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D2.5 POTENTIAL OF LAYERED PAPER DESIGN FOR PAPER PROPERTIES

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Contents

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SUMMARY

There are two different technologies for producing multi-layer sheets – multi-ply sheet forming and stratified sheet forming. Whereas the first technology is state of the art for producing carton board, the second one is relatively new and allows the layering of lower-grammage papers like graphic papers.

By designing the sequence of the layers and selecting suitable materials per layer it is possible to achieve higher bending stiffness or brightness levels even if the sum of the materials is the same as in a single-layer sheet. Therefore layered paper design (or stratification) is a promising measure to improve resource efficiency.

In Work Package 3 of the REFFIBRE project the potential of fractionation for providing side streams for non-paper applications was discussed. Another way of using fractionation for improving resource efficiency is splitting the pulp into individual fractions for use in different layers of a multi-layer paper. This application of fractionation is not new and was previously discussed by Huber et al. (2013). They showed that it is capable of improving the paper properties or reducing the material use.

The available numerical models for bending stiffness and brightness combined with mixing rules can be used to find the best manufacturing conditions depending on the quality of the paper for recycling serving as raw material and on the requirements made on the final paper product.

NOMENCLATURE

ASH	Inorganics and passive organic fines fraction
BS	Bending stiffness
E	Elastic modulus of a sheet or an individual layer
FI	(Active) Fines fraction
K	Specific light absorption coefficient of a sheet or an individual layer
LF	Long fibre fraction
P	(Arbitrary) Paper property
R	Reflectance of a sheet or an individual layer
S	Specific light scattering coefficient of a sheet or an individual layer
SF	Short fibre fraction
t	Mean thickness of a sheet (calliper) of a sheet or an individual layer
T	Transmittance of a sheet or an individual layer
w	Sheet grammage (basis weight) of a sheet or an individual layer
$\underline{v}$	Pulp vector
z_i	Coordinates perpendicular to the paper sheet
ρ	Apparent density of a sheet or an individual layer

1. Introduction

The models to be developed for paper products are intended to help to correlate pulp characteristics, which are changed by various (dry and wet) stock preparation processes, with the quality parameters of the papers produced. The papermaking product and process models describe basic manufacturing processes in a paper mill. Together with resource efficiency indicators to be developed in value chain models, they will contribute to measures designed to increase the resource efficiency of the paper value chain while guaranteeing a stipulated product quality (Figure 1).

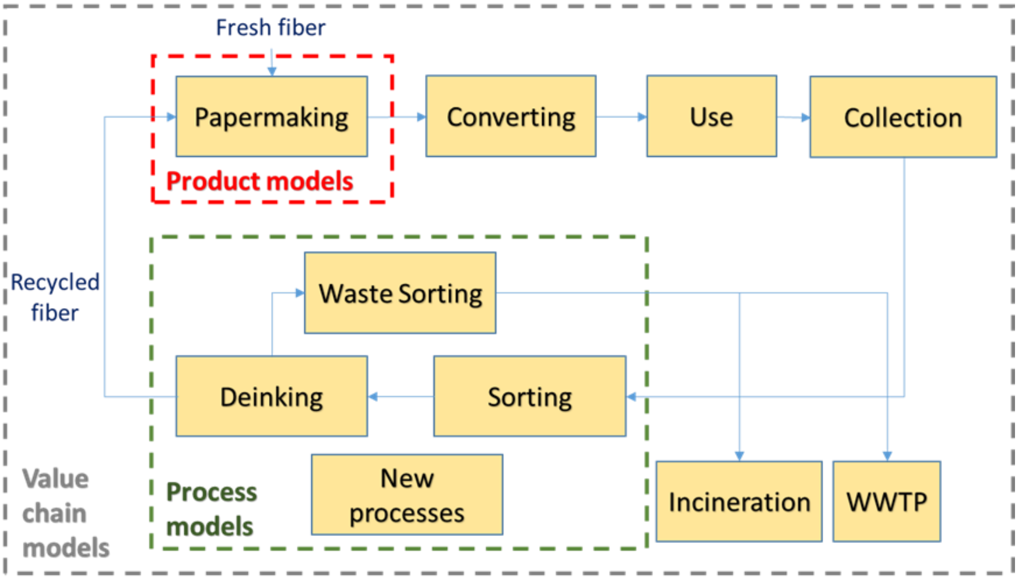

Figure 1: Scope of the different models in the paper value chain

The properties of a single-layer paper sheet are determined by the pulp characteristics and the performance of the paper machine, whereas a multi-layer paper offers some more variables in order to improve the paper properties. By designing the sequence of the layers and selecting suitable materials per layer it is possible to achieve higher bending stiffness or brightness levels even if the sum of the materials is the same as in a single-layer sheet. Therefore, layered paper design (or stratification) is a promising measure to improve resource efficiency.

There are two different technologies for producing multi-layer sheets – multi-ply sheet forming and stratified sheet forming. Whereas the first technology is state of the art for producing carton board, the second one is relatively new and allows the layering of lower-grammage papers like graphic papers. In multi-ply sheet forming the individual layers are formed separately in separate forming sections using several headboxes, and couched together after the forming process. During stratified sheet forming several stock layers are brought together in one headbox. Only one forming unit is used for dewatering (Lucisano et al. 2015). Because of the technology used, it is not possible to clearly distinguish between the individual layers of a stratified sheet. There are transition areas between the layers. Due to retention effects during stratified sheet forming fines and fillers cannot be introduced exclusively in a certain layer. This should be kept in mind when using the results of the next sections. They show the potential of layered sheet forming but depending on the technology to be used, one might have to lower one's sights.

2. Basic theory and formulas

2.1 Bending stiffness

Combining multiple plies to a layered paper design is state of the art for the production of carton board. High bending stiffness is the primary quality characteristic for these paper grades. The theory used for calculating bending stiffness is the so called Classical Laminate Theory (CLT). For a layered paper with in-plane isotropic layers only the knowledge of thickness t_i and elastic modulus E_i of each individual layer is necessary to calculate the resulting bending stiffness (Fellers et al., 1983)

In a first step coordinates in z-direction (perpendicular to the paper sheet) are introduced. For the *i*-th layer the corresponding coordinate of the upper side resp. the lower side is z_{i-1} resp. z_i (Figure 2).

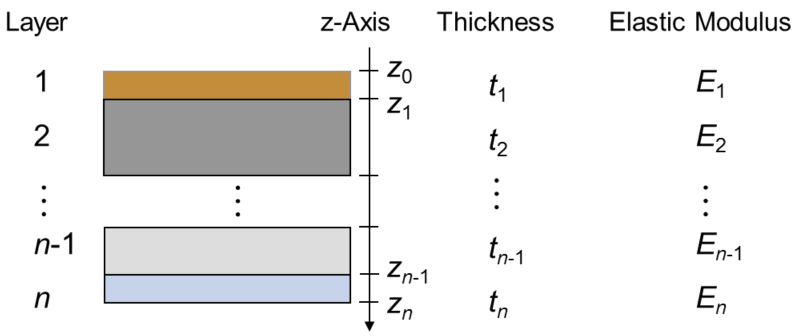

Figure 2: Material model of a stratified paper with n layers (in terms of thickness and elastic modulus)

The new coordinates can be calculated according to

$$z_0 = -\frac{\sum t_i}{2}$$
$$z_i = z_{i-1} + t_i \qquad \text{Equation 1}$$

Next the values A_{BS}, B_{BS} and D_{BS} have to be calculated according to the following formulas:

$$A_{BS} := \sum_{i=1}^{n} E_i \cdot (z_i - z_{i-1})$$
$$B_{BS} := \frac{1}{2}\sum_{i=1}^{n} E_i \cdot \left(z_i^2 - z_{i-1}^2\right) \qquad \text{Equation 2}$$
$$D_{BS} := \frac{1}{3}\sum_{i=1}^{n} E_i \cdot \left(z_i^3 - z_{i-1}^3\right)$$

Finally the bending stiffness of the layered paper follows from

$$BS = D_{BS} - B_{BS}^{\;2} / A_{BS} \qquad \text{Equation 3}$$

If n=1, i.e. in the case of a non-layered sheet, the equations above lead to the already known result $BS=E\cdot t^3/12$.

Instead of the layer thickness t_i the apparent density ρ_i can be used which is directly connected with the grammage w_i of the layer by

$$t_i = \frac{w_i}{\rho_i} \qquad \text{Equation 4}$$

2.2 Reflectance and Transmittance

Multi layering of graphic papers is still in a development phase (Söderberg 2008). Designing the headbox for stratified sheet forming is the major challenge. Nevertheless as shown in the European 7th Framework Programme BOOSTEFF project (Huber 2013) remarkable material savings can be achieved for graphic papers.

It is well known that the optical properties of a layered paper can be very different from those of a non-layered paper even if the sum of materials used is the same. The most frequently applied method for predicting optical paper properties is the Kubelka-Munk theory. The theory tries to describe the behaviour of an illuminated paper by two material characteristics, the specific light scattering coefficient *S* and the specific light absorption coefficient *K* together with the grammage *w* of the paper sheet (Niskanen 1998). It is important to notice that *S* and *K* can vary according to the wave length of the incoming light. Niskanen (1998) also demonstrated how to use the same approach for predicting the optical behaviour of a multi layered sheet as given in Figure 3.

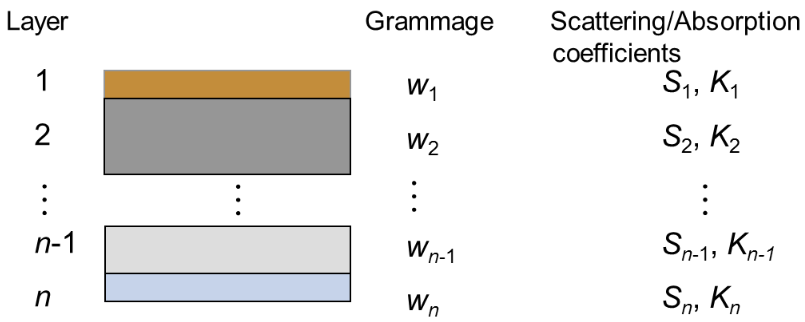

Figure 3: Material model of a stratified paper with n layers (in terms of grammage and Kubelka-Munk coefficients)

In the first step the reflectance *R* and transmittance *T* of each single layer has to be calculated. The reflectance $R_{\infty,j}$ of a sheet with infinite thickness but the same material as in layer j is needed as an interim value.

$$R_{\infty,i} = 1 + \frac{K_i}{S_i} - \sqrt{\frac{K_i^2}{S_i^2} + 2\frac{K_i}{S_i}} \qquad \text{Equation 5}$$

The reflectance R_j and transmittance T_j of a single layer with finite grammage w_j are calculated according to

$$R_i = \frac{\exp\left(S_i w_i\left(\frac{1}{R_{\infty,i}} - R_{\infty,i}\right)\right) - 1}{\frac{1}{R_{\infty,i}}\exp\left(S_i w_i\left(\frac{1}{R_{\infty,i}} - R_{\infty,i}\right)\right) - R_{\infty,i}}$$

$$T_i = \frac{(1-R_{\infty,i})^2 \exp\left(-\frac{1}{2}S_i w_i\left(\frac{1}{R_{\infty,i}} - R_{\infty,i}\right)\right)}{1-R_{\infty,i}{}^2 \exp\left(S_i w_i\left(\frac{1}{R_{\infty,i}} - R_{\infty,i}\right)\right) - R_{\infty,i}}$$

Equation 6

According to the approach introduced by Stokes (1880), combining the first layer and second layer yields one transmittance value $T_{1,2}$ and two different reflectance values $R_{1,2+}$ and $R_{1,2-}$. Reflectance $R_{1,2+}$ is the reflectance when the illuminating light comes from above, i.e. impinges first on layer 1. The reflectance $R_{1,2-}$ refers to the case when the illuminating light comes from below, i.e. first impinges on layer 2.

$$T_{1,2} = \frac{T_1 T_2}{1 - R_{1-} R_{2+}} = T_{2,1}$$

$$R_{1,2+} = R_{1+} + \frac{T_1^2 R_{2+}}{1 - R_{1-} R_{2+}} = R_{2,1-}$$

$$R_{2,1+} = R_{2-} + \frac{T_2^2 R_{1-}}{1 - R_{1-} R_{2+}} = R_{1,2-}$$

Equation 7

Equation 6 yields the transmittance and reflectance of a 2-layer sheet. Regarding this 2-layer sheet as one “layer” and adding a further layer according to Equation 6 yields the transmittance and reflectance of a 3-layer paper. Continuing this process yields the transmittance and reflectance for an arbitrary layered sheet.

Reflectance and transmittance are defined according to the spectrum of the light used. All variables in Equation 5 to Equation 7 are defined for the same wavelength or spectrum of light. When using a light with a centre wavelength of 457 nm the resulting reflectance is called brightness R_{457}.

2.3 Mixing rules

An easy method to calculate paper properties when different pulps are used is the mass weighted mixing rule

$$P = \frac{1}{\sum_{i=1}^{N} w_i}\left(\sum_{i=1}^{N} w_i P_i\right)$$

Equation 8

where $P_1, \ldots, P_N$ are paper properties of N different pulp grades and $w_1, \ldots, w_N$ their weights. Paper properties like elastic modulus, apparent density, specific light scattering coefficient or specific light absorption coefficient should be independent of the paper grammage.

Beginning with Brecht (1963) many authors have investigated the relationships between the mass shares of individual components and the paper properties of mixing results in order to prove Equation 8. Lindholm (1983) and Garceau et al. (1993) used different pulp fractions in their experiments and recombined them afterwards. For light scattering and light absorption they confirmed that the mixing rule according to Equation 8 is valid (in accordance with the theory presented by Kubelka and Munk). For the apparent density and elastic modulus they found more or less significant deviations from the linear behaviour. This is the result of antagonistic or synergistic effects occurring when different pulp fractions are mixed. Garceau et al. (1993) tested some alternative rules. But other rules proved to be only slightly better than Equation 8. Therefore this type of mixing rule will be used for demonstration purposes in chapter 4.

It should be noted that Equation 8 can be improved when a prediction formula *f* is available based on a "pulp vector" $\underline{v_i}$ for the paper property P_i (see Appendix 1)

$$P_i = f(\underline{v}_i) \qquad \text{Equation 9}$$

With Equation 9 the Equation 8 can be substituted by

$$P = f\left(\frac{1}{\sum_{i=1}^{N} w_i} \sum_{i=1}^{N} w_i \underline{v}_i \right) \qquad \text{Equation 10}$$

3. Materials

The material to be used for demonstrating the potential of layered paper design is fractionated paper for recycling pulp. In Work Package 3 of the REFFIBRE project the potential of fractionation for providing side streams for non-paper applications was discussed. Another way of using fractionation for improving resource efficiency is splitting the pulp into individual fractions for use in different layers of a multi-layer paper. This application of fractionation is not new and was previously discussed by Huber et al. (2013). They showed that it is capable of improving the paper properties or reducing the material use.

There are lots of technical solutions to fractionate pulp which yield very different fractions in terms of pulp characteristics. In this report no real fractionated pulps are used. Moreover four basic fractions of a paper for recycling pulp are introduced:

- Long Fibre fraction (***LF***)
- Short Fibre fraction (***SF***)
- (Active) Fibre Fines fraction (***FI***)
- Inorganic Fines and (Passive) Fibre Fines fraction (***ASH***)

There are no standard definitions for these 4 fractions. But typically a McNett-Fractionation can be used to quantitatively determine the mass fractions. Taking a series of McNett fractionation sieves, the long fraction can be defined as the reject on sieve R30, the short fraction as the reject on sieve R200 and both fines fractions as the remaining fraction which passes sieve R200. For discriminating between active fines (i.e. primary fines or flour) and passive fines (i.e. secondary fines or rejects) one can use the bonding ability of the first type of fines, whereas the second type of fines has no bonding ability. A rough estimation is that in pulp based on paper for recycling about half of the fibre fines is active and the other half is passive. These fractions can more or less be generated by existing fractionation technologies.

The pulp used for demonstrating the potential of layered paper design further on in this report is a typical paper for recycling pulp used by a publication paper mill. The pulp characteristics of the original pulp (Feed) and the four fractions are shown in Annex 1. Their mass fractions are summarised in Table 1.

Table 1: Mass shares of individual fractions of the paper for recycling pulp

Pulp fraction	*LF*	*SF*	*FI*	*ASH*
Mass share	30,2%	42,9%	1,1%	25,8%

In the next chapter the question will be answered how to recombine and use these four fractions in a layered paper. A 3-layer paper with 100m^2/g grammage will be used for demonstration. In order to reduce the degrees of freedom the following assumptions are made (see Figure 4):

- The paper is layered symmetrically i.e. top and bottom layer have the same basis weight and use the same mixture of the fractions.
- All fractions are fully used, i.e. the combined mass of the fractions equals the mass of the 3-layer paper.

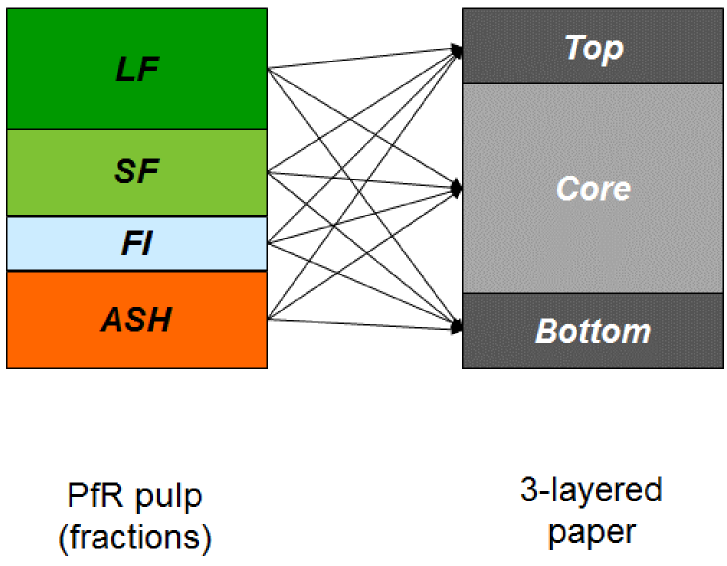

Figure 4: Design of a 3-layer paper and use of the fractions in the layers

4. Optimisation of a 3-layer paper

From a mathematical point of view the optimisation problem to be solved has 4 degrees of freedom. Each of the 4 fractions is to be divided into two portions, one portion will be used in equal shares in the top layer and bottom layer and the other portion will be used in the core layer. As reference for optimisation we use a single-layer 100m^2/g sheet made with the original pulp (Feed). The paper properties are summarised in Appendix 2. Objects of improvement are the bending stiffness (Reference BS_0=0.80Nmm) and brightness (Reference $R_{457,0}$=52.10%).

4.1 Maximising bending stiffness

In a first trial the bending stiffness of the three-layer paper was to be maximised. Using a common optimisation tool (e.g. the EXCEL solver) yields the following composition of the layers:

Table 2: Composition of the layers for maximising bending stiffness

	LF	SF	FI	ASH
	g/m2	g/m2	g/m2	g/m2
Input Top/ Bottom	15,11	0,00	0,00	0,00
Input Core	0,00	42,91	1,08	25,79

The corresponding paper properties of the individual layers and 3-layer sheet are shown in Table 3.

Table 3: Paper properties of the individual layers and overall sheet for maximal bending stiffness

	Grammage (otro)	spec. Energy Press Section	spec. Energy Drying Section	Apparent Density	Roughness (PPS)	Porosity (Gurley)	Tensile	Elastic Modulus	Bending Stiffness (2 Point)	Burst (Mullen)	SCT	Brightness	Opacity
	w	Wpress	Wdry	AD	RPPS	PG	T	E	BS	BU	SCT	R457	O
	g/m2	kWh/t	kWh/t	g/cm3	µm	sec/100cm3	Nm/g	Gpa	Nmm	kPam2/g	kNm/g	%	%
Top/ Bottom	15,11			0,30	5	0,01	48,51	2,30	0,02	3,13	0,02	46,13%	82,51%
Core	69,78			0,57	4	3,61	20,90	1,39	0,13	0,01	0,01	54,67%	99,76%
Total	100,00								1,24			47,52%	99,99%

It seems that separating the pulp into a long fibre fraction and a remaining fraction is an optimal strategy. However a strict separation into a long fibre fraction and a remaining fraction as indicated in Table 2 cannot be achieved by common separation technologies. In order to get a more realistic view various separation efficiencies of the long fibre fraction were simulated (Figure 5, for numerical data see Appendix 3).

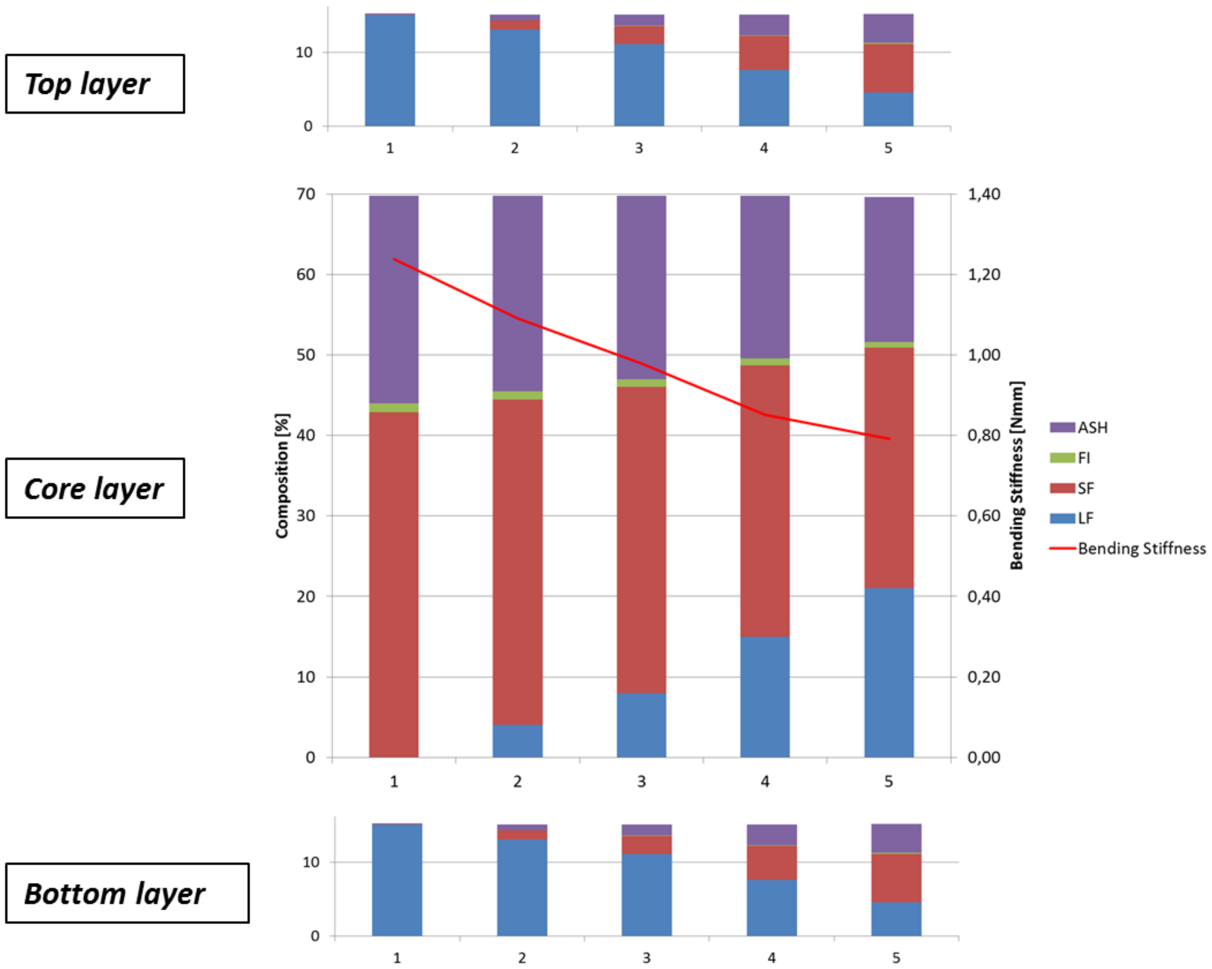

Figure 5: Composition of the layers and corresponding bending stiffness of the 3-layer sheet. Case 1 (the best case) corresponds to Table 2 and case 5 corresponds to the reference case. The cases 2 to 4 are somewhere in between.

4.2 Maximising brightness

The second trial deals with maximising the brightness of the overall 3-layer sheet. Using the Solver optimisation tool of MS EXCEL again yields the best case shown in Table 4

Table 4: Composition of the layers for maximising brightness

	LF	SF	FI	ASH
	g/m2	g/m2	g/m2	g/m2
Input Top/ Bottom	0,00	0,00	0,00	12,89
Input Core	30,22	42,91	1,08	0,00

Obviously Table 4 represents a coated paper where the total ash of the original paper for recycling pulp is used as coating material. The paper properties are summarized in Table 5.

Table 5: Paper properties of the individual layers and overall sheet for maximal brightness

	Grammage (otro)	spec. Energy Press Section	spec. Energy Drying Section	Apparent Density	Roughness (PPS)	Porosity (Gurley)	Tensile	Elastic Modulus	Bending Stiffness (2 Point)	Burst (Mullen)	SCT	Brightness	Opacity
	w	Wpress	Wdry	AD	RPPS	PG	T	E	BS	BU	SCT	R457	O
	g/m2	kWh/t	kWh/t	g/cm3	µm	sec/100cm3	Nm/g	Gpa	Nmm	kPam2/g	kNm/g	%	%
Top/ Bottom	12,89			8,14	4	0,02	-6,12	0,12	0,00	#ZAHL!	#ZAHL!	70,49%	65,34%
Core	74,21			0,33	5	1,64	35,04	1,83	1,09	0,01	0,02	46,16%	99,95%
Total	100,00								1,09			60,61%	99,99%

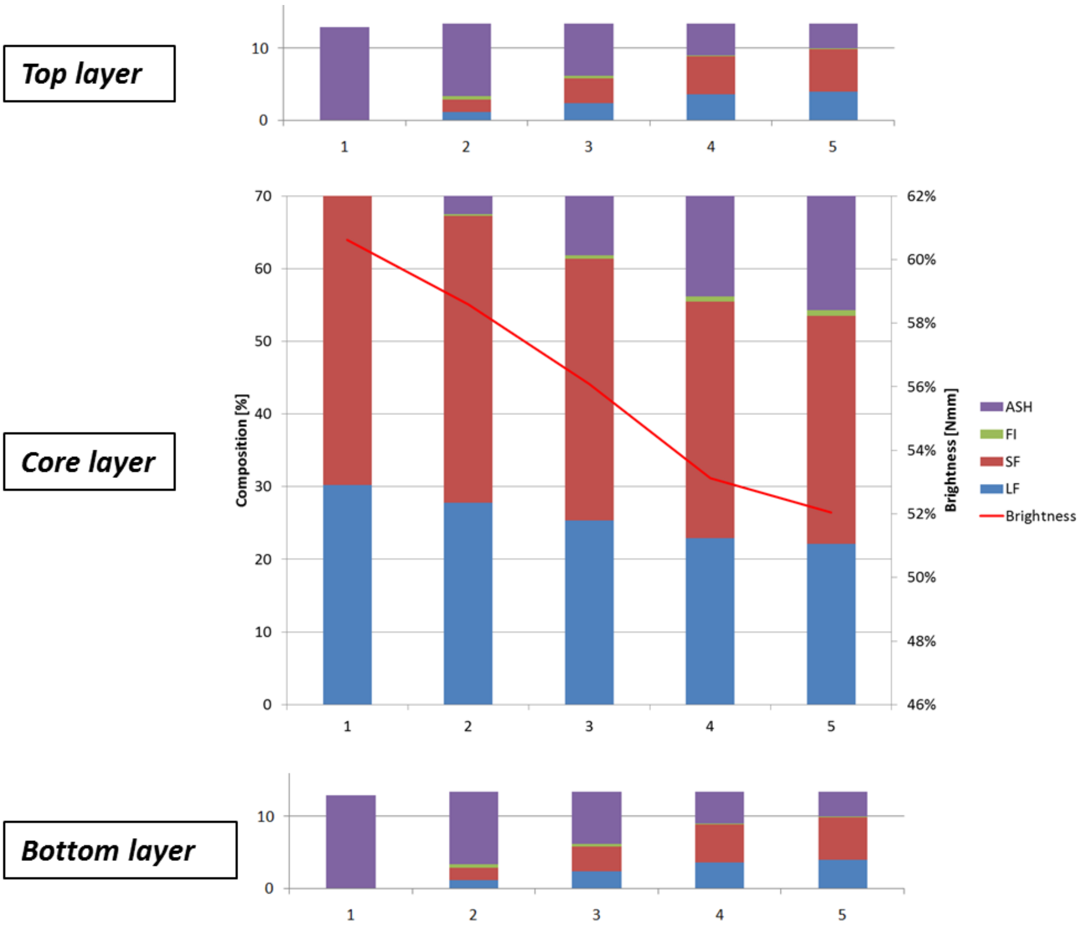

Figure 6: Composition of the layers and corresponding brightness of the 3-layer sheet. Case 1 (the best case) corresponds to Table 4 and case 5 corresponds to the reference case. The cases 2 to 4 are somewhere in between.

Separating inorganic fines and passive fibre fines (ash) from the total pulp can be done by flotation type devices but again (as already discussed in section 4.1) the separation efficiency of common flotation stages is lower than 100%. Figure 6 (for numerical data see Appendix 4) shows the results of simulations where the separation efficiency was stepwise reduced from 100% (case 1) to the reference case (case 5).

4.3 Optimising bending stiffness and brightness simultaneously

The third trial deals with the simultaneous optimisation of bending stiffness and brightness. From Table 3 and Table 5 we learn that the paper properties for maximal bending stiffness do not yield a maximal brightness and vice versa. But when maximising brightness by redistributing ash into the outer layers the data for bending stiffness (see Appendix 4) indicate an improvement of this property. Figure 7 (for numerical data see Appendix 5) shows some alternative strategies for improving both paper properties.

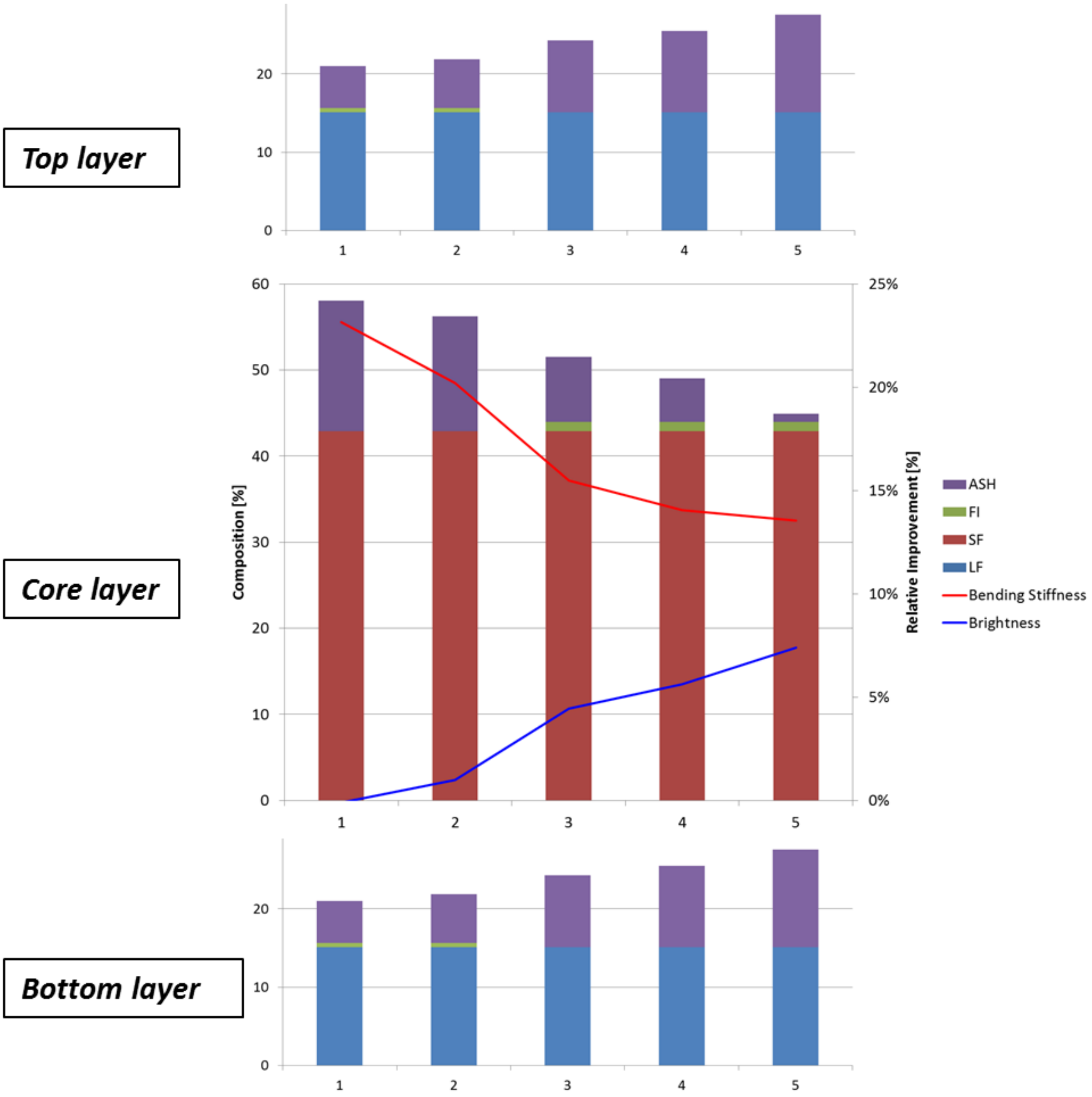

Figure 7: Composition of the layers of a 3-layer sheet and corresponding relative improvement of bending stiffness and brightness

5. Discussion

Figure 5 indicates that a redistribution of the long fibre fraction from the core layer to the outer layer is a promising measure to improve the bending stiffness of a 3-layer sheet. Its level can be increased by up to 50%. This measure can also be used to reduce the thickness by 4% and save materials.

Figure 6 indicates that using the inorganic fines and passive fibre fines fraction(ash) in the outer layer could be the best strategy to improve brightness. Of course the benefit of this strategy depends strongly on the filler quality, i.e. the share of old coating and printing pigments.

The strategy for changing the compositions of the layers shown in Figure 7 is derived from the results shown in Figure 5 and Figure 6. The complete long fibre fraction and varying amounts of filler are redistributed from the core layer into the outer layers.

All results are based solely on numerical modelling calculations which have been introduced in chapter 2. They show that a fractionation of the pulp and subsequent redistribution of the fractions to the individual layers could improve the paper properties remarkably. Of course the results and trends presented in chapter 4 depend on the quality of the paper for recycling used. But the great benefit of the numerical models introduced is that everybody can repeat the calculations with adapted qualities and grades of paper for recycling.

For the calculations of chapter 4, we had assumed that the total pulp is fractionated and all fractions are used in the layered paper sheet. Alternatively only a part of the total pulp could be fractionated. Some fractions could be valorised in side streams (some opportunities have been demonstrated within the REFFIBRE project) whereas the remaining fractions and remaining original pulp are used in a layered sheet.

The numerical model introduced in chapter 2 is very nonlinear. Solving an optimisation problem for this type of models is non-trivial because there can be various local maxima or minima. The optimisation problem is solved stepwise by an iterative procedure. Depending on the type of solver and on the starting values, the optimisation results can differ.

6. Conclusion

Fractionating paper for recycling pulp and redistributing the fractions to the layers of a multi-layered sheet could be an effective method to improve resource efficiency. Even with state of the art fractionation technologies paper properties might be improved or raw material can be saved.

The available numerical models can be used to find the best manufacturing conditions depending on the quality of the paper for recycling serving as raw material and on the requirements made on the final paper product.

Due to the increasing number of variables (number of pulp fractions, number of layers in the multi-layered sheet) it is crucial to use a special software (a so called solver) to solve the optimisation problem and find optimal solutions.

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Appendices

Appendix 1.

Pulp vectors of total pulp and fractions of paper for recycling pulp

Group	Subgroup	Fraction	Parameter	Symbol	Unit	LF	SF	FI	ASH	Feed
			Schopper-Riegler Value	SR	°	25	35	50	50	35
			Water Retention Value	WRV	%	109,0%	109,0%	110,0%	103,0%	107,5%
Fibres	Morphological characteristics	Fines	Fines fraction (Mass share)	FS	%	0,0%	0,0%	100,0%	4,5%	2,2%
			Fibre length (Fines Fraction)	FLFS	µm	120,0	120,0	120,0	120,0	120,0
		Short fibres	Short fibre fraction (Mass share)	SF	%	0,0%	100,0%	0,0%	0,0%	42,9%
			Fibre length (Short Fibre Fraction)	FLSF	µm	948,4	948,4	948,4	948,4	948,4
			Fibre width (Short Fibre Fraction)	WISF	µm	21,9	21,9	21,9	21,9	21,9
			Cell wall thickness (Short fibre fractio	CWTSF	µm	4,0	4,0	4,0	4,0	4,0
		Long fibres	Long fibre fraction (Mass share)	LF	%	100,0%	0,0%	0,0%	0,0%	30,2%
			Fibre length (Long Fibre Fraction)	FLLF	µm	3020,0	3020,0	3020,0	3020,0	3020,0
			Fibre width (Long Fibre Fraction)	WILF	µm	34,2	34,2	34,2	34,2	34,2
			Cell wall thickness (Long fibre fraction	CWTLF	µm	5,0	5,0	5,0	5,0	5,0
	Physical characteristics		Porosity	p		0,70	0,74	0,80	0,80	0,74
			Elastic Modulus	Efib	GPa	43,00	32,00	10,00	5,00	28,12
			Shear Modulus	Gfib	Gpa	2,00	2,00	2,00	2,00	2,00
			Tensile Strength	FZ	MPa	600,00	600,00	600,00	600,00	600,00
			Bonding Strength	b	MPa	11,00	11,00	15,00	5,00	9,50
			Spec. Light Scattering Coeff.	SFib	m2/kg	72,00	72,00	80,00	83,00	74,92
			Spec. Light Absorption Coeff.	KFib	m2/kg	21,00	21,00	21,00	14,00	19,19
			Lignin Content	LIG	%	14,90%	14,90%	14,90%	14,90%	14,90%
Minerals			Minerals (as Ash 525°)	ASH525	%	0,0%	0,0%	0,0%	95,5%	24,6%
	80		Spec. Light Scattering Coeff.	SFill	m2/kg	80	80	80	80	80
			Spec. Light Absorption Coeff.	KFill	m2/kg	0,5	0,5	0,5	0,5	0,5
Dirts			ERIC value	ERIC	%	0,020%	0,020%	0,025%	0,045%	0,027%
			Dirt Specks Specific Area	Ainl	mm²/m²	3700	3700	4400	6900	4533
			Mean Dirt Specks Diameter	Dink	µm	217	217	217	217	217
			Spec. Light Scattering Coeff.	SInk	m2/kg	100	100	100	100	100
			Spec. Light Absorption Coeff.	KInk	m2/kg	8246	8246	8246	8246	8246

Appendix 2.

Paper properties of total pulp and fractions of paper for recycling pulp (see Appendix 1).

	Apparent Density (g/cm^3)	**Elastic Modulus (GPa)**	**Bending stiffness (Nmm)**	**Brightness (%)**
LF	*0.30*	*2.36*	*4.56*	*46.13%*
SF	*0.35*	*1.78*	*2.26*	*46.13%*
FI	*0.57*	*0.99*	*0.28*	*47.61%*
ASH	*0.90*	*0.10*	*0.00*	*70.49%*
Feed	*0.47*	*1.65*	*0.80*	*52.10%*

Appendix 3.

Composition of the layers and corresponding bending stiffness *BS* and brightness R_{457} of a 3-layer sheet when maximising bending stiffness is the primary objective.

	Case		**1**	**2**	**3**	**4**	**5**
Core layer	*LF*	g/m^2	0.00	4.00	8.00	15.00	21.03
	SF	g/m^2	42.91	40.46	38.00	33.70	29.87
	FI	g/m^2	1.08	1.02	0.96	0.85	0.75
	ASH	g/m^2	25.79	24.32	22.84	20.25	17.95
top/bottom layer	*LF*	g/m^2	15.11	13.11	11.11	7.61	4.59
	SF	g/m^2	0.06	1.22	2.45	4.61	6.52
	FI	g/m^2	0.00	0.03	0.06	0.12	0.16
	ASH	g/m^2	0.03	0.74	1.47	2.77	3.92
	BS	Nmm	1,24	1,09	0,98	0,85	0,79
	R457	%	47,52%	48,41%	49,29%	50,79%	52,05%

Appendix 4.

Composition of the layers and corresponding bending stiffness *BS* and brightness R_{457} of a 3-layer sheet when maximising brightness is the primary objective.

	Case		***1***	***2***	***3***	***4***	***5***
Core layer	*LF*	g/m^2	30.22	27.78	25.35	22.91	22.10
	SF	g/m^2	42.91	39.45	36.00	32.54	31.38
	FI	g/m^2	1.08	0.24	0.47	0.71	0.79
	ASH	g/m^2	0.00	5.66	11.32	16.97	18.86
top/bottom layer	*LF*	g/m^2	0.00	1.22	2.44	3.65	4.06
	SF	g/m^2	0.00	1.73	3.46	5.19	5.76
	FI	g/m^2	0.00	0.42	0.30	0.18	0.14
	ASH	g/m^2	12.89	10.07	7.24	4.41	3.46
	BS	Nmm	1.09	0.84	0.76	0.77	0.79
	*R*457	%	60.61%	58.59%	56.10%	53.13%	52.05%

Appendix 5.

Composition of the layers and corresponding bending stiffness *BS* and brightness R_{457} of a 3-layer sheet when maximising bending stiffness and brightness is the primary objective.

			1	***2***	***3***	***4***	***5***
Core layer	*LF*	g/m^2	0.00	0.00	0.00	0.00	0.00
	SF	g/m^2	42.91	42.91	42.91	42.91	42.91
	FI	g/m^2	0.00	0.00	1.08	1.08	1.08
	ASH	g/m^2	15.12	13.34	7.50	5.06	0.94
top/bottom layer	*LF*	g/m^2	15.11	15.11	15.11	15.11	15.11
	SF	g/m^2	0.00	0.00	0.00	0.00	0.00
	FI	g/m^2	0.54	0.54	0.00	0.00	0.00
	ASH	g/m^2	5.33	6.22	9.14	10.36	12.42
	BS	Nmm	0.97	0.95	0.91	0.90	0.90
	*R*457	%	51.99%	52.57%	54.37%	54.98%	55.91%