Model-based control of high-consistency refining

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ABSTRACT

A model-based refiner control system is operating on two lines of high-consistency refiners producing newsprint-quality TMP. The control system uses factor network analysis to predict refiner blow-line consistency on-line, in real time. Blow-line consistencies are then controlled using refiner dilution water. The system has reduced variations in refiner consistency by approximately 40%. A pulp-quality system that measures freeness, fiber size distribution, and shives is being integrated into the consistency-control system, with the goal of monitoring and controlling freeness and fiber size distribution. A planned energy-optimization system will reduce the specific energy required to achieve a given pulp quality.

Application:

This paper illustrates the implementation of model-based consistency control for high-consistency chip refiners. The control system reduces variations in the fiber length and freeness, which can reduce the need for kraft pulp in newsprint production.

Blow-line consistency has long been recognized as a key control variable in the operation of high-consistency chip refiners. If consistency is too low, the refiner cannot be loaded to its design capacity, resulting in low specific energy and high freeness. Decreasing the plate gap to compensate for low specific energy has the drawback of cutting long fibers, which reduces the tear strength of the resulting pulp. Excessively high consistency can also result in poor quality, since the fibers tend to become brittle and break instead of developing high amounts of bondable surface area. There is, therefore, a consistency window that provides a combination of low shive content, good surface development (which gives high tensile and other bonding properties), and increased long-fiber content (which results in high tear).

The purpose of this study was to develop a refiner consistency-control system that would reduce variation in blow-line consistency, thus improving pulp quality. The proposed control system also had to be cost effective and easy to maintain.

PROCESS DESCRIPTION

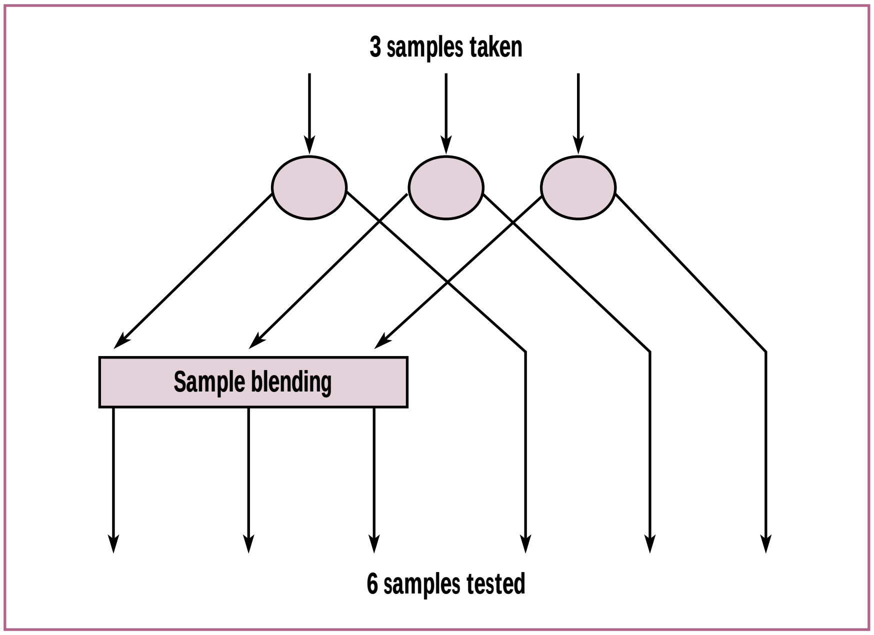
The refiner consistency-control system that was developed is now being used in a TMP mill producing newsprint-quality pulp from a combination of pine, spruce, fir, and hemlock. Chips are screened to remove oversize chips, fines, and knots. The accepts are washed to remove sand and bark. The washed chips are then fed through a high-compression plug screw into a preheater operating at approximately 25 psi. The heated chips are finally fed through a second plug screw into a refiner (Sunds Defibrator RGP 76 CD). This refiner is equipped with a 25,000-hp motor and has both an inner flat refining zone and an outer conical refining (CD) zone. The gaps of both refining zones can be set independently using TDC (true disc clearance) sensors. Refining is performed at approximately 60% consistency, with a target freeness of approximately 350 mL CSF. The pulp passes through a cyclone to separate the steam and then into a secondary refiner. The secondary refiner is also operated at approximately 60% consistency, with a target freeness of approximately 180 mL CSF. The specific energy consumption is 1900–2100 kW·h/a.d. (air dried) metric ton.

The mill has two lines of main-line refiners (Line A and Line B), each of which is operated at 250–300 a.d. metric tons/day. Following each refiner line, the pulp goes to a transfer chest with a 10-min residence time. The contents of each transfer chest are then combined in a common latency chest, which has an approximate residence time of 30 min.

At the beginning of this study, the blow-line consistency from the primary refiner was manually controlled using dilution water added to the chips prior to refining. The refiner design also allows addition of water to both the flat and conical zones, but the mill does not use these dilution points. The secondary refiner blow-line consistency also was manually controlled using dilution prior to the steam-separation cyclone. Like the primary refiner, the dilution points in the flat and conical zones of the secondary refiner are not used.

ANALYSIS OF CONSISTENCY VARIATION

Blow-line consistencies from the primary and secondary refiners in Lines A and B were measured four to six times per day for one year. Analysis indicated that the standard deviation for consistency from the primary refiners was approximately 4.7 units (i.e., 90% of the variation lay within ±9.4 units). The secondary refiners showed a somewhat higher variation



1. Blow-line consistency sampling scheme

	Historical standard deviation	Deviation due to testing variation, %	Deviation due to short-term variation, %
Primary refiners	4.7	10	25
Secondary	6.5	10	35

I. Analysis of blow-line consistency variations

Production rate
Primary preheater pressure
Dilution-water temperature
Primary inlet dilution Primary blow-line dilution
Primary motor load Secondary motor load
Primary inlet pressure Secondary inlet pressure
Primary housing pressure Secondary housing pressure

II. Process variables used in mass and energy balances to calculate theoretical consistencies

at 6.5 units (90% of the variation lay within ±13.0 units).

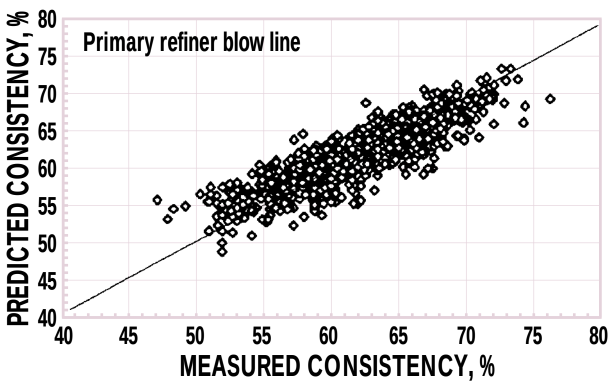
A series of tests was performed to determine the nature of the consistency variations. In these tests, three samples were taken from the blow line in rapid succession. Each sample was then split in two. One set of three splits was blended and then resplit into three new samples. This technique made it possible to isolate the effects of short-term refiner variation from the effects of testing variation. The testing sequence is shown graphically in Fig. 1. Using this sequence, six consistency tests were performed on each set of samples. Twenty sample sets from both the primary and secondary refiners were analyzed, for a total of 240 consistency tests.

The analysis indicated that the testing variation was similar for both the primary and secondary refiners. Testing variation accounted for approximately 10% of the consistency variation. Short-term variation (under 1 min) differed between primary and secondary refiners. In the primary refiners, short-term variation accounted for approximately 25% of the total variation. For the secondary refiner, short-term variation accoun-ted for approximately 35% of the total variation. This difference in short-term variation is consistent with the greater variation in motor load for the secondary refiner compared with the primary refiner, since motor load is the principal cause for short-term consistency variation. The variation in motor load for the secondary refiner reflects the difficulty in feeding as well as sensitivity to variations in fiber consistency from the primary refiner. These results are summarized in Table I.

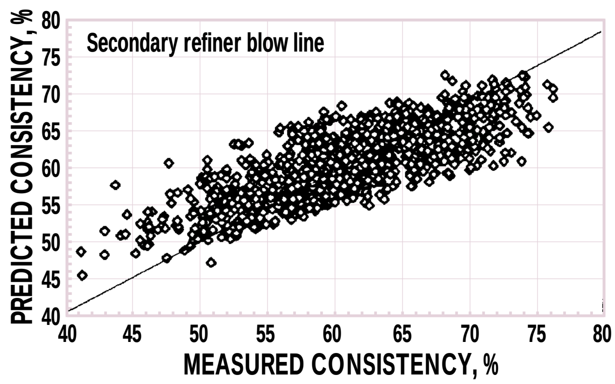
DATA ANALYSIS

The first step in the data analysis was to gather all available process and manual test data. Process data were gathered in the form of 10-min averages. The process data were then merged with manual blow-line consistency tests. Manual tests were performed once every 4–6 hours. Data covering a two-year period were used in the analysis.

The most common technique for analyzing this type of data is some type of regression analysis (such as stepwise multiple linear regression). However, all regression techniques have severe limitations. When the input variables are interrelated—as is always the case in refiner operation—there is no unique solution. The result depends on interpretation. Also by its very design, stepwise regression attempts to limit the number of independent variables that are



2. *Accuracy of factor network model for predicting primary refiner blow-line consistency*



3. *Accuracy of factor network model for predicting secondary refiner blow-line consistency*

to be used in the model. Attempts at using a large number of variables often lead to model instability. Consequently, processes that contain a large number of variables, each with only a subtle effect, are difficult to analyze using conventional regression techniques.

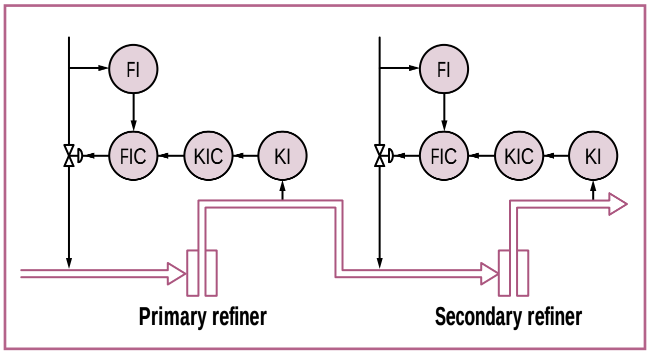
The technique that was used for this study was factor network analysis. This method of analysis is designed to deal with a large number of interrelated variables, exactly the situation where stepwise multiple linear regression is at its weakest. Factor network analysis has been used to analyze a number of pulp and paper processes *(1–4)*, including paper machines, fiber or chip refining, digester operation, wood quality characterization, and bleach plant operation. A further discussion of factor network analysis appears in the appendix at the end of this article.

The factor network model that is used in this system for predicting the blow-line consistency is a combined mechanistic–statistical model as described in an earlier work *(3)*. The model calculations are broken into two parts:

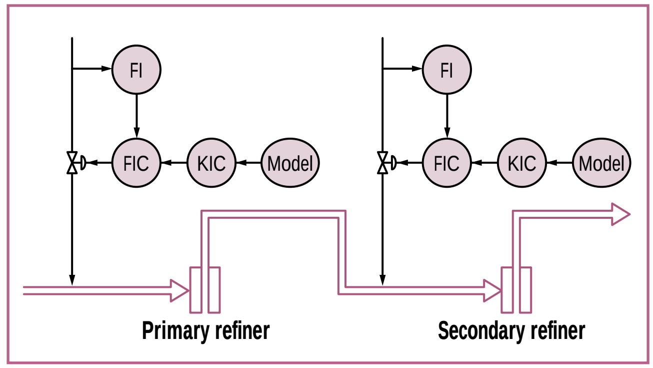
Primary specific energy	Primary theoretical consistency
Secondary specific energy	Secondary theoretical consistency
Total specific energy	(based on the following variables from Table II)
	Production rate
Power split	Primary preheater pressure
	Dilution-water temperature
In-line pulp freeness	Primary inlet dilution
	Primary blow-line dilution
Consistency to latency chest	Primary motor load
	Secondary motor load
Primary CD gap	Primary inlet pressure
Secondary CD gap	Secondary inlet pressure
	Primary housing pressure
Primary flat gap	Secondary housing pressure
Secondary flat gap	
Primary CD temperature	
Secondary CD temperature	
Primary flat temperature	
Secondary flat temperature	
Primary hydraulic pressure	
Secondary hydraulic pressure	

III. *Process variables used in the factor network model for calculating blow-line consistency*

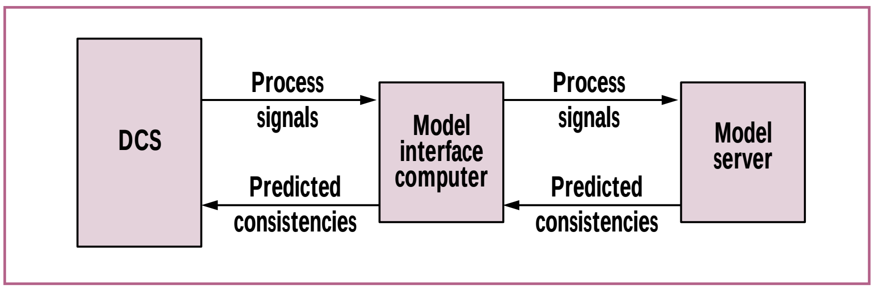
1. In the first stage, process data are used to calculate a theoretical consistency using mass and energy balances. The data used in the mass and energy balances are shown in Table II. Assumptions are made regarding chip moisture, motor idling losses, seal-water leakage, and steam splits.
2. The theoretical consistencies are then combined with additional process data in a factor network model. The data used for calcu-



4. Conventional cascaded refiner consistency-control system



5. Cascaded consistency-control system with model-predicted consistency



6. Physical layout of the refiner blow-line consistency-control system

	Historical standard deviation	Trial-period standard deviation	Reduction in variance, %
A line primary refiner	4.7	3.2	54
B line primary refiner	4.7	3.0	60
A line secondary refiner	6.5	4.5	53
B line secondary refiner	6.5	4.3	57

IV. Reduction in blow-line consistency variation during controlled trial period

lating the blow-line consistencies are shown in Table III.

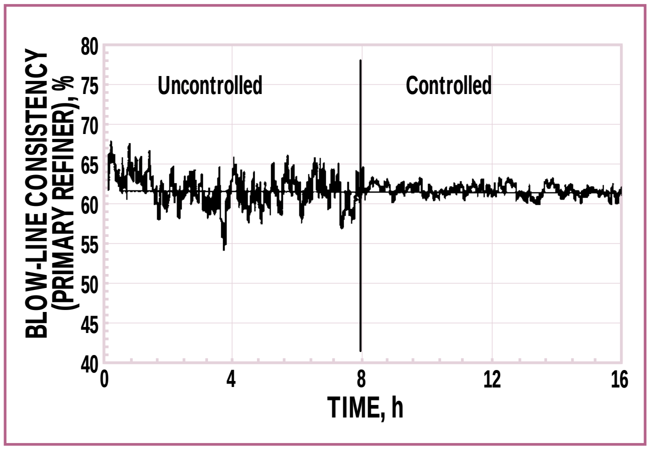
The reason for using two stages of calculations is due to the assumptions that must be made for chip moisture, motor idling losses, seal-water leakage, and steam splits. If these values could be measured on-line in real time, there would be no need for the factor network model. However, since variables such as chip moisture are not being measured on-line, the factor network model is used to compensate the theoretical consistency calculations by measuring changes in variables such as refiner temperatures and hydraulic pressures. The model accuracy for primary and secondary refiners is shown in Figs. 2 and 3, respectively.

CONTROL SYSTEM DESCRIPTION

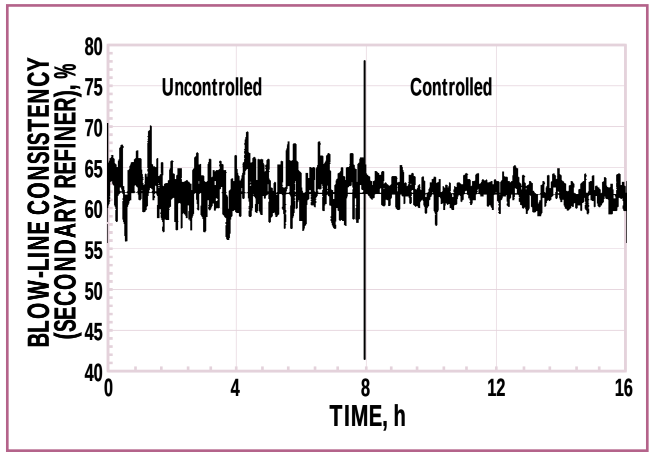
The refiner consistency-control system is similar in design to the conventional cascaded consistency-control system shown in Fig. 4. The blow-line consistency signal is compared against an operator-entered setpoint. A PI (proportional, integral) controller is then used to modify the dilution-water setpoint. The dilution-flow controller (also a PI controller) then modifies the dilution-valve position to achieve the dilution-flow setpoint. There are cascaded consistency controls on both primary and secondary refiners for both refiner lines.

The unconventional part of this consistency-control system is that the blow-line consistency signal does not come from a hardware sensor. Instead, it is a calculated value from the mathematical model, as shown in Fig. 5. The physical layout is shown in Fig. 6. The control interface computer collects data from the DCS (distributed control system) every 30 s. These data are sent via the network to the control server computer. On this computer, the DCS data are used to calculate the blow-line consistency using a factor network model. The predicted consistency is then sent to the control interface computer, where it is uploaded to the DCS.

The goal of this control system is not to remove short-term variation (less than 5 min) in the blow-line consistency, since these variations are mostly filtered out by the transfer and latency chests. Rather, the pur-



7. Controlled and uncontrolled primary blow-line consistency



8. Controlled and uncontrolled secondary blow-line consistency

KEYWORDS
Analysis of variance, consistency, control systems, feedback control, high consistency, measurement, mechanical pulps, models, newsprint mills, on line measurement, paper mills, process control, refiner mechanical pulps, refining, solids content, statistical analysis, thermomechanical pulps.

pose is to remove variations that occur for longer periods (greater than 5 min), which would not be filtered out. For this reason, all consistency predictions are filtered using an exponential filter with a 3-min time constant. This means that the shorter-term variations that were identified through rapid consistency testing (Table I) are not controllable using this system.

CONTROL SYSTEM RESULTS

After the refiner consistency-control system was implemented and tuned, the system's stability was evaluated. The predicted consistencies for the primary and secondary refiners in Line A are shown in Figs. 7 and 8, respectively. During the first period of operation, the blow-line consistency was uncontrolled. When the refiners were placed under consistency control, approximately 80% of the predicted variation in blow-line consistency was removed from the refiner operation.

Blow-line consistency was then monitored over two five-day periods. Manual consistency measurements were taken from blow lines once every two hours. A total of 155 consistency measurements were performed. Consistency targets were set to 62% for the primary and secondary refiners for both refiner lines. The variations in the blow-line consistencies during these trial periods are shown in Table IV. These numbers are consistent with the earlier tests that identified 35–45% of the variation in blow-line consistency as being either short-term variation or tester error (Table I). The remaining variation (55–65%) that is controllable is essentially removed using the control system, as seen in Table IV.

Consistency variations were also analyzed on a weekly basis covering a four-month period. During this time, variation in the primary refiners dropped by approximately 45%, while variation in the secondary refiners dropped by 26%, as shown in Table V. It is difficult to establish the exact reduction in variation, since the consistency setpoints are changed by the operators to adapt for changing raw materials, plate condition, etc. The reduction in variation from the primary refiner is probably fairly accurate, since the operators do not make many changes outside the 60–62% consistency range. However, the setpoint of the secondary refiner is changed more often by the operators and over a much wider range.

One of the primary reasons for having consistency control on high-consistency refiners is to avoid dry cutting. Dry cutting occurs when there is insufficient water to flexibilize the fibers during refining, so that fiber breakage occurs rather than fiber development. The point at which dry cutting occurs differs depending on raw material, plate condition, etc. For the refiners and raw materials used by this mill, consistencies greater than 65% exhibited increased tendency towards dry cutting.

At the same time, high consistency is desirable because it makes the refiner easier to load and increases the plate gaps at a given specific energy. It is thus the goal of any consistency-control system to maintain high consistency while minimizing excursions over the point of dry cutting. During the trial

	Historical standard deviation	Trial-period standard deviation	Reduction in variance, %
Primary refiner	4.7	3.5	45
Secondary refiner	6.5	5.6	26

V. Reduction in weekly blow-line consistency variation over four months

	Historical average consistency	Trial-period average consistency	Reduction in measured consistencies >65%, %
Primary refiner	60.7	60.6	34
Secondary refiner	60.6	60.5	38

*Consistencies above 65% typically lead to dry cutting and subsequent fiber damage

*VI. Reduction in measured consistencies greater than 65%**

four-month period, the consistencies were maintained at pretrial levels (approximately 61%) while reducing the measured excursions over the point of dry cutting (>65% consistency) by 35%. This information is summarized in Table VI.

DISCUSSION

Based on these results, a number of changes have occurred at the mill. First, the operators have decided to quit taking manual tests of the blow-line consistencies. Instead, the operators visually check the blow-line consistencies on a regular basis to confirm that the model predictions are tracking actual blow-line consistencies.

Secondly, the consistency control is being integrated by the operators with a newly purchased pulp-quality monitor, which measures freeness, fiber size distribution, and shive content on-line. The combination of the consistency-control system and the on-line pulp-quality measurement system allows the operators to monitor and control fiber size distribution from the mainline refiners with greater accuracy. This has allowed the paper machine to eliminate the use of costly kraft as a reinforcement furnish on some grades. With the present cost and availability of kraft, this has produced significant cost benefits for the mill.

Closed-loop control of freeness and long fiber was implemented on both refiner lines in June 1996. This control system distributes energy among the four refining zones to achieve the targets for long fiber and freeness. The system adapts to the changing conditions of all plates and chip quality while minimizing the specific energy required to maintain pulp quality.

CONCLUSIONS

A consistency-control system has been successfully implemented on two TMP production lines within one mill, with each line comprising two-stage high-consistency refiners. However, this system does not use an on-line sensor to measure blow-line consistency. Instead, the system uses a factor network model to predict blow-line consistencies from both the primary and secondary refiners.

The control system has reduced consistency variation by about 35%. Operator confidence in the control system is evidenced by their cessation of manual consistency measurements. Integrating the consistency-control system with on-line pulp-quality measurements has increased operator control of the pulp's fiber length. As a result, the paper machine no longer needs to use kraft pulp as a reinforcement furnish, resulting in significant cost benefits. TJ

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APPENDIX

The first step in factor network analysis is based on the traditional multivariate analysis method known as factor analysis. Factor analysis—a data-reduction technique that can be used to analyze a large number of interrelated variables—has two primary goals:

1. To determine how many significant independent properties actually exist in an interrelated data set. Factor analysis does this by examining the degree of correlation among variables. The number of common factors is always less than the number of variables analyzed; and, if there is a high degree of correlation among the variables, the number of common factors required will be small.
2. To take variables with common variation and combine them to form "composite" variables. These composite variables are a mathematical representation of the independent properties that underlie the raw data. These common factors are orthogonal (i.e., 100% independent) by definition.

The form of the equations used to calculate these common factors are:

$$\text{Factor}_1 = a_{1,1}\ \text{Variable}_1 + \ldots + a_{1,n}\ \text{Variable}_n \quad (1a)$$

$$\text{Factor}_2 = a_{2,1}\ \text{Variable}_1 + \ldots + a_{2,n}\ \text{Variable}_n \quad (1b)$$

$$\text{Factor}_k = a_{k,1}\ \text{Variable}_1 + \ldots + a_{k,n}\ \text{Variable}_n \quad (1k)$$

where

Factor_i = the ith common factor
$a_{i,j}$ = model coefficients.

Factor analysis determines the degree of correlation between each variable and each common factor. These correlation coefficients are called the factor loadings. The constants $a_{i,j}$ in Eqs. 1a–1k are determined from the factor loadings. There are many methods for determining the factor loadings. However the chosen method is one that offers the most meaningful interpretation of the common factors.

The common-factor model can then be used to express each variable in the terms of these common factors (Factor_i):

$$\text{Variable}_1 = b_{1,1}\ \text{Factor}_1 + \ldots + b_{n,k}\ \text{Factor}_k \quad (2a)$$

$$\text{Variable}_2 = b_{2,1}\ \text{Factor}_1 + \ldots + b_{n,k}\ \text{Factor}_k \quad (2b)$$

.

$$\text{Variable}_3 = b_{3,1}\ \text{Factor}_1 + \ldots + b_{n,k}\ \text{Factor}_k \quad (2n)$$

where

$b_{i,j}$ = constants.

These two sets of equations (Eqs. 1a–1k and Eqs. 2a–2n) describe the interrelationships among the variables through the use of a small number of completely independent common factors. For a given set of data, there exists an infinite number of different factor loadings.

The factor network models can be used in two different modes: filter mode or input/output mode. In filter mode, both the input variables (what a statistician would call "independent" variables) and output (or dependent) variables are used to calculate the common factors (Eqs. 1a–1k). This mode is used to remove variation in the data that are not common to multiple variables. This method, called "single sample filtering," is often used for removing random testing variations from pulp and paper quality tests.

In input/output mode, only the input variables are used to calculate the common factors (Eqs. 1a–1k). This mode is most commonly used in developing models that perform on-line predictions of variables that cannot normally be measured on-line. However, when using input/output mode, there is one point that must be always kept in mind. It is easy to view input/output-type models in the same way a statistician would, i.e., to imagine that this model was built by independently perturbing the input variables and measuring the response of the output variables. This type of model can be used for optimization, feed-forward control, etc.

The data that are usually analyzed by factor network analysis contain interrelated input data, i.e., the input data are highly correlated to each other. Often this correlation among the input variables exists because of process design and/or process control strategies. If a factor model is built with interrelated input data, but is used as if the input data are independent, the predicted results can be erroneous.