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MODELING NSSC PULPING TO PREDICT AND OPTIMIZE PULP YIELD

Mohammadreza Dehghanifirouzabadi, Abouzar Hatam
Gorgan University of Agricultural Sciences and Natural Resources
Faculty of Wood and Paper Sciences and Engineering, Department of Pulp and Paper Technology
Gorgan, Iran

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ABSTRACT

Due to the inconsistency problem in NSSC pulp yield and disturbances in its papermaking properties for corrugated board grade at Mazandaran Wood and Paper Industries Company (MWPI), an empirical model was developed to predict pulp yield and to optimize cooking conditions. Multivariable regression analysis was used for model building. The results show that chemical charge and cooking time are the most important variables affecting NSSC pulp yield.

It was concluded that the developed model can be employed to predict pulp yield, to optimize cooking conditions within the range of mill production rate and to achieve NSSC pulp with better and more consistent properties for making corrugated board grade.

KEYWORDS: Modeling, NSSC pulping, pulp yield, corrugated paperboard.

INTRODUCTION

Yield in pulping has a pronounced effect on the properties of the pulp fibers. The yield of NSSC pulp is the major factor influencing the final product quality. Most mills producing corrugating medium do not control pulp yield as a routine operation (Ingruber and Kocurek 1985). The main reason is the lack of a sufficiently simple, rapid, and accurate method of estimatingdigester yield forsemi-chemicalpulps (Wandelt and Mroz 1992).

The large number of variables and high costs of mill trials are some of the problems encountered when optimizing the operation of pulping process. Thus, having a good working model can reduce the number of trials required.

In continuous NSSC pulping system, the production rate is a varying parameter. Since, level of chips in the digester is controlled to be constant, variations in production speed will cause serious disturbances in residential time of chips in the digester therefore, as production rate changes, other cooking parameters including chemical charge, temperature and pressure should be optimized so that the NSSC pulp yield is kept at a reasonably constant level. Otherwise, variations in production rate will bring about changes in pulping process thus, pulp yield and in particular, its lignin and hemicellulose contents will change. Lignin and hemicellulose contents of NSSC pulp directly affect pulp fiber stiffness, fiber refining ability and finally corrugated board applied properties. This will lead to disturbances in pulp strength properties which is not desirable from the corrugated paperboard properties point of view (Casey 1980).

To overcome the inconsistency problem in NSSC pulp yield at MWPI and with regard to the annual production of around 100.000 tons NSSC pulp at this company, this case study was conducted to predictive modeling of NSSC pulping process following the method reported by Lohrasebi and Paszner (2001). This NSSC pulp is used for manufacturing of corrugated paperboard in a medium board paper machine at MWPI.

MATERIAL AND METHODS

NSSC pulping process at MWPI is based on mixed medium to high density hardwoods like oak, beech, Siberian elm, iron wood, sweet locust, alder, white mulberry and hornbeam from northern local forests of Iran.

Dependent (response or Y) variable was selected to be production rate (RPM) ranging from 18-36 rpm which is the number of rotation (round) of two discharger screws at the bottom of the digester in minute. Discharging rate determines the retention time of chips in the digester at cooking temperature. Hence, in this study, the desired production rate was used as the time available for each cook (Casey 1980).

Independent variables were as follows:

Cooking liquor flow rate ($l.min^{-1}$), NSSC digester yield or total yield (%) as % of oven dry wood, digester pressure (bar), cooking temperature (°C), and blow valve opening position (%).

Cooking liquor flow rate ranges from 66-122 $l.min^{-1}$,

NSSC digester yield or total yield ranges from 72.1-80.5 %,

Digester pressure ranges from 6.7-8.1 bar,

Cooking temperature ranges from 169-177°C,

Blow valve opening positions ranges from 43-59 %.

The model building data were mill cooking data of NSSC pulping process at MWPI. SPSS software (proc multi-variate linear regression) was employed to analyze the data and build model.

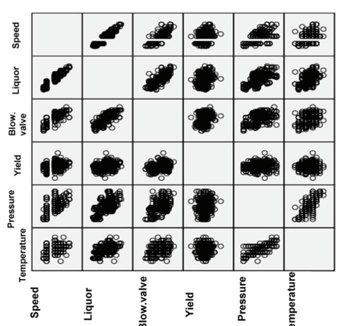

Fig. 1: Scatter-plot matrix.

To find the "best" equation, the following subset selection procedures were employed: forward and backward elimination, and stepwise. Comprehensive treatment and full explanation of model-building procedures are presented in the publication by Lohrasebi and Paszner (2001).

According to Lohrasebi and Paszner (2001), analysis is facilitated by assembling the scatter plots in a scatter-plot matrix, as indicated in Fig. 1, in which the Y variable for any one scatter plot is the name found in its row, and the X variable is the name found in its column. Such a scatter-plot matrix demonstrates the relationships among the variables by comparing the scatter plot within a row or a column (Neter et al. 1996). A useful complement to the scatter-plot matrix is the correlation matrix (Tab. 1). It is noted that the correlation matrix is symmetric, and that its main diagonal contains 1s.

Tab. 1: Correlation matrix (R coefficient).

		P. rate	**Liquor**	**Blow .valve**	**Yield**	**Pressure**	**Temperature**
P. rate	Pearson correlation	1	.939**	.870**	.310**	.486**	.426**
	Sig. (2-tailed)		.000	.000	.000	.000	.000
	N	434	434	434	434	434	434
Liquor	Pearson correlation	.939**	1	.827**	.257**	.501**	.439**
	Sig. (2-tailed)	.000		.000	.000	.000	.000
	N	434	434	434	434	434	434
Blow. valve	Pearson correlation	.870**	.827**	1	.281**	.417**	.359**
	Sig. (2-tailed)	.000	.000		.000	.000	.000
	N	434	434	434	434	434	434
Yield	Pearson correlation	.310**	.257**	.281**	1	.161**	.132**
	Sig. (2-tailed)	.000	.000	.000		.001	.006
	N	434	434	434	434	434	434
Pressure	Pearson correlation	.486**	.501**	.417**	.161**	1	.854**
	Sig. (2-tailed)	.000	.000	.000	.001		.000
	N	434	434	434	434	434	434
Temperature	Pearson correlation	.426**	.439**	.359**	.132**	.854**	1
	Sig. (2-tailed)	.000	.000	.000	.006	.000	
	N	434	434	434	434	434	434

**. Correlation is significant at the 0.01 level tailed

According to Neter et al. (1996), the two most important assumptions to be tested include normality and uniformity of variance of the error terms. When these two assumptions are not met, transformation of Y variable is needed. Since normality of error terms and uniformity of error variance were not met properly, transformation of the production rate was examined and log t (t as production rate) was found to make the error-variance reasonably constant and residuals normal. After proper transformation was completed, the multi-variatelinear regression was run (using SPSS software) to obtain the model parameters.

Following the transformation, the "best" combination of variables, full model, was found to be:

$$\text{Log } t = b0 + b1C + b2\,K + b3P + b4\,T + b5B \qquad (1)$$

where: b0, b1,b2,b3,b4 and b5 - are regression coefficients,
t – production rate (RPM),
C –cooking liquor flow rate ($l.min^{-1}$),
K- pulptotal yield (%),
P -digester pressure (bar),
T-cooking temperature (°C),
B - blow valve opening position (%).

Next, the "best" subsets were selected, running F-tests and comparing R^2. In this study, as mentioned earlier, different selection procedures were employed, i.e., forward, backward, and stepwise. They were run since it is always better to run them all in order to identify "good" equations and subsequently to choose the "best" among all "good" candidates (Lohrasebi and Paszner 2001). After comparing the outputs, the "best" equation was selected from stepwise procedure.

RESULTS AND DISCUSSION

As Tab. 2 shows, there is a general significant relationship between the NSSC pulping condition variables and the pulp yield. Thus, the full model could be developed (Eq. 1).

Tab. 2: Analysis of variance for full model (Eq. 1) with R2 = 0.922.

Source	SS	DF	MS	F	Sig.
Model	2.332	5	.466	1.014E3	.000[a]
Error	.197	428	.000		
Total	2.529	433			

Selection of the "best" subset

The "best" equation was selected from several choices provided by the stepwise procedure. To find the "best" equation, the value of R^2 was compared, and the "best" model was selected where R^2 was at its peak: A model with two variables:

$$\text{Log } t = 0.414 + 0.006C + 0.006\,K \qquad (2)$$

As the ANOVA Tab. 3 shows, two variables including liquor flow rate and pulp yield are important pulping variables that contributed significantly to developing of the above reduced model.

Tab. 3: Analysis of variance for reduced model (Eq. 2) with R^2 = 0.889.

Source	SS	DF	MS	F	Sig.
Model	2.247	2	1.123	1.720E3	.000[a]
Error	.282	431	.001		
Total	2.529	433			

Test for uniformity of error variance

One method to examine the constancy of variance of the error terms is to plot standardized residuals (Y_i-Y_i) versus unstandardized predicted values (Rezaee and Soltani 1988). As Fig. 2 shows, distribution of data points nearly follows a random pattern indicating that the error variance is reasonably homogeneous.

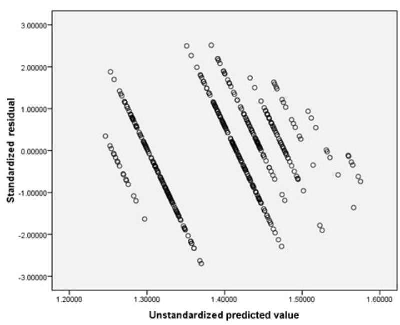

Fig. 2: Scatterplot of standardized residuals versus unstandardized predicted values.

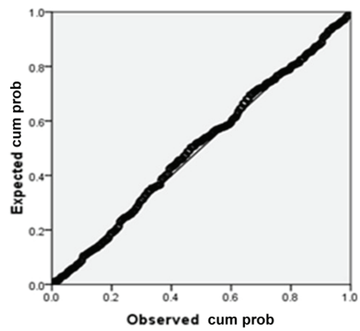

Fig. 3: Normal probability plot of regression standardized residual (residuals versus expected values).

Test for normality of error terms

As performed here, it is usually a good strategy to examine other types of departures first, before concerning with the normality of the error terms. This is because, other types of departures can affect the distribution of residuals (Neter et al. 1996). For example, residuals may appear to be not normally distributed since an inappropriate regression model was used or because non-constant error variance was involved.

Normal probability plot

A good method to examine the normality assumption is to use normal probability plot of the residuals. Here, each residual is plotted versus its expected value under normality (Fig. 3). As in this figure, a plot that is nearly linear suggests agreement with normality, that is, distribution of the error terms does not depart substantially from a normal distribution (Neter et al. 1996).

The final model

The final empirical model was developed using overall 434 data points. The final multiple regression equation to predict mixed hardwood NSSC pulp yields as follows:

$$\text{Log t} = 0.414 + 0.006\text{C} + 0.006\text{K} R^2 = 0.889 \quad (3)$$

$$\text{Log t} -0.414 - 0.006\ \text{C} = 0.006\ \text{K}$$

where: t - production rate in round per minute (RPM) defined as cooking time in this study and is the number of rotation (round) of the discharger screws at the bottom of the digester in minute. Considering the constancy of digester level at different production speed, discharging rate determines the retention time of chips at cooking temperature in the digester and therefore cooking time can be estimated based on discharging or production rate,

C - flow rate of cooking liquor in liter per minute ($1.min^{-1}$) introduced to the chips which is concentration or charge of cooking chemicals based on oven dry chips,

K - NSSC pulp total yield in % (based on oven dry wood).

The units for the parameters (regression coefficients) in the above model are as follows: b_0(rpm), b_1 [rpm min (l^{-1}), b_2 [rpm (%)$^{-1}$].

In the final developed model, interpretation of the effects of production rate as cooking time and liquor flow rate as chemical charge on NSSC pulp yield is also mathematically valid by taking the term liquor flow to the left side of the Eq. 3 and finding negative sign for the coefficient b1, it can be inferred that there is a reverse relationship between chemical charge and pulp yield in NSSC pulping process. This means increasing the cooking liquor flow rate (chemical charge based on oven dry wood) will result in decreasing in pulp yield at a constant cooking time. The same can be applied for a decrease (or increase) in cooking time at a constant liquor flow rate.

Eq. 3 shows that in NSSC pulping of mixed medium to high density hardwoods and at any mill desired production rate, the yield of NSSC pulp can be predicted based on liquor flow rate. This model can also be employed to predict and optimize yield when production rate and liquor flow rate change simultaneously.

It was found that the effect of cooking liquor charge on NSSC pulp yield is in accordance with the results of other studies done on kinetics of delignification for the same pulping process on aspen hardwood species (Chari 1980, Keskin and Kubes 1990).

In addition to liquor flow rate, another effective parameter on delignification and hemicellulose degradation during NSSC pulping is the ratio between cooking liquor chemical components i.e. carbonate to sulfite ratio. Generally NSSC cooking liquor is composed of sodium sulfite and sodium carbonate with a given ratio. The latter components of cooking liquor acts as buffer for neutralization of organic acids released from hemicellulose hydrolysis during NSSC pulping. The buffering agent also prevents from further hemicellulose loss through maintaining of cooking pH around 7.0 at the end of cooking period.

Whenever, there were some disturbances in the ratio of cooking liquor components at MWPI and particularly when liquor became stronger in its buffering characteristic, some reports were found from corrugated paper mill operators indicating that, while energy loads of refiners at corrugated paper mill were incredibly low, however, the refined pulp was slow in the CSF freeness at that time.

As an explanation to this fact, it seems that disturbances in the ratio of carbonate to sulfite in liquor composition affect hemicellulose and lignin degradation reactions during NSSC pulping and probably leads to preserving more contents of hemicellulose in the pulp due to stronger buffering characteristic. The pulp is fast beating, tending to be highly swollen and thus, CSF freeness will drop with a very mild refining load at paper mill.

This can also be proven by the fact that hardwood predominant hemicellulose is xylan type which is more stable in alkaline condition and will be more retained in the pulp during NSSC pulping process. In spite of disturbances in chemical ratio of cooking liquor components, the pulp yield may even be maintained at the same level but with different lignin and hemicellulose contents and with different papermaking properties for corrugated board paper. Although the CSF freeness in such kind of NSSC pulp is low, but since the pulp fibers have not been properly refined, the corrugated board paper will be low in tearing strength and especially in foldingen durance due to lower fiber bonding and fiber flexibility (Casey 1980).

CONCLUSIONS

It was found that chemical charge and cooking time are the most important factors affecting NSSC pulp yield within the ranges studied at MWPI, and that, cooking temperature and digester pressure did not show significant statistical effect on NSSC pulp yield. As it can be indicated by the Eq. 3, at high production speeds (≥30 rpm), since cooking time becomes seriously short, if liquor flow rate is not at its optimum rate, the kinetic of pulping reactions is disturbed. The pulp yield increases undesirably and exceeds beyond the range needed for acceptable corrugated board properties and even may cause break at paper machine.

In this investigate on, the effects of pulping parameters including cooking liquor flow rate as chemical charge and cooking time as production rate on the pulp yield are consistent with known physical and chemical reactions taking place during NSSC pulping.

The final developed model can be applied for NSSC pulping optimization purposes. It may also besuch an empirical black box model of types as developed in the system identification method which can be employed in Model Predictive Control (MPC) strategy of NSSC pulp yield dynamic control in the future (Seborg et al. 2003).

Another research is yet needed to be done at MWPI for determining the effects of the ratio of liquor components on NSSC pulping and for finding the optimum ratio of carbonate to sulfite in cooking liquor to achieve the best balance between lignin and hemicellulose contents of the pulp and corrugated board applied properties.

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Mohammadreza Dehghanifirouzabadi, Abouzar Hatam*
Gorgan University of Agricultural Sciences and Natural Resources
Faculty of Wood and Paper Sciences and Engineering
Department of Pulp and Paper Technology
P.O. Box 4913815739
Gorgan
Iran
* Corresponding author: abhatam@yahoo.com