innventia the on-line measurements were found to be easy to carry-out and it was also found that they can be used for trouble shooting, process analysis and process control. The measurements made with the OptoPlatform can be made once a second if necessary.

**3.3.4 Group-plotting**
A method used in the work of finding correlations between different properties is group-plotting. When data is group-plotted all the data of the x-variables are sorted according to an increasing y-variable. The y-variable are the paper property chosen. The x-variables are for example the fibre...
properties and refining parameters. The data are then divided into different intervals with the y-variable as the basis. The mean values of all the different x-variables and also the mean value of the y-variable in the different intervals are calculated. By doing this, correlations between a y-variable and different x-variables can be found. One example of a correlation is when the mean values of a x-variable increases with the increasing mean values of a y-variable. When the historical data was investigated the criterion for a correlation was that the same correlation should be found between a y-variable and an x-variable for three different grammages of WTL (white top kraft liner). The product properties depend on the specification of the board, for example the specification of the grammage, therefore the different products had to be treated separately.

3.3.5 Multivariate data analysis
In both basic research and applied technology it is often necessary to measure many properties and variables of a system or a process. The data collected is therefore almost always multivariate with multiple variables measured on multiple samples or at multiple time points. The multivariate data contain much more information than univariate data when it is correctly measured on intelligently selected observation and variables. To get insight to the system that is studied, it is not enough to just look at the data. It needs to be analysed and the information in the data should be expressed in an understandable way, for example as a graph. After the multivariate analysis, the results can be related to the objectives of the investigation and the scientific context. Multivariate Data Analysis, MVDA, provides a toolbox of flexible data analytical tools. Two useful multivariate projection methods that are useful are principal component analysis, PCA\textsuperscript{20}, and partial least squares projections to latent structures, PLS\textsuperscript{21}. There are three different types of basic problems to which the multivariate tools can be applied:

1. Overview of a data table
2. Classification and/or discrimination among groups of observations
3. Regression modelling between two blocks of data (X and Y)

These groups do also reflect the major stages of the multivariate analysis. It often starts with a simple overview of the information which can be obtained by using the PCA. This gives a summary which shows how the observations are related and if there are any deviations. The ability of PCA to uncover both smooth time trends and sudden shifts in the data makes it useful in process data analysis. The PCA also gives an understanding of the relationships among the variables, it describes the correlation structure in X. Often an initial PCA of a data set reveals groping among the observations. This may be an indication that there is a need for further PCA modelling of each such group, in order to fine-tune the analysis. The last stage of the analysis of the data is regression modelling between two blocks of data, X and Y. The aim is to predict Y from X for new observations. This kinds of modelling is achieved with the PLS method which can be seen as a regression extension of PCA. The X-variables, called the factors, are signals which are sampled frequently at regular time intervals. The Y-variables, called the responses, are measured less frequently than the X-variables.

\textsuperscript{20} Wold S., et al. (1984)
\textsuperscript{21} Jackson J.E. (1991)
and can be things like quality of the product or yield. The responses are often laborious and more expensive and time-consuming to measure compared with the factors. With appropriate data and a workable PLS model it can be possible to find out how the factors influence the responses, how the responses correlate with each other and how to adjust the factors to get a desired profile of the responses.\textsuperscript{22}

A PLS-model is validating through the $R^2$ and $Q^2$. The $R^2_X$ and $R^2_Y$ are fraction of the Sum of Squares (SS) of all the x’s and all the y’s, explained by the current component. This means that the $R^2_X$ and $R^2_Y$ shows how well the model fits to the data of x and y. A value on $R^2$ of one means that the correlation is perfect and a value of zero mean no correlation at all. The $Q^2$ is the fraction of the total variation of the x’s that can be predicted by a component, as estimated by the cross-validation (CV). The CV is the way to find the optimal model dimensionality. It is a way to test the significance of the PCA- or PLS-model. Parts of the data are kept out of the development of the model. Instead of these values predictions are used and later on the predicted values are compared to the actual values. The prediction error sum of squares, PRESS, is the square differences between the values that are predicted and the observed values. SIMCA computes the overall PRESS/SS for each component, where SS is for the previous component. A component is considered to be significant if PRESS/SS is statistically smaller than 1.0.\textsuperscript{23} In this work it was the program SIMCA-P+ that was used for the MVDA analysis.

\subsection*{3.3.6 Study 1: Historical process data}

The data used were registered between the 11th of October in 2009 and 11th of October in 2010 and collected from PI, a process information system. When the paper properties are tested on the board the properties of all the different pulps often affects the results. Therefore, when the historical data were investigated, the fibre properties for all the pulps on PM 4 were taken into account. The 32 most common PulpEye parameters (available in PI) were included in the analysis. The refiner energy and the flow through the refiners for all the pulps and the SEL for the unbleached pulp were included in the analysis. All the analysed properties of the board were measured at position 7 (the middle position).

Three WTL-products (EA125, EA130 and EA135) were analysed by the group-plotting and by the MVDA. The PLS-model was used in the work of finding correlations. The paper properties investigated were:

- Air resistance (Gurley method)
- Burst strength
- SCT
- Scott Bond


\textsuperscript{23} Eriksson L., et al. (2006) page 382-383
Due to the fact that the coarseness calibration was made after the work had started, not so much data had been registered when it was time to do the analysis. The coarseness variations were analysed by plotting the trends of the data. This analysis included all the qualities produced during that time.

### 3.3.7 Study 2: Analysis of pulp samples from the production

Unbleached pine pulp samples were collected randomly from the daily production at PM4 between October the 7th and October the 28th, before and after the refiners. The pH was controlled immediately and the samples were analysed by manual measurements on PulpEye. Laboratory sheets were made and the properties tested were:

- Air permeability
- Density
- Elasticity module
- Scott Bond
- SCT
- Strain
- TEA
- Tensile index
- Tensile stiffness index
- z-strength.

The 44 most common PulpEye parameters (available in PI) were included in the analysis and the data was analysed by MVDA.

### 3.3.8 Study 3: Refiner setting trial

A trial with different refiners settings was made at PM4’s unbleached pine pulp the 29th of November. The test run was made in order to validate the effects on fibre properties when some interesting refiner parameters were varied. The refiner parameters investigated were:

- Intensity
- Total flow through the refiners
- Different refiner segments

The SK6, SK7 and SK8 have one type of segments that are newer while the SK9 and SK10 have an older type of segment. The differences between the segments can be seen in table 5. In this study three refiners were used at the same time. All the parameters except for the tried ones were held as
constant as possible during the trial. Table 6 shows how the investigated refiner parameters were set.

Table 5. Differences between the refiner segments.

<table>
<thead>
<tr>
<th>Refiner</th>
<th>$z_{ref}[m]$</th>
<th>No-load energy [kW]</th>
<th>Diameter [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK6</td>
<td>28</td>
<td>156</td>
<td>39</td>
</tr>
<tr>
<td>SK7</td>
<td>28</td>
<td>156</td>
<td>39</td>
</tr>
<tr>
<td>SK8</td>
<td>28</td>
<td>156</td>
<td>39</td>
</tr>
<tr>
<td>SK9</td>
<td>30.7</td>
<td>230</td>
<td>42</td>
</tr>
<tr>
<td>SK10</td>
<td>30.7</td>
<td>230</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 6. Planned settings for the refiner parameters during the test run. The refiner energy was set to be constant and the constant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Recirculation through the refiners</th>
<th>Refiner segments</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maximum</td>
<td>SK6, SK7, SK8</td>
<td>Slightly decreasing</td>
</tr>
<tr>
<td>2</td>
<td>Minimum</td>
<td>SK6, SK7, SK8</td>
<td>Slightly decreasing</td>
</tr>
<tr>
<td>3</td>
<td>Minimum</td>
<td>SK6, SK7, SK8</td>
<td>Steeply decreased</td>
</tr>
<tr>
<td>4</td>
<td>Minimum</td>
<td>SK6, SK9, SK10</td>
<td>Slightly decreasing</td>
</tr>
</tbody>
</table>

Pulp was taken out before and after the refiners at the first and the last sample and only after the refiners at the second and the third sample. On-line measurements were done on the beaten pulp during the trial. The unbeaten pulps used as references were manually analysed in PulpEye. Because some work had to be done on PulpEye in the end of the trial, only one on-line measurement was made at the last sample. In order to get one more measurement, a manually analysis was made on pulp from the last sample. Pulp from all the pulp samples was sent to Innventia for crill measurement. Laboratory sheets were made out of pulp from all the samples. The properties tested were:

- Air resistance
- Density
- Scott Bond
- SCT
- Tensile index
• Tensile stiffness index
• z-strength

The data was analysed by trying to find correlations between the variations of the paper properties and the fibre properties. From the results it could also be seen which refiner settings that was beneficial for a certain paper property. Pulp from all the samples were send to Innventia for crill measurements.

3.4 Results and discussion

3.4.1 Study 1: Historical process data

The fact that there are a lot of parameters constantly changing on the paper machine and incoming pulp variations makes it difficult to get significant results out of the process data. Only data of the fibres, refiners and board was used in the MVDA (Multivariate data Analysis). This lead to problem with poor significance when using the MVDA and therefore the results can only be used as guidance. In table 7 the values of $R^2_Y$ and $Q^2$ from the MVDA can be seen for the investigated board properties.

Table 7. The values of the $Q^2$ and $R^2_Y$ for the MVDA’s made on the historical data of air resistance, burst strength and Scott Bond.

<table>
<thead>
<tr>
<th>Property</th>
<th>Quality</th>
<th>$R^2_Y$ (measured value)</th>
<th>$Q^2$ (predicted value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air resistance</td>
<td>EA125</td>
<td>0.532</td>
<td>0.433</td>
</tr>
<tr>
<td>Air resistance</td>
<td>EA130</td>
<td>0.555</td>
<td>0.464</td>
</tr>
<tr>
<td>Air resistance</td>
<td>EA135</td>
<td>0.460</td>
<td>0.343</td>
</tr>
<tr>
<td>Burst strength</td>
<td>EA125</td>
<td>0.380</td>
<td>0.297</td>
</tr>
<tr>
<td>Burst strength</td>
<td>EA130</td>
<td>0.474</td>
<td>0.346</td>
</tr>
<tr>
<td>Burst strength</td>
<td>EA135</td>
<td>0.261</td>
<td>0.209</td>
</tr>
<tr>
<td>Scott Bond</td>
<td>EA125</td>
<td>0.379</td>
<td>0.260</td>
</tr>
<tr>
<td>Scott Bond</td>
<td>EA130</td>
<td>0.410</td>
<td>0.340</td>
</tr>
<tr>
<td>Scott Bond</td>
<td>EA135</td>
<td>0.368</td>
<td>0.297</td>
</tr>
</tbody>
</table>

Secondary effects are important and can give misleading results and totally wrong conclusions can be made. One example of a secondary effect is if a fibre property leads to a low value on a specific paper property. This will e.g. lead to an increased refining which in turn leads to a higher value on the specific paper property. Then the MVDA may say that the bad values on the fibre property leads to high values on the paper property because of the secondary effect of the increased refining.
Table 8 shows some of the different mean values of the air resistance intervals (y-variable) and the x-variables from the group-plot. The fibre properties marked with a light blue colour shows a dependency on the air resistance. The red numbers are not included in the analysis in order to exclude incorrect values. Dependencies between air resistance as the y-variable and an x-variable could only be found for one or two products at the time and therefore no correlation is said to be found. This does not mean that no correlations exist, but it is clear that it is a lot of noise.
Table 8. Part of a group-plot where the air resistance is set to be the y-variable. The fibre properties marked with a light blue colour shows a dependency on the air resistance. The red numbers are not included in the analysis in order to avoid including incorrect values.

EA125

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-29.99</td>
<td>3.20</td>
<td>3.80</td>
<td>3.50</td>
</tr>
<tr>
<td>30.00-34.99</td>
<td>3.41</td>
<td>3.54</td>
<td>3.30</td>
</tr>
<tr>
<td>35.00-39.99</td>
<td>3.52</td>
<td>3.57</td>
<td>3.36</td>
</tr>
<tr>
<td>40.00-44.99</td>
<td>3.66</td>
<td>3.69</td>
<td>3.46</td>
</tr>
<tr>
<td>45.00-49.99</td>
<td>3.80</td>
<td>3.73</td>
<td>3.47</td>
</tr>
<tr>
<td>50.00-54.99</td>
<td>3.73</td>
<td>3.70</td>
<td>3.49</td>
</tr>
<tr>
<td>55.00-</td>
<td>3.93</td>
<td>3.89</td>
<td>3.67</td>
</tr>
</tbody>
</table>

EA130

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-29.99</td>
<td>3.56</td>
<td>3.54</td>
<td>3.36</td>
</tr>
<tr>
<td>30.00-34.99</td>
<td>3.62</td>
<td>3.68</td>
<td>3.42</td>
</tr>
<tr>
<td>35.00-39.99</td>
<td>3.68</td>
<td>3.64</td>
<td>3.45</td>
</tr>
<tr>
<td>40.00-44.99</td>
<td>3.69</td>
<td>3.69</td>
<td>3.47</td>
</tr>
<tr>
<td>45.00-49.99</td>
<td>3.70</td>
<td>3.82</td>
<td>3.65</td>
</tr>
<tr>
<td>50.00-54.99</td>
<td>3.84</td>
<td>3.86</td>
<td>3.62</td>
</tr>
<tr>
<td>55.00-</td>
<td>3.95</td>
<td>3.77</td>
<td>3.42</td>
</tr>
</tbody>
</table>

EA135

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-29.99</td>
<td>3.56</td>
<td>3.43</td>
<td>3.27</td>
</tr>
<tr>
<td>30.00-34.99</td>
<td>3.79</td>
<td>3.69</td>
<td>3.47</td>
</tr>
<tr>
<td>35.00-39.99</td>
<td>3.83</td>
<td>3.81</td>
<td>3.61</td>
</tr>
<tr>
<td>40.00-44.99</td>
<td>3.91</td>
<td>3.90</td>
<td>3.67</td>
</tr>
<tr>
<td>45.00-49.99</td>
<td>4.03</td>
<td>3.89</td>
<td>3.71</td>
</tr>
<tr>
<td>50.00-54.99</td>
<td>4.15</td>
<td>3.95</td>
<td>3.66</td>
</tr>
<tr>
<td>55.00-</td>
<td>3.77</td>
<td>3.77</td>
<td>3.58</td>
</tr>
</tbody>
</table>

Figure 5 shows a PLS-model, made on the historical data for the WTL-quality EA125, with the air resistance as the y-variable. PLS-models for the WTL-quality EA130 and EA135 were also made. All the insignificant x-variables were excluded from the models. Parameters that gave positive contribution in all the PLS-models was:

- **MSR** for the unbleached pine. More fine material gives a more compact structure.
• **Length fraction 1** for the unbleached pine.

• **Sum of the shives** for the unbleached pine.

• **SEL** for SK6. This can be because a high intensity at the first refiner may give a lot of fibre length reduction and therefore lead to increased fines creation and thereby also increased air resistance due to a more compact structure.

Parameters that gave negative contribution in all the PLS-models with air resistance as the y variable was:

• **Concentration** of the bleached birch. This probably has to do with how the fibres response to the refining process.

• **Arithmetic fibre length** of unbleached pine fibres. Perhaps this result comes from the fact that less fibre length reduction also gives less fine material. Less fines material will in turn give a more open structure. So perhaps it is not actually the long fibres affecting the air resistance, but the smaller amount of fines.
Figure 5. The PLS-model for EA125 where the fibre properties and the refiner parameters are set to be the x-variables and the air resistance [Gurley seconds] is the y-variable. Only the significant parameters can be seen. $R^2_X=0.232$, $R^2_Y=0.532$, $Q^2=0.433$

No correlation could be found when the burst strength index was set to be the y-variable in a group-plot. Dependencies between burst strength index and a x-variable could only be found for one product at the time.
PLS-models for the EA125, EA130 and EA135 where the y-parameter was the burst strength index was made in the same way as for the air resistance, see figure 5. Parameters that gave a positive contribution in all the PLS-models with burst strength as the y variable was:

- **Arithmetic fibre length** for both the bleached and the unbleached pine and for the bleached birch.

- **Length weighted fibre length** for both the bleached and the unbleached pine and for the bleached birch.

- **Length fraction 4 and 5** for both the bleached and the unbleached pine and for the bleached birch could be found to give positive contributions in all the figures.

- **Segment length** for unbleached pine.

It could also be seen that the lower fibre length fractions (fraction 1, 2 and 3) only gave negative contributions in the PLS-models with burst strength as the y-variable. So the conclusion is that the fibre length seems to affect the burst strength.

When the Scott Bond was set to be the y-variable in the group-plots for EA125, EA130 and EA135 three correlations was found. Correlation to the Scott Bond was seen for the curl fraction 5 for unbleached pine, kinks/fibre and kinks/mm, both for unbleached pine. These dependencies can be seen in the group-plots shown in figure 6, 7 and 8.

![Figure 6](image)

**Figure 6.** The plot for the group-plot where the mean value for curl fraction 5, unbleached pine, shows correlation to the Scott Bond.
Parameters that gave positive contribution in all the PLS-models with Scott Bond as the y-variable was:

- **Concentration** of the bleached birch pulp
- **Kinks/mm**
- **Kinks/fibre**
The group-plot and the MVDA were consistent for the kinks and curl. This can be due to the fact that the long and curly fibres will have an increased ability to get entangled. This may in turn lead to more and stronger bonds.

Parameters that gave a negative contribution in all the PLS-models with Scott Bond as the \( y \)-variable was:

- **MSR** for the unbleached pine.
- **Refining energy** for the unbleached pine.
- **Flow through the refiners**, both for the bleached and the unbleached pine.
- **Concentration** of bleached pine pulp.

It could also be seen that fines and short fibres from bleached birch and in most cases also bleached pine, had a positive contribution to the Scott-Bond and that the longer fibre fractions (length fraction 4 and 5) from the bleached pulps (pine and birch) often had negative contribution.

Figure 9 shows the coarseness variations for the different pulps at PM4 after the refining. As can be seen the bleached birch has generally the lowest coarseness values, the unbleached pine in general the highest values and bleached pine is somewhere in between. The figure shows all the correct measured values between the 30th of November and the 16th of December, for all the qualities produced at PM 4.
Figure 9. The coarseness variations between the 30th of November and the 16th of December for the PM4 pulps.

Figure 10 shows the variations of coarseness in the different pulps at PM5. As can be seen the bleached birch pulp has generally the lowest coarseness values and the unbleached bottom layer (L1) and unbleached middle layer (both softwood pulps) has generally the highest values. The bleached pine is somewhere in between.
Figure 10. The coarseness variations between the 30th of November and the 16th of December for the PM5 pulps.

Coarseness variation of more than 0.1 unit can be seen and if these are significant variations, this probably have effects on the paper properties. If the unbleached bottom layer of PM4 is compared to the unbleached layers PM5, a difference can be seen. This is somewhat strange due to the fact that these values are based on the same pulp. The explanation is probably that the refining is affecting the fibre wall thickness. Different products are demanding different amount of refining energy and PM4 and PM5 are not producing the same products.

3.4.2 Study 2: Analysis of pulp samples from the production
Figure 11 shows the fines share, MSR and length weighted length for the pulp samples. It can be seen that the fines share and the MSR do not correlate, but that the fines share and the length weighted fibre length are following each other more. The creation of fines will give fibre length reduction. In table 8 other important fibre properties for the pulp samples can be seen.
Figure 11. MSR and fines share on one axis and the length weighted fibre length on the other, for both the beaten (B) and unbeaten (U) pulps.

Table 9. Fibre parameters measured by PulpEye both for the beaten and unbeaten pulps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Note</th>
<th>LWeightWid</th>
<th>LWeightCurl</th>
<th>Shive Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>U</td>
<td>B</td>
<td>U</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>29</td>
<td>29</td>
<td>3,9</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>30</td>
<td>29</td>
<td>4,0</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>30</td>
<td>29</td>
<td>4,2</td>
</tr>
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<td>4</td>
<td></td>
<td>29</td>
<td>29</td>
<td>4,2</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>29</td>
<td>27</td>
<td>4,6</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>30</td>
<td>29</td>
<td>4,0</td>
</tr>
<tr>
<td>7</td>
<td>Hard to dewater.</td>
<td>29</td>
<td>29</td>
<td>4,5</td>
</tr>
<tr>
<td>8</td>
<td>Start up pulp. Long time to PE analysis</td>
<td>29</td>
<td>29</td>
<td>3,8</td>
</tr>
<tr>
<td>9</td>
<td>Start up pulp. Long time to PE analysis</td>
<td>29</td>
<td>29</td>
<td>4,5</td>
</tr>
<tr>
<td>10</td>
<td>Long time to PE analysis</td>
<td>28</td>
<td>28</td>
<td>5,7</td>
</tr>
</tbody>
</table>

Figure 12 shows the Scott Bond, z-strength and the density for the pulps and table 10 shows some other important paper properties for the pulps. The refiner settings for the samples can be seen in table 11.
Figure 12. The Scott Bond, z-strength and density for the samples from trial 2, both the beaten (B) and unbeaten (U) samples.

Table 10. The paper properties for samples from trial 2 (analysis of pulp from the production).

<table>
<thead>
<tr>
<th>Date</th>
<th>Sample</th>
<th>Tensile index [kNm/kg]</th>
<th>Tensile stiff. index [MNm/kg]</th>
<th>Air permeability [m/(Pa x s)]</th>
<th>SCT [kN/m]</th>
<th>Strain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U</td>
<td>B</td>
<td>U</td>
<td>B</td>
<td>U</td>
<td>B</td>
</tr>
<tr>
<td>2010-10-07</td>
<td>1</td>
<td>43</td>
<td>73</td>
<td>5,0</td>
<td>6,5</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-08</td>
<td>2</td>
<td>41</td>
<td>77</td>
<td>4,8</td>
<td>7,2</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-09</td>
<td>3</td>
<td>39</td>
<td>72</td>
<td>4,6</td>
<td>6,5</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-10</td>
<td>4</td>
<td>43</td>
<td>76</td>
<td>4,9</td>
<td>6,7</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-11</td>
<td>5</td>
<td>39</td>
<td>73</td>
<td>5,1</td>
<td>6,9</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-12</td>
<td>6</td>
<td>36</td>
<td>69</td>
<td>4,6</td>
<td>6,7</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-13</td>
<td>7</td>
<td>39</td>
<td>94</td>
<td>4,8</td>
<td>8,2</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-14</td>
<td>8</td>
<td>40</td>
<td>88</td>
<td>4,7</td>
<td>7,4</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-15</td>
<td>9</td>
<td>43</td>
<td>84</td>
<td>4,9</td>
<td>7,6</td>
<td>3577</td>
</tr>
<tr>
<td>2010-10-16</td>
<td>10</td>
<td>48</td>
<td>71</td>
<td>5,4</td>
<td>6,6</td>
<td>3577</td>
</tr>
</tbody>
</table>
Table 11. The refiner settings for the samples from trial 2 (analysis of pulp from the production).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Kappa</th>
<th>SK6 SEL, [Ws/m]</th>
<th>SK7 SEL, [Ws/m]</th>
<th>SK8 SEL, [Ws/m]</th>
<th>SK9 SEL, [Ws/m]</th>
<th>Refining energy [kWh/ton]</th>
<th>Prod, [tonnage/h]</th>
<th>Prod through SK, [tonnage/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51</td>
<td>2,8</td>
<td>2,3</td>
<td>1,4</td>
<td>-</td>
<td>111</td>
<td>13</td>
<td>13</td>
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<tr>
<td>2</td>
<td>53</td>
<td>2,9</td>
<td>2,9</td>
<td>2,0</td>
<td>1,3</td>
<td>128</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>52</td>
<td>2,6</td>
<td>2,5</td>
<td>1,9</td>
<td>1,6</td>
<td>121</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>2,4</td>
<td>2,8</td>
<td>2,2</td>
<td>1,8</td>
<td>134</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>3,0</td>
<td>2,8</td>
<td>2,5</td>
<td>2,1</td>
<td>143</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>3,0</td>
<td>2,8</td>
<td>2,5</td>
<td>1,0</td>
<td>142</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
<td>2,8</td>
<td>2,9</td>
<td>1,8</td>
<td>1,3</td>
<td>265</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>2,2</td>
<td>2,2</td>
<td>1,2</td>
<td>0,7</td>
<td>176</td>
<td>7</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2,2</td>
<td>2,2</td>
<td>2,0</td>
<td>0,7</td>
<td>157</td>
<td>9</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>33</td>
<td>2,5</td>
<td>1,8</td>
<td>1,8</td>
<td>-</td>
<td>117</td>
<td>12</td>
<td>21</td>
</tr>
</tbody>
</table>

Sample 5, pulp from 2010-10-13, had some deviating fibre properties for the beaten pulp (see figure 11 and table 9). Deviation could be seen for:

- MSR
- Fines share
- Fibre length
- Fibre width
- Curl

The reason for the deviations for the beaten pulp from sample 5 may be found in the settings of the refiners. A possible explanation could be higher SEL for SK 9 at the time. As can be seen in table 5, the SK 9 have another type of segments compared to the other refiners used and it is possible that this type refiner segment treats the fibres different compared to the segments in SK6, SK7 and SK8. As can be seen in figure 12 and table 10, the paper properties had no deviations for sample 5.

The beaten pulp at sample 7, pulp from 2010-10-15, was hard to dewater. When the fibre properties (see figure 11 and table 9) were investigated, the deviating fibre parameters were:

- MSR
- Sum of shives

The reason for the very high MSR can be found in table 11. The pulp had low kappa number and the refining energy was very high at the time. The fines share was high for sample 7, but the extremely high MSR can not only be explained by that. The sum of shives for the unbeaten pulp from sample 7 was the lowest of all samples. This can be explained by the low kappa number. The reason for the increased sum of shives during beating is also probably due to the bad combination of the low kappa number and high refiner energy. The shives created during beating are not actual shives, but more...
clusters of fibres. In figure 12 it can be seen that the density, Scott Bond and the z-strength was high for the beaten pulp. In table 10 high values of the tensile strength and tensile stiffness can be seen for the beaten pulp from sample 7.

Sample 8 and 9 were pulp from 2010-10-27, the start up of the paper machine after the autumn stop. When the fibre properties (see figure 11 and table 9) were investigated the deviating fibre parameters were:

- MSR
- Fibre length
- Sum of shives

When looking in figure 12 it can be seen that the MSR was high for both the beaten pulp 8 and 9. Sample 8 had shorter fibres and more fines than most of the other samples. The reason for these deviations can be the higher refining energy at both samples 8 and 9 (table 11). The unbeaten pulps at sample 8 and 9 had high sum of shives as can be seen in table 9. That could have been the reason for the increased refining energy demand. The high sum of shives was probably due to disturbance in the cooking process. In figure 12 it can be seen that the density, Scott Bond and the z-strength was high for both the beaten pulps from sample 8 and 9. The beaten pulps from sample 8 and 9 also had a high tensile strength and tensile stiffness as can be seen in table 10.

The variations in the incoming pulp can be an important factor if the refining process wants to be optimised. This tells us both how the cooking process has been working and how the refiner settings should be set. Especially the impact of shives, both in the board making process and for the final board properties, is interesting and not much investigated. Today the PulpEye measurements have to be done manually on unbeaten pulp, because the PulpEye measurements are only done on-line after the refining process. If information can be available earlier, money can be saved and therefore information about the incoming pulp is very important.

3.4.3 Study 3: Refiner setting trial

The refiner settings, kappa number and production rate during the trial can be seen in table 12 and 13. Samples of unbeaten pulp at the beginning and the end of the trial worked as reference pulps in order to see variations in the incoming pulp. Table 14 shows the data from PulpEye for the different samples. It can be seen that the fibre properties were varying between the two reference pulps.
**Table 12.** The values of SEL for the different refiners during the refiner setting trial.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tid</th>
<th>SK6 SEL [Ws/m]</th>
<th>SK7 SEL [Ws/m]</th>
<th>SK8 SEL [Ws/m]</th>
<th>SK9 SEL [Ws/m]</th>
<th>SK10 SEL [Ws/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2010-11-29 11:07</td>
<td>3,1</td>
<td>2,5</td>
<td>2,5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2010-11-29 11:22</td>
<td>3,1</td>
<td>2,5</td>
<td>2,5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2010-11-29 11:37</td>
<td>3,1</td>
<td>2,5</td>
<td>2,5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2010-11-29 11:51</td>
<td>3,1</td>
<td>2,5</td>
<td>2,5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2010-11-29 12:25</td>
<td>3,1</td>
<td>2,5</td>
<td>2,5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2010-11-29 12:40</td>
<td>3,1</td>
<td>2,5</td>
<td>2,5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2010-11-29 13:25</td>
<td>3,1</td>
<td>2,8</td>
<td>2,1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2010-11-29 13:39</td>
<td>3,1</td>
<td>2,9</td>
<td>2,1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4 (manually sample)</td>
<td>2010-11-29 15:00</td>
<td>3,1</td>
<td>0</td>
<td>0</td>
<td>2,5</td>
<td>2,5</td>
</tr>
<tr>
<td>4</td>
<td>2010-11-29 15:50</td>
<td>3,1</td>
<td>0</td>
<td>0</td>
<td>2,5</td>
<td>2,5</td>
</tr>
</tbody>
</table>

**Table 13.** Important parameters during the refiner setting trial.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tid</th>
<th>Kappa number</th>
<th>Production [tonnage/h]</th>
<th>Total energy [kWh/tonnage]</th>
<th>Total flow through SK [tonnage/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2010-11-29 11:07</td>
<td>50</td>
<td>16</td>
<td>114</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
<td>2010-11-29 11:22</td>
<td>49</td>
<td>16</td>
<td>116</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
<td>2010-11-29 11:37</td>
<td>48</td>
<td>16</td>
<td>113</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
<td>2010-11-29 11:51</td>
<td>48</td>
<td>17</td>
<td>111</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>2010-11-29 12:25</td>
<td>-</td>
<td>16</td>
<td>109</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>2010-11-29 12:40</td>
<td>-</td>
<td>17</td>
<td>109</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>2010-11-29 12:54</td>
<td>-</td>
<td>17</td>
<td>110</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>2010-11-29 13:25</td>
<td>48</td>
<td>17</td>
<td>110</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>2010-11-29 13:39</td>
<td>48</td>
<td>17</td>
<td>111</td>
<td>19</td>
</tr>
<tr>
<td>4 (manually sample)</td>
<td>2010-11-29 15:00</td>
<td>48</td>
<td>18</td>
<td>105</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>2010-11-29 15:50</td>
<td>47</td>
<td>17</td>
<td>116</td>
<td>23</td>
</tr>
</tbody>
</table>
It can be seen in table 14, that the data suggests that the fibres get longer and wider and that the amount of fines is decreased during beating. The coarseness for the pulp at sample 1 increased during beating according to the data. Probably that measurement of the unbeaten sample 1 was made incorrect.

The intensities at SK6, SK9 and SK10, sample 4, were calculated to be the same as the intensities of SK6, SK7 and SK8 at sample 1. This makes it possible to compare the different segments. It seems that the fibres are treated in a harsher way in SK9 and SK10 compared to the other refiners. Sample 4, when the SK9 and SK10 were used, had pulp with:

- Lower fibre length
- Lower fibre width
- Higher fines content
- Higher MSR

In figure 13 it can be seen how much crill that was generated during the refining process. The variation of the KFP*PMD0/PMD (the parameters are explained in the appendix), before and after the refining process, is a measure of how much crill that is generated per surface unit. Both pulp sample 1 and 4 have references of unbeaten pulps. Therefore the generation of crill during the refining process can be seen for pulp sample 1 and 4. For pulp sample 2 and 3 only the levels after the refining can be seen.
Figure 13. How much crill that have been generated during the refining process as KFP*PMD0/PMD (for explanations see appendix).

Figure 13 shows that the amount of crill is increased by the refining process in all four cases. The differences of crill between the beaten samples are small but still statistically significant. It can also be seen that the unbeaten pulps have different starting points of crill. When comparing the change for sample 1 with sample 4, sample 1 generated more crill. The change of volume per specific surface for the suspended material (PMD) was statistically the same for sample 1 and 4, even though the values of the reference pulps differed. As can be seen in table 13, the incoming kappa number is somewhat higher for sample 1 compared to sample 4. This can have had some effects on the generation of crill.

A mean value of the parameter KFP*·PMD0/PMD between reference sample 1 and 4 can be used in order to try to make an indication about the crill development for all the samples. The mean value of the unbeaten pulps, is then subtracted from the values of the parameter KFP*·PMD0/PMD for the beaten pulps. If that is done, it can be seen that sample 1 have the highest crill amount and then comes sample 2, 3 and sample 4 have the lowest amount. If the values are correct that means that high flow through the refiners, together with a slightly decreasing intensity when SK6, SK7 and SK8 are used, will give the highest generation of crill. The refining process should be optimised to give high amount of crill in order to increase the pulp strength. It seems like the segments used in SK9 and SK10 gives a harsher refining and generates less crill compared to SK6, SK7 and SK8. This is the opposite of what one would have guessed due to the fact that SK9 and SK10 are older segments. One guess is that it would generate more crill if, for example, four refiners are used instead of three, with unchanged total SEL. A drawback can possibly be that the energy consumption for the “no-load” may be higher when several refiners are used.

The results from the measurements made on the hand sheets of the pulps, collected at the sample 1 to 4, can be seen in figure 14 to 20. A summary of the results in these figures can be seen table 15. The correlation between the paper properties and the fibre properties found can also be seen in table 15. Neither the fibre properties nor the paper properties do always have much variation between the samples. Therefore it can be hard to draw any conclusions when looking at these results.
Figure 14. The density for the laboratory sheets made from the pulps at the different samples.

Figure 15. The air resistance for the laboratory sheets made from the pulps at the different samples.

Figure 16. The SCT for the laboratory sheets made from the pulps at the different samples.

Figure 17. The tensile index for the laboratory sheets made from the pulps at the different samples.

Figure 18. The Scott Bond for the laboratory sheets made from the pulps at the different samples.

Figure 19. The z-strength for the laboratory sheets made from the pulps at the different samples.
Figure 20. The tensile stiffness index for the laboratory made from the pulps at the different samples.

Table 15. The order of the refiner settings, from best to worst, for the paper properties tested on hand sheets made from pulp from the samples. The best and the worst refiner setting are described.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Best to worst sample</th>
<th>Best refiner settings</th>
<th>“Worst” refiner settings</th>
<th>Fibre property mean values showing correlation (or opposite correlation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCT, Tensile stiffness index</td>
<td>2, 1, 3, 4</td>
<td>2: Minimum flow, SK6, SK7 and SK8, Slightly decreasing SEL</td>
<td>4: Minimum flow, SK6, SK9 and SK10, Same SEL slope as sample 1</td>
<td>Length weighted shive length, Length fraction 2 and 3</td>
</tr>
<tr>
<td>Air resistance (Gurley), Scott Bond</td>
<td>3, 2, 4, 1</td>
<td>3: Minimum flow, SK6, SK7 and SK8, Steeply decreasing SEL</td>
<td>1: Maximum flow, SK6, SK7 and SK8, Slightly decreasing SEL</td>
<td>None</td>
</tr>
<tr>
<td>Density, TEA index, Tensile index</td>
<td>1, 3, 2, 4</td>
<td>1: Maximum flow, SK6, SK7 and SK8, Slightly decreasing SEL</td>
<td>4: Minimum flow, SK6, SK9 and SK10, Same SEL slope as sample 1</td>
<td>MSR, Arithmetic fibre width</td>
</tr>
<tr>
<td>Strain</td>
<td>1, 3, 4, 2</td>
<td>1: Maximum flow, SK6, SK7 and SK8, Slightly decreasing SEL</td>
<td>2: Minimum flow, SK6, SK7 and SK8, Slightly decreasing SEL</td>
<td>None</td>
</tr>
<tr>
<td>z-strength</td>
<td>3, 4, 2, 1</td>
<td>3: Minimum flow, SK6, SK7 and SK8, Steeply decreasing SEL</td>
<td>1: Maximum flow, SK6, SK7 and SK8, Slightly decreasing SEL</td>
<td>None</td>
</tr>
</tbody>
</table>

It seems that the SCT and the tensile stiffness are decreased by shorter fibres and that longer fibres may increase these paper properties. The fibre parameter that showed correlation to the SCT and the tensile stiffness were the length weighted shive length. An opposite correlation to the SCT and the tensile stiffness could be seen for the length fraction 2 and 3. Other fibre length parameters did not show the exact correlation/opposite correlation, but showed the same indication. Both the results from the historical process data and data from the test run indicate that SCT is increased with a decreased flow.

The Scott Bond is said to be a measure of the strength of the fibre joints. This means that it should be increased with an increased fines fraction and flexibility. Sample 3 had the highest value of the Scott Bond as can be seen in figure 18. According to the measurements, sample 3 did neither have the highest amount of fines, crill or low coarseness value. It is possible that neither of the parameters did
have enough variations, so the margin of error exceeded the variations. Another important thing is that the coarseness does not totally correlate with the fibre flexibility, because it does not take the diameter of the fibre or the fibre wall density into account. The same settings that gave the highest and the lowest Scott Bond values, also gave the highest and lowest z-strength. This means that the settings at sample 3 probably are the most profitable ones if the out-of-plane strength wants to be increased. The air permeability showed the same pattern as Scott Bond did. It would have been more reasonable if the Scott Bond showed the opposite correlation to the air resistance. It can be seen in figure 15, that sample 3 had higher air resistance compared to the other samples. This could not be explained by deviating fibre parameters. Perhaps this was due to some changed machine parameter. The air permeability for the unbeaten pulps could not be measured due to too high porosity.

The tensile index should depend on the crill. No such correlation could be found, but the highest crill also gave the highest tensile index. A correlation found was between the tensile index and the MSR. This is interesting due to the fact that the MSR in turn depends on the crill.

When looking in table 15 it can be seen that the sample 1 and 3 gave high values for many of the paper properties. This is probably due to a favourable combination of several fibre properties, obtained by the refiner settings at sample 1 and 3. It could for example be seen that sample 3 had generally less shives compared to the other samples.

3.5 Conclusion
Both the group-plots and MVDA’s based on the historical process data, showed that the Scott Bond was increased with increased amount of kinks and curl for the unbleached pine pulp (softwood pulp). The MVDA’s also showed that the fibre length may affect the burst strength, which also could be seen in the study of the pulp samples from the production. The coarseness values within the same type of pulp had variations of more than 0.1 unit. These variations will most likely have effects on the paper properties. It was indicated in the analysis of the pulp from the production, that the sum of shives may have impact on paper properties. Crill is a property that may be of great importance. In the refiner setting trial the differences in crill for the samples were small but statistically significant. It was hard to see correlations between fibre properties and paper properties in the refiner setting trial. This could have been due to small variations of the different parameters, but also the human factor at the laboratory. It seemed like the older segments in SK9 and SK10 treated the pulp harsher compared to the newer segments in SK6, SK7 and SK8, the opposite to what one would have guessed. This work shows that the normal production conditions are handled very well and normally the variations are not that big. It can be seen though, that problems do appear when parameters are deviating from the normal case. These situations are not always handled optimally. One example can be seen for sample 7 in study 2, where the kappa number is very low and at the same time the refiner energy is very high.

3.6 Recommendations
Crill is a parameter that should be further investigated. The generation of crill in the refiners can be of great help to predict the pulp strength. It would be interesting to do an investigation about the crill generation when different segments and refiner strategies are tried. It would also be interesting
to measure crill at different kappa number, to see how the different pulps response to the refining. The shive parameters and its impact on both the refining process and the paper properties should be more investigated, due to the fact that variations can be seen for the incoming pulp. Today these variations are not analysed or measured. In order to optimise, for example the refining process, measurements on the incoming pulp should be done. In that way it would be possible to develop more optimised refining strategies. An efficient way to work is to do measurements when the incoming pulp parameters are deviating. It should also be more investigated how the most common deviating pulp parameters should be handled in the refining process and at the board machine. PulpEye measurements and laboratory sheets, for strength testing, should be done in order to investigate the effects of different pulp deviations. This work is easier to do if on-line PulpEye measurements are done, not only after the refining process, but also before. Laboratory sheets from pulps with different coarseness should also be made and tested in order to investigate the effects of the varying coarseness further. The communication between the pulp production and the board machines is recommended to be further developed. This is especially important when pulp parameters are deviating from the normal case due to disturbances, for example in the cooking process. This should increase the chances to handle the more difficult situations more optimal.

For one manually made measurement, the unrefined sample had more fines compared to the sample after the refining process. It should therefore be further investigated whether the measurement of fines are affected by some unknown parameters. Measurements on water can be done in order to see if the problem is fibres or fines in the water or maybe if the washing between measurements is insufficient. Another possible reason can be quick and large pulp variations.

4 Sources of error
There is always a time difference between the pulp data and the product property data used at a certain time.
5 References

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Appendix

PulpEye parameters

Fibre dimensions

**Length** (mm) – Length weighted fibre length (mean value).

Length = \( \frac{\sum (l^2)}{\sum l} \) – The summations is for every fibre longer then defined fines/fibre limit (0.2 mm).

\((l – fibre length for every individual fibre)\)

**Width** (my) – Length weighted fibre width (mean value).

Width = \( \frac{\sum (b \times l)}{\sum l} \) – The summations is for every fibre longer then defined width limit (0.5 mm).

\((l – fiberlängd för enskild fiber)\)

\((b – fiberbredd för enskild fiber)\)

**Curl** (%) – Length weighted fibre curl (mean value).

Curl = \( \frac{\sum (f \times l)}{\sum l} \) – The summations is for every fibre longer then defined curl limit (0.5 mm).

\((l – fiberlängd för enskild fiber)\)

\((f – fiberform för enskild fiber)\)

**Share** (%) – The length weighted length fractions has the following classification:

Class 1: 0.2 – 0.5 mm
Class 2: 0.5 – 1.0 mm
Class 3: 1.0 – 1.5 mm
Class 4: 1.5 – 2.5 mm
Class 5: 2.5 – 5.0 mm

**Width** (my) – Width fraction. Mean width (length weighted) for the different classes according to the length fractions. It is based on all fibres longer than a set length (normally 0.5 mm)

**Curl** (%) – Curl fraction. Mean curl length weighted) for the different classes according to the length fractions. It is based on all fibres longer than a set length (0.5 mm)

**Fines** (%) – Fines share (content of fines)

Fines = \( \frac{\Sigma a}{\Sigma A} * 100 \) (%) – Fines share in the analysed sample.

\((\Sigma a – Total area for fibre objects defines as fines. Normally L < 0.2mm.)\)

\((\Sigma A – Total sum of area for all the analysed objects.)\)

Observe that above fines definition is until an established standard is available.

**Coarseness** (mg/m) – Coarseness level

Coarseness is calculated by a known pulp weight and thereafter the total length of the fibres in the samples can be calculated.
Kinks
A "Kink" (or knee) is an unnatural spraining along the fibre. It can also be explained as a sharp change of the direction of the fibres that do not naturally exist when the fibre is untreated. A number of parameters controls the calculations and decides what is going to be treated as a kink and what is going to be treated as a natural bend. The result is summarised in a couple of different parameters, which all is calculated at fibres longer then a given length (normally 1.5 mm)

Kinks/fiber – Number of kinks per fibre (mean value).
Kinks/mm – Number of kinks per mm.
Segment length – Average length between knees or fibre ends. Segment length approach full fibre length when the number of kinks is low
Kinks angel – Average angle of the found kinks.

Shive content
Mean width of the shive is area / length
För beräkningen av spetvikt approximeras spetans volym med en cylinder med längden L och en omkrets som motsvaras av spetans medelbredd. Volymen ges då av $V = L \cdot b^2 \cdot \frac{\pi}{4}$.

Sum (#/g) – Number of shives (per 1 gram pulp) with B>75 my and L>0.3mm.
Broad (#/g) – Number of shives broader than 150 my.
Long (#/g) – Number of shives longer than 1.5 mm.
Weight (%) – Total weight of shives for all shives broader than 150 my. The shive weight is given by the following equation:

Shive weight = $\rho \cdot \Sigma V$ where the volume is summed up for the in questioned shives and multiplied with a density factor.

Number (#/g) – Number of shives in different width fractions. The classes are:
- Class 1: 75 – 150 my
- Class 2: 150 – 300 my
- Class 3: 300 – 500 my
- Class 4: 500 -

Crill (not measured by PulpEye):
- PMD which is a measure of volume per specific surface for the suspended material (size from 1 micrometer which includes fines, fibre fragments and fibres). A process that breaks up suspended objects increases the surface at a constant volume and PMD will decrease.
- **KFP** which is the ratio between measured surface for the crill + suspended material and the measured surface only for the suspended material.

- **KFP*** which is standardised KFP against the reference value for the unbeaten pulp where all the crill is washed away. The KFP* is thereby a measure of how much crill that is generated per fibre surface (KFP*=Surfaces inclusive the crill/surfaces exclusive the crill).

- **PMD0** which is a mean value of the PMD for the unbeaten pulp.

- **KFP*PMD0/PMD** is used to standardise the generation of crill against how much extra fibre surface that also is created during the refiner process.

The KFP* is affected if the surface for the crill is changed but also if the surface for the suspended material is changed. To eliminate the dependency on the changed surface of the suspended material, the KFP* is normalised by how much the surface for the suspended material is changed during the process. The change of surface is characterised by the parameter PMD0/PMD. The variation of the KFP*PMD0/PMD, before and after the refining process, is therefore a measure of how much crill that is generated per surface unit.