Optimization of the (CD) (EO) bleaching sequence at Champion's Quinnesec Mill

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Statistical modeling techniques are a convenient way to process mill data to predict pulp qualities and other parameters from key operating variables.

In the fall of 1986, the Quinnesec mill agreed to sponsor a chemical engineering student under the graduate internship program at Michigan Technological University. The project was to be the statistical modeling of the bleach plant, with the goals of (a) economic optimization through reducing operating costs and (b) improvement of the fundamental knowledge base. In the study of the (CD)(EO) bleaching sequence at the mill, statistical modeling was used to predict optimum (CD)(EO) conditions for an incoming pulp with selected properties.

The (CD)(EO) bleaching process

A general flowsheet for the (CD)(EO) bleaching sequence at Quinnesec is given in **Fig. 1.** Kraft pulp produced from a mixture of hardwoods enters the bleaching process after passing through a high-density storage chest at about a 10% consistency. The pulp is diluted to about a 3% consistency with the filtrate from the chlorination stage (CD) by the time it passes through a blend chest, where the suspension is mixed.

The pulp proceeds to a static mixer where chlorine gas and chlorine dioxide solution are injected into the pulp stream. The injector water includes both (CD) filtrate and a chlorine water solution which comes from the chlorine dioxide generator at the mill. The total applied chlorine varies from 3% to 5% for the (CD) stage and is set based upon the properties of the incoming pulp. The total amount of chlorine includes the chlorine gas, the chlorine dioxide concentration expressed as chlorine gas, and the chlorine associated with the chlorine water. A 10% chlorine dioxide substitution is usually maintained.

After the static mixer, the pulp passes to the chlorination tower, an upflow tower, at a consistency of around 2.7% and a temperature near 60°C (140°F). After this (CD) tower, the pulp is washed in a rotary drum washer using a combination of warm water, filtrate from the first extraction stage (EO), and filtrate from the first chlorine dioxide stage (D1).

The pulp mat from the (CD) washer is diluted with sodium hydroxide (14% by wt.) before it enters the (EO) steam mixer, where 65-psig steam is added to raise the temperature to around 68.3°C (155°F). The pulp proceeds to the oxygen gas mixer, where oxygen gas is applied at approximately 0.25% based on oven-dry pulp. The pulp stream then proceeds to the (EO) pretube, which leads to the top of the (EO) tower, a downflow tower. There is a dilution zone at the bottom of the (EO) tower where (EO) filtrate is added and the temperature is usually about 60°C (140°F).

The (CD)(EO) bleaching process is completed at the (EO) washer, where a combination of hot water and D1 filtrate are used as shower water. The pH of the (EO) washer vat is typically maintained at around 10.6.

Statistical modeling of the (CD)(EO) sequence

The Quinnesec mill is ideal for a statistical study because its information systems provide nearly all of the data required to completely describe the bleaching process. Statistical modeling techniques are a convenient way to process the mill data to predict pulp qualities and other parameters from key operating variables.

Description of the data

The data used in this analysis come either from sensors located at key points in the system or from the pulp mill laboratory. **Table I** summarizes the variables used in the statistical modeling process for the "trial data set." The table also summarizes statistics for each of the variables for the trial data set and the time lag category in which each variable is classified.

Data coming from mill sensors are collected by a Foxboro SMS system and may be collected either from daily SMS logger reports (hourly averages) or from a millwide Vax computer. Data collected from the Vax is stored using ASEA's Superview software and may be

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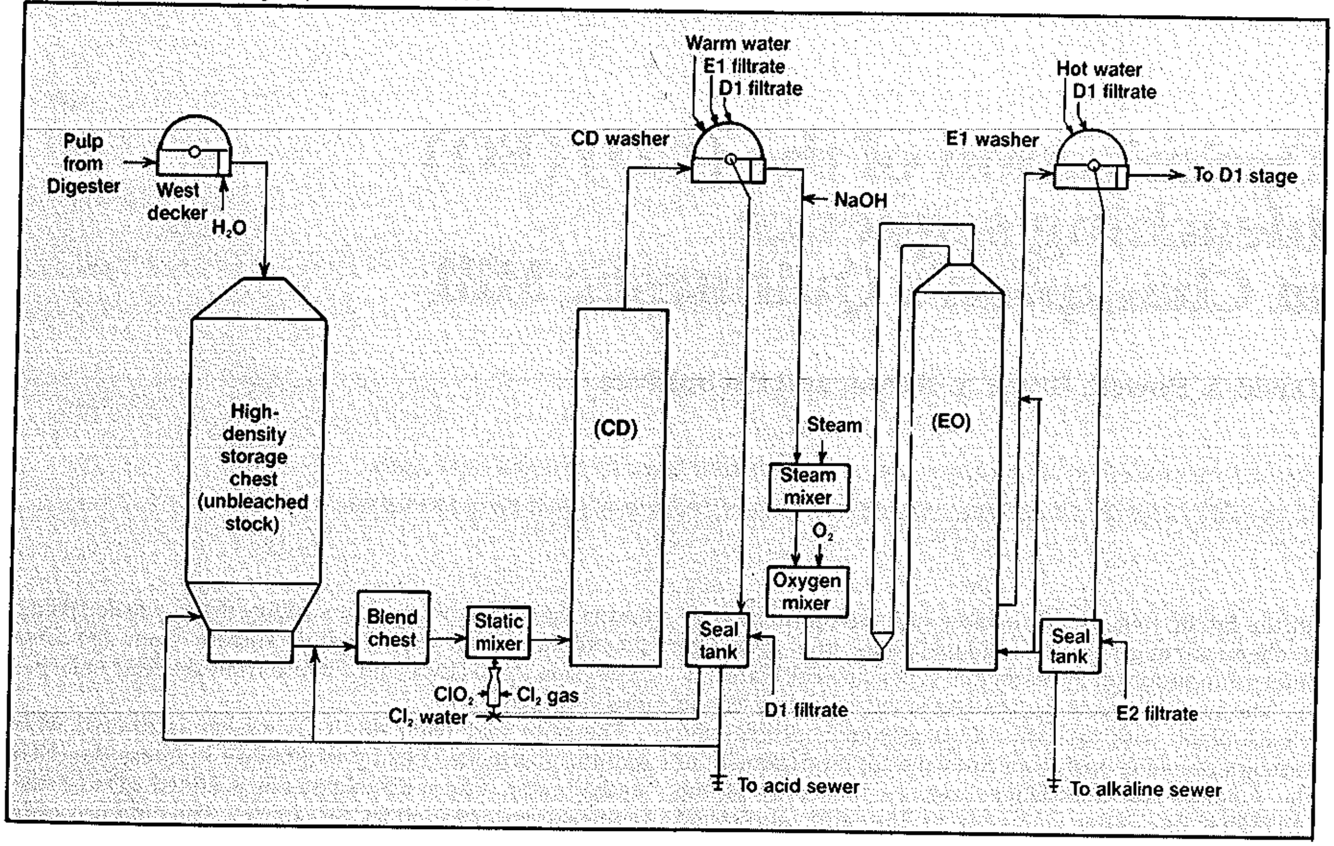
1. The (CD)(EO) bleaching sequence at Quinnesec



retrieved as 3-min, 15-min, hourly, or daily averages of the measurements made by the sensors. Hourly averaged data were used for this study because the point data collected from the pulp mill laboratory are limited to an hourly basis.

Data from the pulp mill laboratory are taken from individual measurements typically made every other hour. However, statistical models developed for this report are based on trial data, for which pulp mill laboratory measurements were made every hour for key process variables. Data are required on an hourly basis if a time-series analysis is to be used in building statistical models.

Some of the raw data coming from the mill were standardized according to the flow rate of o.d. pulp through the system. Chlorine gas, chlorine dioxide, oxygen gas, and chlorine from the chlorine water flow were standardized to a percent applied chemical based on o.d. pulp. Chemical concentrations of the chlorine dioxide and chlorine water were measured frequently to increase the accuracy of their addition rates.

Time-series analysis of bleaching data

To account for the time-series effects of the system, the bleaching data were realigned so that changes in the dependent variables at time t would be caused by changes in independent variables at time $(t - x)$. Here, x is a time lag that depends on the residence times of the pulp in various pieces of process equipment. Residence times were calculated, based on the physical characteristics of the system and the prevailing rate of pulp flow through the system. Looking at Table I, x may be thought of as the time it takes the pulp being affected by an independent variable to reach the point where the corresponding dependent variable is measured.

The independent variables were divided into four different time lag categories based on the physical location in the system where they are measured. In these categories, "decker" denotes variables measured at the west decker prior to the high-density unbleached stock storage chest. "CD" is used for variables measured after the high-density storage chest and prior to entering the (CD) tower. "E1" is used for variables measured after the (CD) tower and prior to entering the top of the (EO) tower. "No lag" denotes variables measured at the bottom of the (EO) tower and beyond in the process. Table I indicates the category in which each of the independent variables is classified.

Once the residence times for the major process equipment were known, the key independent variables for a given dependent variable model were then "lagged" according to these residence times and the appropriate time lag category. The data were manipulated using a SAS (*1*) statistical program file so that the time lags for independent variables were allowed to vary according to flow conditions at the time of measurement (*2*).

Experimental design for the trial data set

By statistically analyzing routine bleaching data, we derived preliminary models that revealed key operating parameters for optimizing the bleach plant. To verify the results of the preliminary models and to remove much of the bias from the bleaching data, a bleaching trial was completed based on the orthogonal experimental design shown in **Table II**. The data from this experiment composed the "trial data set."

I. Key process variables used to develop statistical models

	Mean value (trial data)	*Minimum value*	*Maximum value*	*Time lag category*
Key independent variables				
Decker filtrate conductivity	2513.6066	1770.0000	4290.0000	decker
Incoming K number	12.6253	10.7000	14.2000	CD
Incoming viscosity, mPa·s	44.2616	33.9000	54.9000	CD
(CD) applied chlorine, %	3.7240	3.0361	4.6184	CD
(CD) applied chlorine dioxide, %	0.1579	0.06584	0.2730	CD
(CD) temperature, °F	139.9188	134.3100	142.5200	CD
(CD) residence time, min	29.3393	27.9656	30.8525	CD
(EO) steam mixer temperature, °F	154.7399	146.0800	165.6800	E1
(EO) applied oxygen gas, %	0.2576	0.2561	0.2587	E1
(EO) residence time, min	43.4318	40.8005	46.5332	E1
(EO) vat pH	10.3178	9.6000	11.2000	no lag
Dependent variables				
(CD) pulp color	21.0013	15.1700	24.9500	CD
(CD) washer corrosion, amps	12.6852	3.3100	55.1000	E1
(CD) washer vat residual chlorine, %	0.0172	0.0040	0.1100	E1
(CD) pulp brightness, %	46.7897	40.6000	52.9000	E1
(EO) pulp viscosity, mPa·s	34.8623	10.2000	46.5000	no lag
(EO) pulp K number	1.9178	1.4000	2.5000	no lag
(EO) pulp brightness, %	52.7870	48.1000	56.5000	no lag

II. Experimental design for bleaching trials

Run	*(CD) applied chlorine gas, %*	*(CD) applied chlorine dioxide, %*	*(EO) steam mixer temp., °F*	*(EO) washer vat pH*	*(CD) chlorine dioxide substitution, %*	*(CD) total applied chlorine, %*
nominal	2.71	0.141	155	10.50	12.00	3.08
1	3.12	0.062	165	10.00	5.00	3.29
2	3.12	0.219	165	10.00	15.55	3.70
3	2.30	0.062	165	10.00	6.66	2.46
4	2.30	0.219	165	10.00	20.00	2.87
nominal	2.71	0.141	155	10.50	12.00	3.08
5	2.30	0.219	145	11.00	20.00	2.87
6	2.30	0.062	145	11.00	6.66	2.46
7	3.12	0.219	145	11.00	15.55	3.70
8	3.12	0.062	145	11.00	5.00	3.29
nominal	2.71	0.141	155	10.50	12.00	3.08
9	3.12	0.219	165	11.00	15.55	3.70
10	2.30	0.219	165	11.00	20.00	2.87
11	2.30	0.062	165	11.00	6.66	2.46
12	3.12	0.062	165	11.00	5.00	3.29
nominal	2.71	0.141	155	10.50	12.00	3.08
13	2.30	0.062	145	10.00	6.66	2.46
14	3.12	0.219	145	10.00	15.55	3.70
15	3.12	0.062	145	10.00	5.00	3.29
16	2.30	0.219	145	10.00	20.00	2.87
nominal	2.71	0.141	155	10.50	12.00	3.08

III. Slopes of model functions with respect to independent variables

	(CD) color	(CD) washer corrosion, amps	(CD) vat residual	(CD) brightness	(EO) viscosity	(EO) K number	(EO) brightness
Decker conductivity	. . .	0.009	0.00001	. . .	. . .	-0.0001	. . .
Incoming K number	-1.42	8.366	0.00501	-2.155	5.213	-0.0772	-0.935
Incoming viscosity	. . .	. . .	. . .	. . .	0.763	. . .	. . .
(CD) applied chlorine	2.80	-26.176	-0.03524	1.297	-10.204	0.2229	2.824
(CD) applied chlorine dioxide	14.36	-73.446	-0.09268	7.087	44.127	0.1237	13.242
(CD) temperature	-0.95	0.946	. . .	-0.904	0.217	-0.0631	-0.162
(CD) residence time	. . .	. . .	. . .	-1.130	-2.201	. . .	. . .
(EO) steam mixer temperature	. . .	. . .	. . .	. . .	-0.173	-0.0158	0.046
(EO) applied oxygen gas	. . .	. . .	. . .	. . .	1607.880	65.6084	. . .
(EO) residence time	. . .	. . .	. . .	. . .	. . .	-0.1346	0.087
(EO) vat pH	. . .	. . .	. . .	. . .	1.036	. . .	1.236
Model R^2 coef., %	86.25	88.27	64.70	36.76	81.41	75.77	79.16

The experimental design in Table II is a two-level factorial design that independently varies the (CD) applied chlorine gas, the (CD) applied chlorine dioxide, the (EO) steam mixer temperature, and the (EO) vat pH. These four variables were considered to be the most important in the (CD)(EO) bleaching sequence. The order of the experimental runs was partially randomized for the trial. Nominal conditions were selected based on current operating conditions. The high and low values for each experimental variable were set from the nominal values.

The nominal amounts of chlorine gas and chlorine dioxide were determined on an air-dry basis and were based on the incoming K number of the pulp. A K number multiplier of 0.28 was used to determine the nominal total applied chlorine excluding the chlorine associated with the chlorine water. This approach compromises the power of the experimental design but is necessary to avoid high (CD) residual chlorine levels and producing off-quality pulp. The high and low values for chlorine gas and chlorine dioxide were determined by varying the total applied chlorine by 20% of its nominal value and ranging the chlorine dioxide substitutions from 5% to 20%. The experimental design in Table II is based on an incoming pulp K number of 11.0.

To maximize the benefit of the experimental design, controllable, nonexperimental variables were held constant. The (CD) temperature, the (CD) chlorine water flow, the (EO) oxygen application, and all wash flows were considered to be the most important of these variables.

Description of statistical models

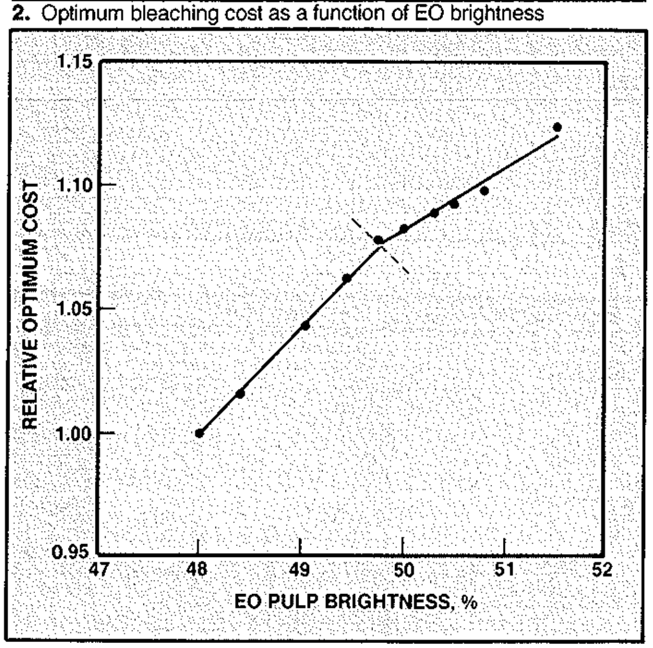
We selected multivariable linear regression as the statistical modeling technique for analyzing the bleaching data. The prediction equation for an estimated regression function takes the general form:

$$Y = b_o + \Sigma(b_i X_i) \qquad (1)$$

where

Y = the predicted value of the dependent variable
b_0 = the intercept of the regression line
X_i = an independent variable

2. Optimum bleaching cost as a function of EO brightness



b_i = the change in Y per unit increase in X_i (*2*).

The data used to develop a statistical model are assumed to have only random error. The statistical models we developed were built using techniques available in the SAS statistical software package (*1*).

The two most important criteria a model must meet are (a) significance at a selected confidence level and (b) low variance inflation factors (VIF). A statistical model must not only meet an overall level of significance, but each independent variable in the model must also be significant. We selected a confidence of 90% for these models. The second criterion used was that the VIF for independent variables should not exceed 10, which is a general rule of thumb used by statisticians (*3*). A VIF in excess of 10 means that some of the independent variables are highly collinear with others, and this relationship can affect the parameter estimates, b_0 and b_i.

Once these two criteria are met, the model is developed

IV. Optimum (CD) (EO) bleaching conditions as a function of E1 pulp brightness

(EO) brightness	(CD) applied chlorine gas, %	(CD) applied chlorine dioxide, %	(EO) steam mixer temp., °F	(EO) washer vat pH
48.00	3.041	0.0659	146.77	10.65
48.40	3.157	0.0658	147.94	10.70
49.05	3.361	0.0669	148.76	10.69
49.45	3.573	0.0680	147.29	10.85
49.75	3.039	0.2351	146.78	10.48
50.00	3.038	0.2484	146.80	10.40
50.30	3.041	0.2615	146.56	10.39
50.50	3.038	0.2690	146.40	10.40
50.80	3.038	0.2730	146.90	10.48
51.52	3.159	0.2730	148.28	10.70

to have a high coefficient of multiple determination. The coefficient of multiple determination, R^2, is the proportionate reduction of the total variation in a dependent variable (Y) associated with the use of a set of independent variables (X_1, X_2, X_3, . . .) (*4*). This coefficient therefore reflects a model's ability to predict changes in a dependent variable.

Building statistical models by inspection

Statistical models were developed by inspection for the selected dependent variables using the trial data set. Building a model by inspection means that once a few variables are incorporated in a model, new independent variables are selected on the basis of their correlations with the residuals of the current model. The residuals are the differences between the observed values of the independent variable and the predicted values. Variables were also selected by keeping in mind which key process variables should be in a given model from a theoretical standpoint. Variables are added to a model until no other variables can enter the model at a selected level of significance. significance.

To keep the VIFs below 10, the independent variables were centered and scaled by subtracting their minimum values for the data set and dividing by their standard deviations. This calculation reduces the collinearity between the averages of the key independent variables and the averages of these variables raised to various powers (*3*). To create nonlinear variables, key independent variables were raised to several powers, ranging from 0.2 to 3.0, so that a better fit with the bleaching data could be obtained.

Selection of dependent variables for statistical analysis

Seven dependent variables were selected for the statistical analysis of the trial data set. These variables were the (CD) color, the (CD) washer corrosion amps, the (CD) washer vat residual chlorine, the (CD) pulp brightness, the (EO) pulp viscosity, the (EO) pulp K number, and the (EO) pulp brightness. The (CD) color is measured just prior to entering the (CD) tower. The (CD) washer corrosion amps and the (CD) washer vat residual were measured in the vat of the (CD) washer. The (EO) pulp viscosity, the (EO) K number, and the (EO) pulp brightness were measured from pulp removed from the mat on the (EO) washer.

Applying the statistical models to (CD)(EO) bleaching

Here, we will not list in detail the statistical models for the trial data set. Instead, we will take a simple approach to analyzing the results of the models. This approach is to determine the slopes of the model functions with respect to independent variables at average operating conditions.

These slopes indicate the relative importance of key operating variables on selected dependent variables. These slopes may also be converted into cost analysis slopes using current cost data. Cost slopes would reflect the relative effects of key operating parameters on dependent variables on a cost basis.

Slope analysis technique

We derived the slopes of individual model functions by taking the partial derivatives of the model functions with respect to each of the independent variables. These slopes reflect the change in the dependent variables that can be produced by a unit change in the independent variables given that all other variables in the model are constant.

Table III summarizes these slopes for the seven models developed. The larger the magnitude of the slope, the greater the effect an independent variable has on a dependent variable if it is adjusted. If no slope is given for an independent variable, then this variable is either not significant in affecting the dependent variable or is measured beyond the dependent variable in the system.

The nature of the independent variable corresponding to a slope should be considered. For example, a unit change in a bleaching chemical would be a much more dramatic change in bleaching conditions than a unit change in temperature. Also, if the the sign of a slope in Table III is positive, the change is a favorable one. Favorable changes in dependent variables are:

- Lower (CD) washer corrosion amps
- Lower (CD) residual chlorine
- Lower (EO) K numbers
- Higher (CD) colors
- Higher (CD) brightness
- Higher (EO) viscosities
- Higher (EO) brightness.

The table also lists the R^2 coefficients for each of the models developed. As these coefficients indicate, the models are generally able to explain 80% of the variation in the dependent variables. The lower coefficients for the (CD) vat residual and (CD) brightness models may indicate larger experimental errors associated with their measurements.

Results of slope analysis

A number of conclusions were drawn from the slopes in Table III as to the effects of the different independent variables.

Decker conductivity. The decker conductivity is primarily a measure of the amount of soda carry-over that enters the bleaching process from the pulping process. As the amount of soda carry-over increases, active chlorine in the (CD) stage is consumed more by the aqueous portion of the incoming suspensions and less by the pulp. This shift is confirmed by the positive slopes of the (CD) amps and (CD) vat residual models with respect to the decker conductivity. The models predict that increases in decker conductivity tend to reduce the residual chlorine at the end of the (CD) stage. The (CD) washer amps are an online indication of the residual chlorine in the (CD) washer vat.

The models also predict that as the decker conductivity increases, the (EO) pulp K number increases. Given that the decker conductivity reduces the amount of chemicals that act on the pulp in the (CD) stage, less delignification should occur with higher decker conductivities.

Incoming K number. The incoming K number of the pulp was measured coming out of the blend chest prior to the (CD) stage. The incoming K number was significant in all of the models developed for the trial data set. In terms of pulp brightness, the higher incoming K numbers tend to reduce the (CD) color, the (CD) brightness, and the (EO) brightness, as expected.

The slopes in the table indicate that incoming K number tends to decrease both the (CD) amps and the (CD) vat residual. These results were also expected because the pulp consumes more chemicals in the (CD) stage with higher lignin concentrations. Also, higher incoming K numbers are predicted to increase the (EO) pulp viscosity. A more selective attack on the lignin portion of the pulp at higher lignin concentrations reduces the degradation of cellulose. Finally, the models predict that with higher incoming K numbers, the (EO) K number tends to increase.

(CD) applied chlorine and chlorine dioxide. Possibly the most important knowledge to be gained from the study of the (CD)(EO) bleaching sequence is the relationship between the chlorine and chlorine dioxide in terms of bleaching performance.

The chlorine variable used in the analysis includes both the chlorine gas and the chlorine associated with the chlorine water. The slopes show that both chlorine and chlorine dioxide are beneficial in increasing the (CD) color, the (CD) brightness, and the (EO) brightness. The chlorine dioxide is much more powerful per unit weight than chlorine in improving brightness. For the chlorine dioxide to be more cost effective, however, it must be approximately five times as powerful as chlorine.

This relationship is true for the (CD) color and the (CD) brightness, but not for the (EO) brightness. The ratio of the slope for the chlorine dioxide to the slope for chlorine in the (EO) brightness model is about 4.7. These relationships may only be valid at average operating conditions.

For the (CD) amps and (CD) vat residual, both the chlorine and chlorine dioxide tend to increase these variables as expected. In delignification, chlorine is predicted to be about 1.8 times as effective as chlorine dioxide per unit weight in reducing the (EO) K number at average operating conditions.

According to the model slopes, increases in chlorine tend to reduce (EO) viscosity, while increases in chlorine dioxide tend to increase (EO) viscosity. This prediction seems realistic in that chlorine degrades the cellulose. On the other hand, chlorine dioxide is believed to protect the pulp.

These results favor the use of chlorine, according to the (EO) brightness and (EO) K number models. However, the use of chlorine dioxide may be required to maintain an adequate (EO) viscosity. Therefore, a more formal analysis is needed to balance the bleaching performance of these chemicals against their costs.

(CD) temperature. Another interesting result in this statistical modeling study involves the (CD) temperature. Although the (CD) temperature was not a planned experimental variable in the bleaching trial, it did vary from 56.8°C to 61.4°C (134.3-142.5°F), which should give an indication of its effect on the dependent variables. As the (CD) temperature increases, the models predict that the (CD) color, the (CD) brightness, and the (EO) brightness decrease. Also, increases in (CD) temperature tend to increase the (EO) viscosity and the (EO) K number, according to model slopes at average operating conditions. Finally, (CD) temperature is predicted to reduce the (CD) amps, although temperature was not significant in the (CD) vat residual model.

Based on these results, the (CD) temperature should be reduced so that improved brightness and delignification are obtained in the (CD)(EO) sequence. Lower (CD) temperatures may drive the (CD) residual chlorine upward, however. This tendency would limit the use of chlorine and chlorine dioxide in the (CD) stage, because of environmental restrictions.

(EO) steam mixer temperature. The slopes of model functions with respect to the (EO) steam mixer temperature suggest that increases in this variable tend to lower the (EO) viscosity, raise the (EO) K number, and increase the (EO) brightness. Therefore, the only pulp quality that is improved by increasing the (EO) steam mixer temperature is the (EO) brightness. It may be surprising that higher (EO) temperatures actually increase the (EO) K number, but this trend was also discovered in previous modeling efforts using different bleaching data.

These results indicate that a reduction in (EO) steam mixer temperature would both reduce bleaching cost and improve two of the three measured (EO) pulp characteristics. The reduction in (EO) brightness predicted by reducing the the (EO) temperature could be offset by increasing the (EO) vat pH slightly. In the past year, average (EO) steam mixer temperatures have been reduced from 73.9°C to 68.3°C (165-155°F) without any notable reductions in pulp quality. Further reductions should further reduce bleaching costs without any harmful effects according to model predictions.

Effect of (EO) applied oxygen gas. Although the (EO) applied oxygen gas variable is significant in the (EO) viscosity and (EO) K number models, there is some question about the results, because this variable was held nearly constant for the bleaching trial. Values for the (EO) oxygen gas ranged only from 0.256% to 0.259% for the trial data set.

This narrow range would normally be expected to make this variable insignificant in the models, especially in light of the experimental error associated with its measurement. This variable may be significant in affecting pulp qualities, but further experimental work is needed to more accurately evaluate its relative importance.

(EO) vat pH. The (EO) vat pH was significant in improving both the (EO) viscosity and the (EO) brightness. In increasing the (EO) brightness, the slopes indicate that the (EO) vat pH is much more powerful than the (EO) steam mixer temperature. The (EO) vat pH was not significant in the (EO) K number model. These results argue that there is a trade-off between the (EO) steam mixer temperature and the (EO) vat pH and that the (EO) vat pH is favored in terms of pulp qualities.

Optimization of the (CD)(EO) bleaching sequence

The (CD)(EO) bleaching sequence was optimized for the experimental variables in the trial data set. Nonexperimental variables in the statistical models were set to average values for the trial data set. Because of limited time, the optimization was evaluated only at average conditions for the properties of the incoming pulp (viscosity, K number, and decker conductivity). Ultimate optimization will involve deriving optimum operating conditions for a variety of incoming pulp conditions.

The strategy taken in the optimization was to select a desired (EO) brightness and minimize the operating costs while maintaining acceptable (CD) vat residuals and (EO) viscosities. The (EO) brightness was selected over the (EO) K number for the optimization procedure because the primary purpose of the bleaching process is to produce pulp with high brightness. The (CD) vat residual should be maintained below a level of 0.01 g/L so that safety standards are not exceeded. Also, the (EO) viscosity should be kept above 30 mPa·s.

The constraints set for the experimental variables were that they were not to exceed their minimum and maximum values for the trial data set. It is inappropriate to extrapolate the correlations beyond the available data, and reasonably broad ranges were used in the trial.

With this optimization strategy and the constraints on operating variables, the optimum (CD)(EO) conditions were predicted from the statistical models and a cost function by solving a system of four nonlinear equations in four unknowns. We used personal computer software to solve the equations at selected values for the (EO) pulp brightness, and the results of the optimization are given in **Table IV**.

The table shows that predicted optimum (CD)(EO) bleaching conditions for the selected incoming pulp may be divided into two distinct groups, depending on the target (EO) brightness. The first group includes the set of optimum conditions required to produce (EO) brightnesses from 48.00% to 49.45%. This group uses low chlorine dioxide substitution in the chlorination stage to produce a pulp of lower brightness. For this group, adjustments in chemicals in the chlorination stage to improve brightness should be made mainly with chlorine. The optimum (EO) steam mixer temperature is around 64.4°C (148°F), and the optimum (EO) vat pH is around 10.7.

As the use of chlorine increases for the first group, the (CD) vat residual constraint becomes a limiting factor. Therefore, predicted optimum (CD)(EO) conditions switch to high chlorine dioxide substitution for the second group to prevent exceeding the specified (CD) vat residual. The selected (EO) brightnesses range from 49.75% to 51.52%. The optimum (EO) steam mixer temperature is about 63.9°C (147°F), and the optimum (EO) vat pH is around 10.5.

Figure 2 shows the two distinct groups of predicted optimum operating conditions. Relative optimum (CD)(EO) bleaching cost is represented as a function of target (EO) brightness. The graph not only distinguishes between the two groups of optimum conditions, but it also shows that the change in cost per unit increase in (EO) brightness is lower at higher brightness levels where higher chlorine dioxide substitutions are used in the (CD) stage.

Optimum (EO) stage conditions suggest that the (EO) steam mixer temperature should be set at about 63.9°C (147°F) and that the (EO) vat pH should be in the range of 10.4–10.7. Typical current operating conditions for the (EO) stage are a steam mixer temperature of 68.3°C (155°F) and a vat pH of 10.6. Current vat pH appears to be appropriate, but the (EO) steam mixer temperature should be reduced by 4.4°C (8°F). This temperature reduction would save the mill about $0.45/ton of o.d. pulp, or about $115,000 per year.

Several sets of optimum conditions are considered, but which set is the true optimum? In other words, what should be the value for (EO) brightness at which to optimize the entire bleaching sequence? This question can only be answered by evaluating the relative performance of the last three stages of the bleaching sequence, DED, and balancing this performance against the performance of the (CD)(EO) sequence in terms of cost.

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