O PAPEL vol. 72, num. 8, pp. 50 - 55 AUG 2011

OFFICE PAPER BULK OPTIMIZATION IN A PAPER MACHINE USING MULTIVARIATE TECHNIQUES

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Keywords: Bulk, multivariate, optimization, paper machine

ABSTRACT

This work aimed at identifying the primary causes of paper bulk variations at an industrial paper machine by multivariate process data analysis and experimental design techniques as a tool to define production strategies that minimize bulk's variations and/or maximize bulk's objective.

Process data for two different paper products of a paper mill were collected, corresponding to a two-year period. These data were used as input for a multivariate analysis, including PCA and PCR using paper bulk as a dependent variable. PCR models of paper bulk identified the most significant variables affecting it: pulp beatability, refining strategy, shoe-press operating conditions and some furnish properties. The interpretation of the main principal components suggests that paper bulk variations are most probably caused by the misalignment of refining operating conditions in the presence of pulp quality variations, which are compensated by shoe-press variables in order to assure paper machine runnability. Based upon the multivariate analysis conclusions, a preliminary laboratorial experimental design was performed involving the controlled variation, at three levels, of industrial pulp specific refining energy and pressure of a lab press. ANOVA analysis of these results revealed that bulk depends on the quadratic effect of press pressure.

INTRODUCTION

Paper bulk is a property primarily determined by fibre biometry, which depends on its turn from wood species, paper machine specifications and paper additives morphological properties. Other variables may indirectly influence bulk. For instance, refining and/or pulp beatability influence bulk in the sense that this co-varies with mechanical properties. However, when bulk is evaluated for a specific fibre matrix consolidation level, as measured by tensile, bulk will only depend on the above-mentioned primary variables.

The market agents perceive printing and writing paper bulk as a quality trait. The maximization of bulk related to product's roughness properties and wet web strength necessary to assure an acceptable level of paper machine runnability is an important goal in paper production. Moreover, paper bulk has an important impact on process economy due to basis weight manipulation in order to cope with caliper objectives. Within this context, a typical variation pattern was identified in 2 paper products: first 9 months with high paper bulk and a following 12 month period with a lower paper bulk, with a reversion trend on the last 3 months (**Figure 1**). These oscillations were inevitably

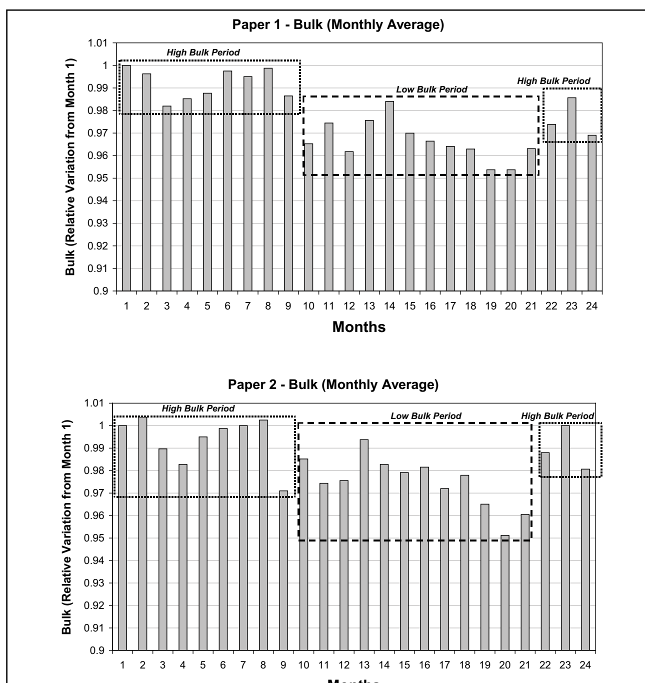

Figure 1. Relative variation of monthly averaged bulk for two paper grades with the identification of "high bulk" and "low bulk" periods

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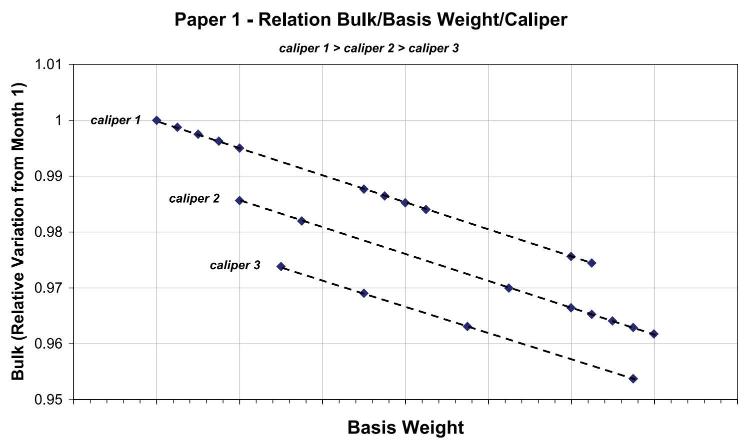

Figure 2. Effect of bulk variation on basis weight adjustments for several paper calipers

reflected in paper basis weight and/or caliper levels. (**Figure 2**).

Based upon this information, it was decided to develop a study that aimed to identify paper bulk primary causes of variation through mill data multivariate analysis and experimental design techniques. The output information will help to define production strategies that minimize bulk variations and/or maximize its value.

MATERIALS AND METHODS

Mill data multivariate statistical analysis

Mill data was collected according to **Table 1** variables for 2 paper products ("paper 1" and "paper 2"), and for the 24-month period in which paper bulk's variations were identified (Figure 1). These variables were selected in the assumption that they could influence or reflect, directly or indirectly, paper bulk quality. Daily data were converted in monthly averages, with the perspective of mitigate the short-term variations effect.

Multivariate statistical analysis is based upon the relative covariation between variables. Therefore, it's necessary to normalize the variation range for each variable by its standard deviation. The screened and standardized data were analyzed using PCA (*Principal Components Analysis*) and PCR (*Principal Component Regression*) techniques:

- PCA – Analysis of pulp properties data set;
- PCR – Development of a multivariate bulk regression model for "paper 1" and "paper 2" expressed in terms of an independent data set comprising pulp properties, pulp refining and paper machine operating conditions.

In addition to typical multivariate model parameters (scores, loadings, regression coefficients), a new parameter was introduced (VIP). The VIP parameter evaluates the cumulative importance of an independent variable in the regression model composed by several principal components (**Equation 1**).

$$VIP_k = \sqrt{\sum_{i}^{n} (L_{ki} \times PC_i)^2} \qquad \text{(Equation 1)}$$

VIP_k – parameter that translates the importance of *k* variable on PCR modeling;
L_{ki} – *loading* of *k* variable on *i* principal component;
PC_i – explained variance of the dependent variable on *i* principal component.

Table 1. Variables included in the multivariate analysis

Class	Description of variables
Pulp properties	*Pulp*: °SR @ 1000 rev. PFI; PFI revolutions at 30°SR; tensile @ 30°SR; bulk @ 30°SR; tear @ 30°SR; Gurley permeability @ 30°SR. *Slush Pulp:* °SR at 1000 rev. PFI; wood.
Pulp refining	Specific refining energy; °SR refined pulp.
Paper machine	Production rate; headbox consistency; headbox temperature; OBA mass; OBA surface; pulp; broke; ashes; shoe-press pressure; shoe-press tilt; breaks; steam; calender pressure front side (LC) and drive side (LA).
Paper properties	Basis weight, caliper, bulk, tensile MD and CD, tear MD and CD, burst, roughness.

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Table 2. Samples included in the experimental design to assess the influence of refining and pressing on bulk

#		Variables		Analysis		
		SRE (kWh/t)	Pressure (bar)	PCR	ANOVA	Graphic
Full Factorial	1	60	1	X	X	X
	2	90	4	X	X	X
	3	120	8	X	X	X
	4	60	1	X	X	X
	5	90	4	X	X	X
	6	120	8	X	X	X
	7	60	1	X	X	X
	8	90	4	X	X	X
	9	120	8	X	X	X
10		0	1			X
11		0	4			X
12		0	8			X

Table 3. **Main laboratorial sheet testing developed in the experimental design**

Test	Sample	Method
Moisture	wet sheet after pressing	ISO 287 - 1985
Wet tensile	wet sheet after pressing	NP EN 1924-2 adapted
Bulk	dry sheet	NP EN 20534
Tensile	dry sheet	NP EN 1924-2
Permeability Gurley	dry sheet	ISO 5636-5:2003
Roughness Bendtsen	dry sheet	ISO 8791-2:1990

Laboratorial experimental design

After statistical analysis it was decided to assess the independent effect and its interactions of pulp refining and sheet pressing on paper bulk. A laboratorial *3 level Full Factorial* experiment series was set as shown on **Table 2**.

A complementary analysis was made on the unrefined pulps. Pulps were collected at the refining line that feeds the paper machine of this study. Several laboratorial sheets were produced, in which pressing was undertaken in a manual press using a 2min+2min sequence at nominal pressure. Blotting paper was replaced every pressing run. In addition to bulk, other sheet properties were evaluated, including wet web properties. **Table 3** relates the main laboratory trials involved in this experiment set.

RESULTS AND DISCUSSION

Mill data multivariate statistical analysis

From pulp quality PCA analysis (**Figure 3**) it's possible to identify 2 independent variation patterns that explain about 78% of X variations (PC1=61%, PC2=17%). The first variation pattern (PC1) apparently represents the changes on pulp beatability, which coincides with paper bulk variation pattern (Figure 1). High paper bulk period coincides with low beatability pulp (+rev.30ºSR; -ºSR1000rev.) when compared to low paper bulk period. This result is a first indication that pulp beatability variation, occurred between both these periods, may have contributed to paper bulk differentiation.

The PCR regression model of "paper 1" bulk, expressed in

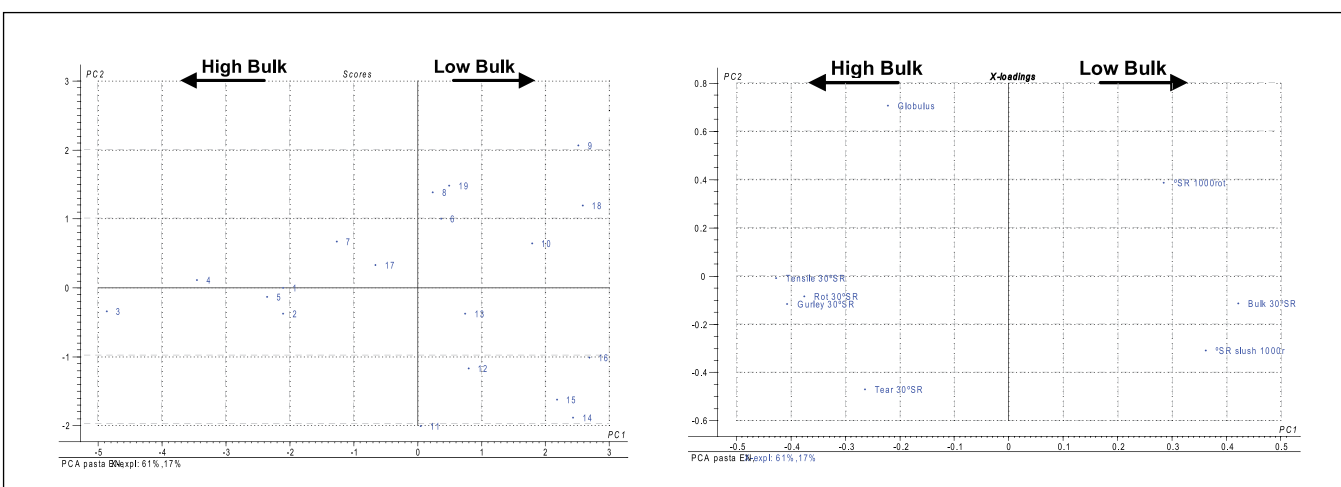

Figure 3. **Scores diagram (left) and loading diagram (right) for pulp properties PCA analysis. X explained variance: PC1=61%; PC2=17%**

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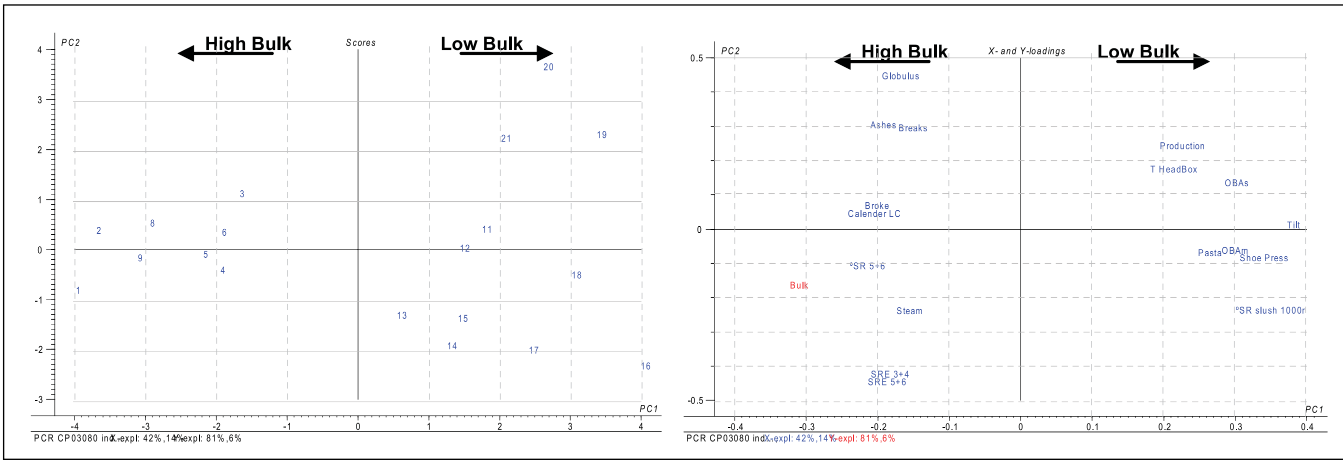

Figure 4. Scores diagram (left) and loading diagram (right) for "paper 1" bulk PCR model. Y explained variance: PC1=81%; PC2=6%

terms of pulp variables and paper machine conditions, allows us to identify a high/low bulk segregation pattern. As shown on **Figure 4**, this pattern is the main contributor for the explanation of paper bulk variations (PC1=81%). The most relevant variables for the characterization of this system are the ones related to both pulp beatability and refining, furnish composition, shoe-press and calender. Paper basis weight and paper caliper were not considered in this analysis since these don't influence paper bulk.

These variables are only a control response to bulk variations in order to assure paper quality specifications. Based upon the covariations map expressed through PC1 axis, it's possible to suggest some conceptual explaining mechanisms that support paper bulk variations. However, a single covariation of each variable with paper bulk is nothing but only an isolated "photogram" of a still unassembled "motion picture". Thus, it's necessary to integrate all available information, through PC1, with a logical reasoning on the background. The present information has induced us to believe that non-equivalent adjustment of pulp refining, in the presence of pulp beatability variations, could have been the primary factor behind paper bulk variations. This theoretical possibility is based on the following reasoning:

- The relative variation diagram of Figure 4 reveals an increase of pulp beatability (-rev.30ºSR; +ºSR1000rev.) starting from the 9th month, which was overcompensated by a specific refining energy decrease (-SRE). This excessive compensation induced a decrease in the refined pulp ºSR (-ºSR). As per these conditions of higher pulp beatability and lower ºSR after beating, the pulp fibres have a lower bond potential. Eventually, to compensate such a fact, shoe-press pressure and tilt were increased (+tilt, +shoe-press). Apparently, this adjustment overcompensated the loss in wet web strength because daily paper machine breaks decreased (-breaks), even though this kind of problems can be caused by other reasons. For all this, we consider that the pressure and tilt increase on shoe-press was the most probable responsible for bulk decrease (-bulk), even with a parallel decreasing of calender pressure (-calander LC).

The results transcription refers to "Paper 1" data analysis. The results for "Paper 2" are similar, even though the multivariate models are less accurate (PC1=73%; PC2=4%). Moreover, other variables came up as relevant for the PCR bulk model. The **Figure 5** ranks the most relevant variables for the PCR bulk models of both paper series.

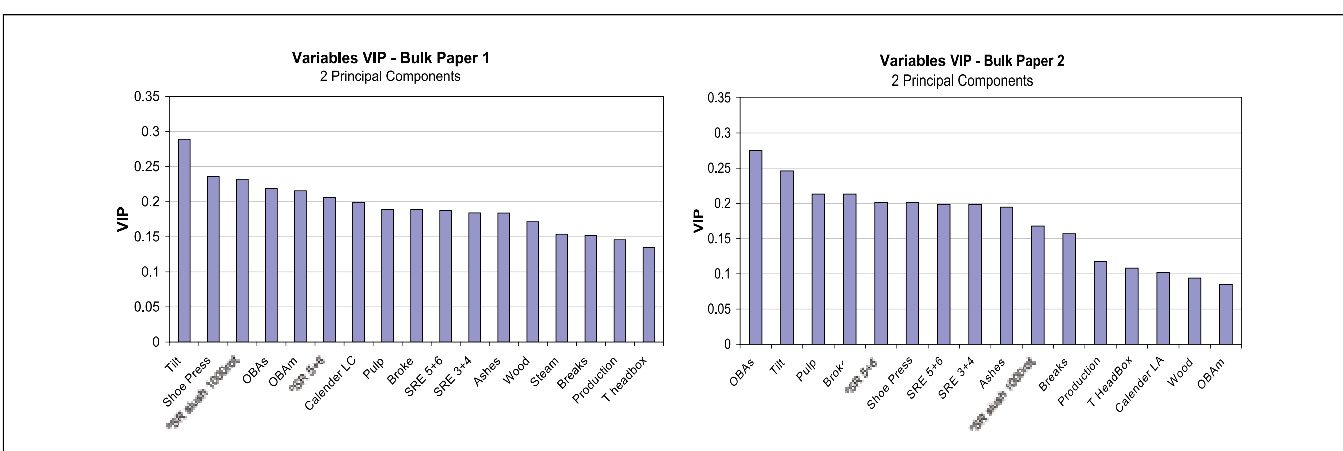

Figure 5. Ranking "VIP" of the most important variables affecting bulk PCR models for two paper grades. Y explained variance for paper 1: PC1=81%; PC2=6%; Y explained variance for paper 2: PC1=73%; PC2=4%

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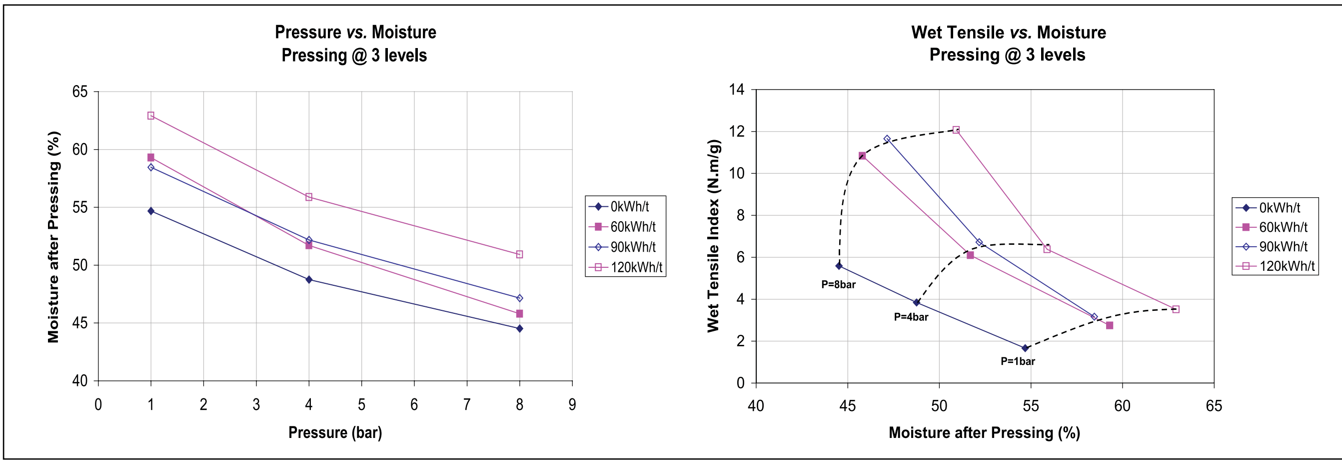

Figure 6. Left: influence of refining and pressing on sheet moisture; right: relation between sheet moisture and wet tensile after pressing for different levels of refining and pressing

Laboratorial experimental design

The multivariate analysis results indicate a cross effect between pulp beatability/refining and wet web pressing. It is aim of this work to validate this result through an industrial experimental design. Before this, it was decided to develop a laboratorial study with aim at identifying possible quadratic and/or interactive effects between design variables. This would be valuable information in designing the industrial experiment.

Theoretically, paper moisture after pressing is one of the key parameters that determine paper sheet density (higher moisture, higher paper bulk). However, paper moisture is limited by the mechanical resistance that paper sheet must withstand in order to guarantee a certain level of runnability. The **Figure 6** (left) illustrates pressing and refining influence of lab sheet moisture, revealing that pressing induces a higher variation span on this property than refining. However, the effect of moisture over tensile strength depends on how this variation is imposed (Figure 6 right). Decreasing pressing conditions, for constant refining, induces an increase of sheet moisture, which in turn determines a decrease in wet tensile strength. In opposition, an increase in refining conditions, for constant pressing, determines an increase of sheet moisture as a result of an increase of fibre water retention potential. Concurrently, an increase in fibre bond potential also occurs, which compensated the moisture increase, leading to an increase of the lab sheet wet tensile strength. However, for the tested refining conditions (60 kWh/t-120 kWh/t), this increasing is marginal, meaning that the increase in fibre bond potential is somewhat compensated by the increase in sheet moisture.

The influence of pressing and refining on lab sheet bulk is illustrated on **Figure 7**. It's possible to verify that pressing is more detrimental than refining. Having in consideration that refining marginally influences wet tensile strength, it's possible to define a reference level of this variable through pressing adjustments. In this context, bulk is maximized for low refining input (Figure 7 left). For instance, for a pressure of 4 bar bulk achieves a maximum level at a minimum refining energy of 60 kWh/t. The resultant lab sheet moisture is about 52% (Figure 7 right), which is lower than the ones associated with lab sheets with higher refining inputs (e.g. 120

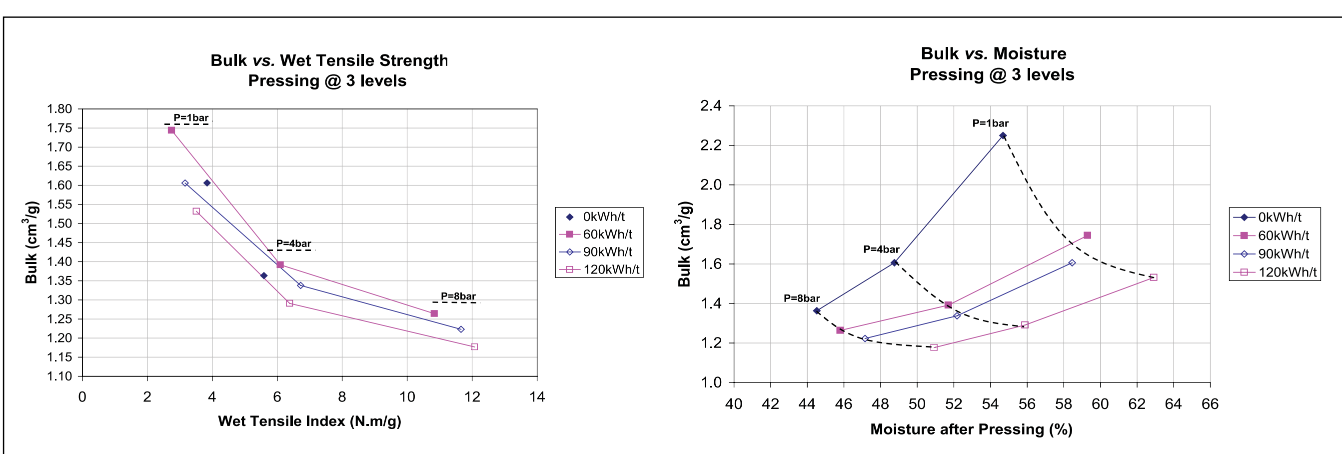

Figure 7. Left: relation between bulk and wet tensile for different levels of refining and pressing. Right: relation between sheet moisture and bulk for different levels of refining and pressing

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Table 4. Results of ANOVA for independent effects (refining and pressing) on several paper properties. Significant effects for p<0.05 (grey cells). Inclusion of explained variance by each linear effect on the dependent variables

Dependent variables	Independent linear effects ANOVA / PCR		Quadratic effects (ANOVA)		Interactions (ANOVA)
	Refining (A)	Pressing (B)	A^2	B^2	A x B
Moisture	p=0.0018 / 11%	p=0.0001 / 84%	p=0.014	p=0.022	p=0.22
Wet tensile	p=0.042 / 1%	p=0.00001 / 99%	p=0.30	p=0.18	p=0.40
Bulk	p=0.0055 / 9%	p=0.0002 / 80%	p=0.54	p=0.0059	p=0.77
Tensile	p=0.0003 / 35%	p=0.0001 / 61%	p=0.77	p=0.01	p=0.84
Permeability Gurley	p=0.0009 / 39%	p=0.0009 / 42%	p=0.12	p=0.48	p=0.003
Roughness Bendtsen	p=0.001 / 23%	p=0.0002 / 62%	p=0.63	p= 0.0028	p=0.03

kWh/t), and with a lower bulk. Thus, bulk is maximized guarantying lower sheets moisture after pressing, which apparently contradicts the above mentioned theory. The effect of sheet moisture on bulk also depends on the way this variation is undertaken: through pressing (positive covariation between moisture and bulk) or through refining (negative covariation between moisture and bulk).

Table 4 presents the main ANOVA results associated to the effects of independent variables (refining and pressing) on several paper properties. The independent effects are significant (p<0.05) for all properties. Complementary, these independent effects were analyzed through a PCR perspective using the explained variance of the dependent variable. In this case, even though both effects are significant, refining explains only 1%, while pressing explains 99% of wet tensile strength variations.

Thus, for the scope of this work, pressing is largely responsible for the wet tensile strength variations. This conclusion can be applied to sheet moisture and bulk, but at a lower extension. These results confirm the observation made through the graphic analysis of Figure 6 e Figure 7. Dry tensile strength, Gurley permeability and Bendtsen roughness are influenced in a more equal balance between refining and pressing.

Regarding the quadratic and interactive effects, it is possible to identify a significant quadratic effect of pressing on bulk. This result has several implications over a future industrial experimental design, namely, the mandatory inclusion of more than 2 experience levels.

CONCLUSIONS

The multivariate statistical analysis of two paper grade production data has allowed to identify the main variables that explain at least 77% of paper bulk variations: pulp beatability (ºSR), specific refining energy (SRE, ºSR), shoe-press strategy (pressure and tilt) and furnish properties (OBAs, broke and ash). The interpretation of the relative covariations between variables indicate that the non-equivalent adjustment of refining properties, when facing pulp beatability variations, may have been the primary factor responsible for paper bulk variations recorded during this period. This situation has led to an increase of pressing conditions, which may have been the direct responsible for the decrease of paper bulk.

Concerning the laboratorial study of the influence of refining and pressing on paper properties for a predetermined wettensile standard, it was shown that bulk is maximized for low specific refining energies with higher pressing levels in order to adjust the wet tensile objectives.

The influence of sheet moisture after pressing on wet tensile and bulk depends on how its variation is accomplished: through refining (positive covariation between moisture and wet tensile; negative covariation between moisture and bulk) or through pressing (negative covariation between moisture and wet tensile; positive covariation between moisture and bulk).

Despite the fact that all independent effects are significant, it was shown that pressing is responsible for the large part of sheet moisture, wet tensile and bulk variations. It was also shown that bulk depends on the quadratic effect of pressing. This result has several implications on a future industrial experimental design.

Acknowledgment

Professor Marco Seabra from the Chemical Engineering Department of Science and Technology Faculty of Coimbra University for his help in understanding the theoretical aspects related to the available experimental design models. ■

This paper has been presented at the XXI TECNICELPA Conference and Exhibition / VI Iberoamerican Congress on Pulp and Paper Research - CIADICYP 2010 in Lisbon, Portugal.