Dynamic behavior of a pulp processing and reject refining plant

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ABSTRACT

There has been a very rapid and substantial increase in the use of computer simulation in the pulp and paper industry in recent years. In particular, dynamic simulation has been recognized as a valuable tool for process optimization, process control, and operator training.

In this paper, we discuss the dynamic behavior of the pulp processing part of a CTMP plant. Simulations of the effects of disturbances (feed stock consistency, freeness, shive content, fiber fractions) and operating conditions (screen reject rates and reject refiner specific energy) on the final pulp quality are performed and discussed. Pulp freeness, long fiber fraction, shive content, and consistency are used to describe the pulp quality.

In a CTMP or TMP plant, following wood chip refining, the plant comprises a series of unit operations aimed at enhancing and controlling pulp quality. These unit operations are: latency chest to remove latency and straighten fibers; screens to remove debris, shives, long stiff fibers, and other undesirable materials; reject refiners to further refine debris and shives while fibrillating long stiff fibers; and/or cleaners to remove dirt, low specific surface fibers, and heavy contaminants.

Despite the importance of screening and reject refining on the final pulp properties, very little attention has been paid to the dynamic behavior and control of this part of the mill. A dynamic simulator has thus been developed, and simulations of the effects of feed disturbances and operating conditions on the final pulp quality have been performed. Pulp freeness, long fiber fraction, and shive content are used to describe the pulp quality, as they can be measured on-line. Since pulp consistency has a significant effect on the operation of screens and reject refiners, it was also included in the model.

The 325 metric tons/day screening system used in this work consists of a typical two-stage screening with one-stage reject refiner. The accept from the primary screen is sent to the decker, and the secondary screen stage concentrates the shives rejected by the primary stage. The accept from the secondary screen is recycled to the primary screen, while the reject from the secondary screen is further treated via reject refining and reject screening (**Fig. 1**).

MODELING AND SYSTEM DYNAMICS

In an industrial screening and reject refining plant, surge tanks are used to provide flexible operation of the plant. Screening is a very fast process in comparison to tank dynamics. When accept or reject valves are manipulated, the resulting stock flows responding to the valve setting can be described as a first order system with a time constant of a few seconds and minimal time delay. The screen dynamics can be attributed to a combination of the response of the flow control valve and the effects of changes in fiber mat consistency or thickness at the reject side of the screen plate. The time constants of the tanks, on the other hand, are in the order of ten minutes or more. It is thus appropriate to assume that the dynamics of the screens can be neglected when studying the dynamics of the whole pulp processing plant. A complete description of the mathematical models developed for each process unit can be found in Qian (*1*).

Tanks

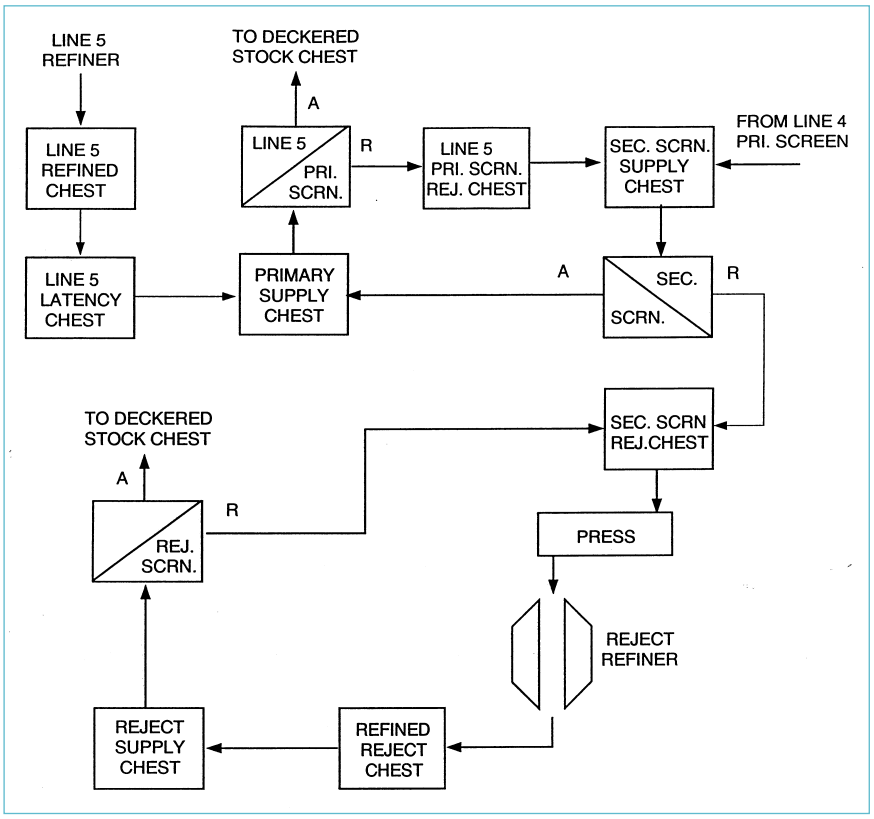
When modelling surge tanks, perfect mixing was assumed and mass balances were used to predict consistency, long fiber fraction, and shive content. Freeness, on the contrary, is not a conservative property, and empirical equations must be used. There are very few studies about freeness of pulp blends, but Partanen and Koivo (*2*) have showed that the logarithm of freeness can be used to model the relation between the freeness of the blend and the freeness of the pulps being blended. Therefore the following equation was proposed for modelling the outlet freeness from a perfectly mixed tank:

$$\frac{d\ln(CSF_o)}{dt} = \sum_{i=1}^{n} \frac{F_{in,i} \bullet C_{in,i}}{V \bullet C_o} \left[\ln(CSF_{in,i}) - \ln(CSF_0)\right] \quad (1)$$

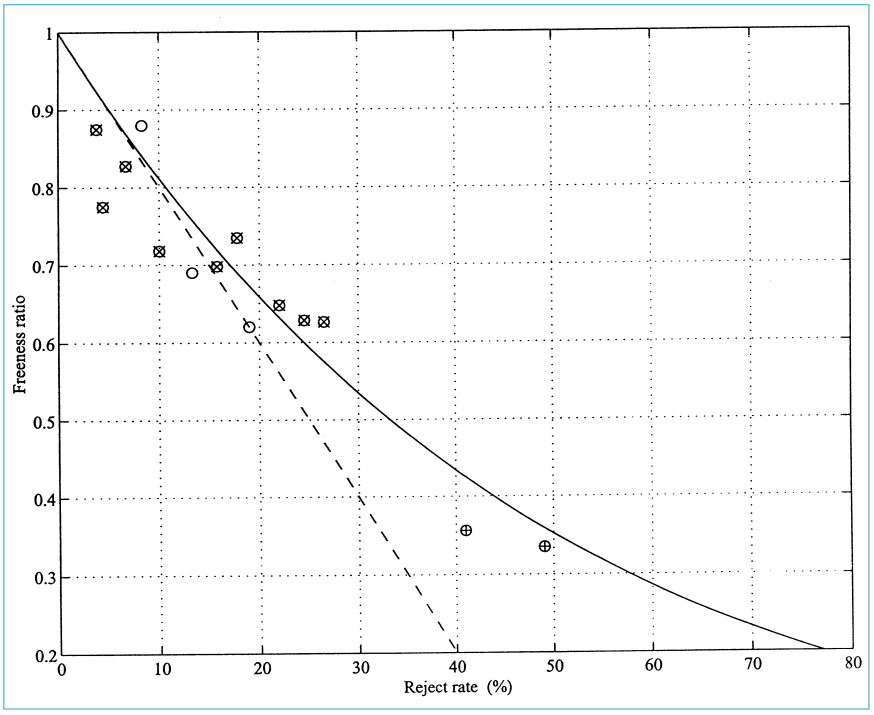
Latency chest

Pulp produced at high consistency refining conditions contains aggregates of twisted and kinked fibers and shows high freeness and poor physical properties. If the pulp is diluted at temperatures above 60°C for at least 20 minutes in the latency chest, the lignin hemicellulose structure softens and the stress in the cellulose, called latency, is removed.

To achieve the dual objectives of long residence time and good mixing, dams are usually put inside the chest to prevent by-pass, and agitation is applied to enhance mixing at



1. Flowsheet of the pulp screening and reject refining process.



2. Freeness ratio versus reject rate.

the inlet of the chest. The flow pattern in a latency chest can be seen as a perfect mixed flow followed by plug flow. The residence time associated with the perfect mixing and plug flow region depends on the design and operation of the latency chest. Our tracer response tests showed a typical ratio of 20% mixing and 80% plug flow.

As the main objective of a latency chest is to remove latency, special attention has to be paid to the modelling of pulp freeness. It was observed by Mohlin (*3*) that the drop in freeness was fairly constant for pulps having a freeness greater than 100mL when latency is completely removed. So with respect to pulp freeness, the latency chest can be modelled by a perfectly mixed tank in series with a plug flow and followed by a constant drop in freeness:

For the perfectly mixed region of the latency chest, an equation similar to the one developed for tanks was used.

For the plug flow region:

$$CSF_{PF,o}(t) = CSF_{PF,i}(t - \tau) \quad (2)$$

and, for the freeness drop:

$$CSF_{LC,o} = CSF_{PF,o} - CSF_{\delta} \quad (3)$$

Pulp screens

The purpose of screening is to remove undesirable materials such as shives, large fiber bundles, and grits. To characterize the performance of a screen, two parameters are commonly used. They are the "efficiency", E and the "reject rate", R. The screen performance equation based on the plug flow model (*4*) was used to calculate the shive removal efficiency from the reject rate:

$$R^{\beta_{SV}} = \frac{P_r \bullet C_r \bullet SV_r}{P_f \bullet C_f \bullet SV_f} \quad (4)$$

Although the above equation was developed for shives, similar equations can conceptually be used to describe fiber fractionation (*5*). For long fibers, the following equation relating reject rate to the long fiber

removal efficiency was used:

$$R^{\beta_{LF}} = \frac{P_r \bullet C_r \bullet LF_r}{P_f \bullet C_f \bullet LF_f} \qquad (5)$$

For a good performance screen, the screen quotient, β_{SC}, will have a value close to zero, while the screen quotient for short fibers and fines will be close to one. The values of β_{SC} and β_{LF} for any particular screen can be obtained from the fiber fractions in the reject and feed streams. In our simulations we used a value of 0.94 for β_{SC} and 0.87 for β_{LF}.

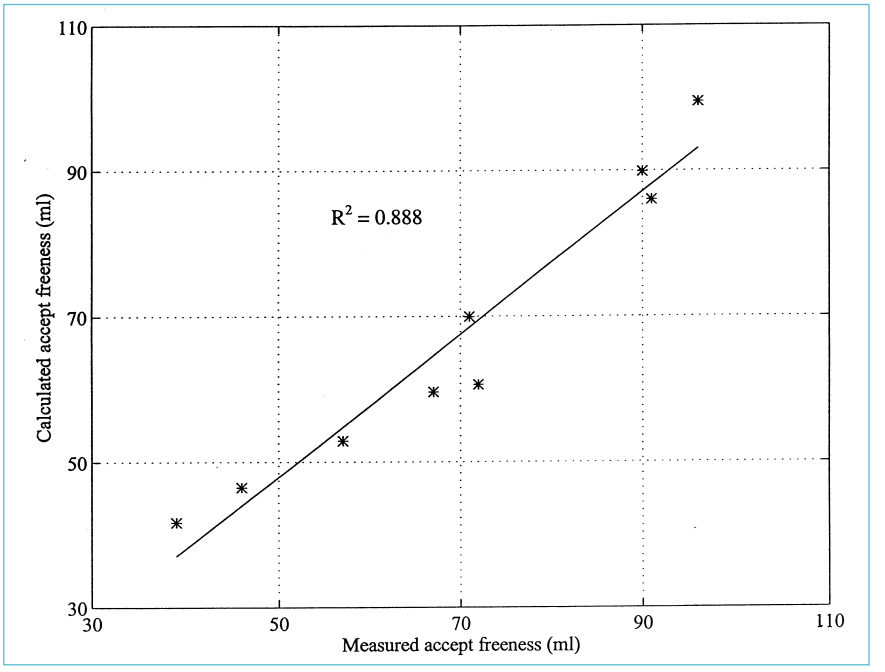
Apart from shive removal and fiber fractionation, another variable of interest is the pulp consistency and how it changes through a screen. Gooding and Kerekes (*6*) have investigated the consistency drop and reject thickening of the pressure screen under different reject ratios, R_v. Their model was used for predicting the consistency change through a screen. The reject thickening factor and consistency drop are given by the following equations respectively:

$$T_{rej} = R_v^{(P-1)} \qquad (6)$$

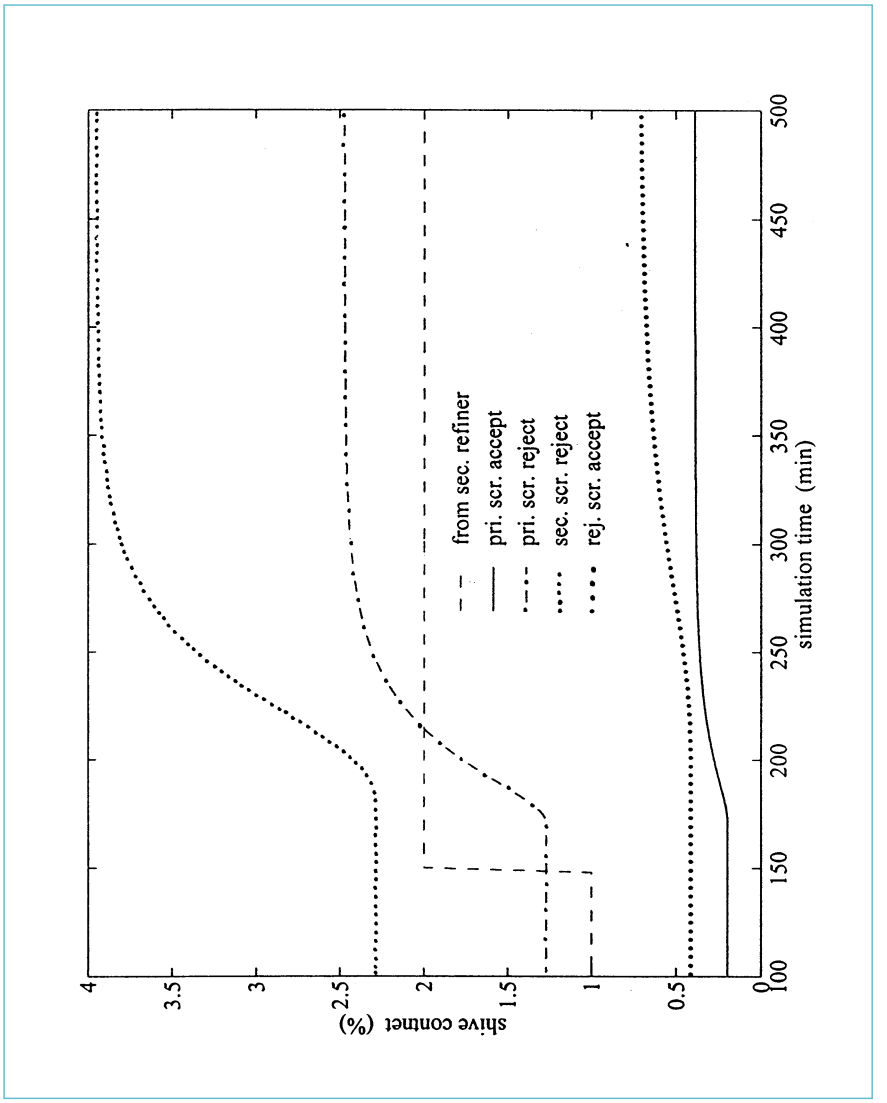
$$D = \frac{R_v^{P} - R_v}{1 - R_v} \qquad (7)$$

In addition to shive content and fiber fractions, freeness was chosen to characterize pulp in the screening process since on line measurement of freeness is commonly used in the industry.

A model was thus needed to calculate freeness of the accept and reject stock from freeness of the feed stock and operating conditions of a screen. Since pulp freeness is not a conservative property, the effect of splitting or mixing of pulp streams



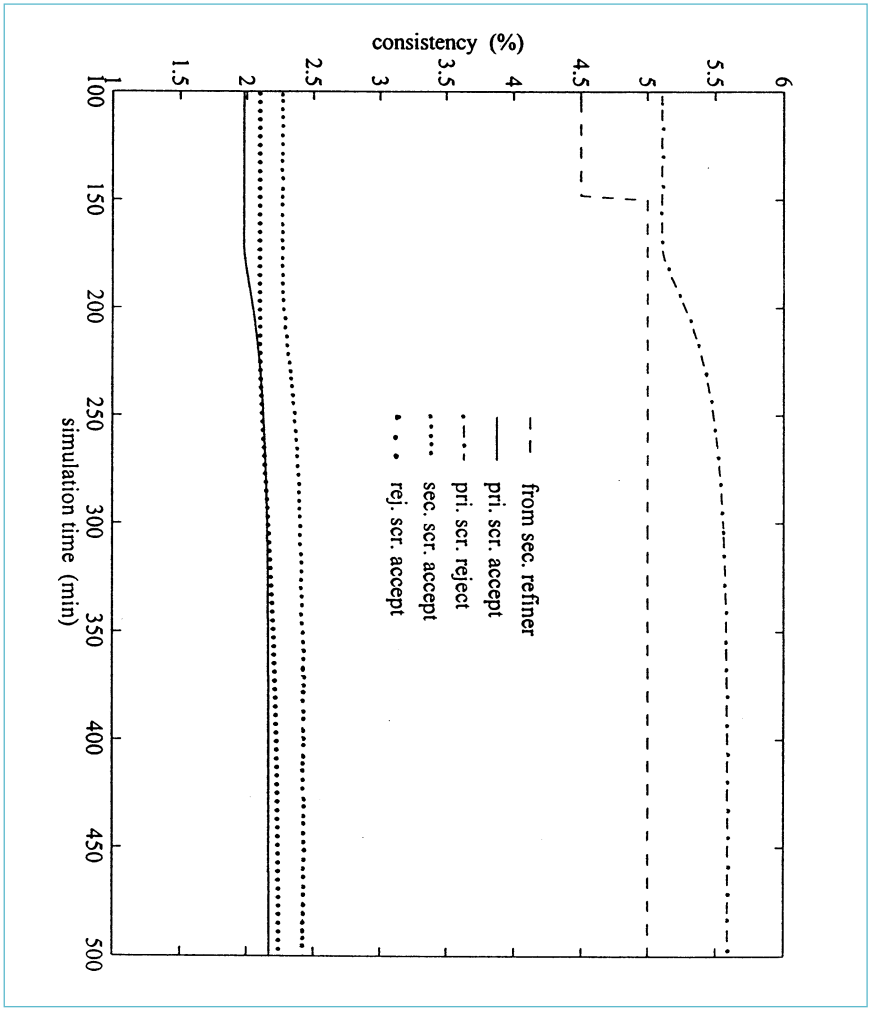
3. Predicted versus measured accept freeness.



4. Reponses to a step change in shive content from the main line refiner discharge.

	Freeness, mL	Consistency, %	Shives, %	Long fibers, %
Feed				
Mill data	111.0	4.22	0.20	46.4
Accept				
Model	43.4	2.43	0.056	27.9
Mill data	41.0	2.88	0.06	20.3
Reject				
Prediction	296.7	6.04	0.279	55.9
Mill data	287.0	6.73	0.34	53.7

I. Mill data vs. results of a steady-state simulation.



5. Responses to a step change in consistency from the main line refiner discharge.

on freeness is not clear. In order to predict the accept flow freeness from the feed flow freeness over a wider range of reject rates, we have derived the following relationship from mill data (**Fig. 2**):

$$\frac{CSF_a}{CSF_f} = e^{-2.08 \times R_s} \qquad (8)$$

Figure 3 shows the agreement between the model predictions and accept freeness data collected at the mill and from the literature.

Assuming that the freeness of pulp streams into and out of a screen follow the rule proposed by Partanen and Koivo (*2*), the following equation can be derived:

$$P_f \bullet C_f \bullet \ln CSF_f = P_a \bullet C_a \bullet \ln CSF_a + P_r \bullet C_r \bullet \ln CSF_r \qquad (9)$$

Combining the two previous equations gives the following expression between the reject freeness and feed freeness:

$$\frac{CSF_r}{CSF_f} = e^{2.08x(1-R_s)} \qquad (10)$$

Reject refiner

The task of the reject refiner is to reduce shives and to further fibrillate long fibers. A mathematical model similar to the one developed by Qian and Tessier (*7*) for main line refiners is used to predict the pulp properties from the reject refiner operating conditions.

SIMULATIONS

First, a steady state simulation of the primary screens was performed and the simulation results compared to mill data to validate the screen model. **Table I** shows the good agreement between the model predictions and the mill data. Then, dynamic simulations have been carried out to investigate the impact of feed disturbances and operating conditions on the pulp processing plant behavior.

Dynamic responses to a change in feed shive content

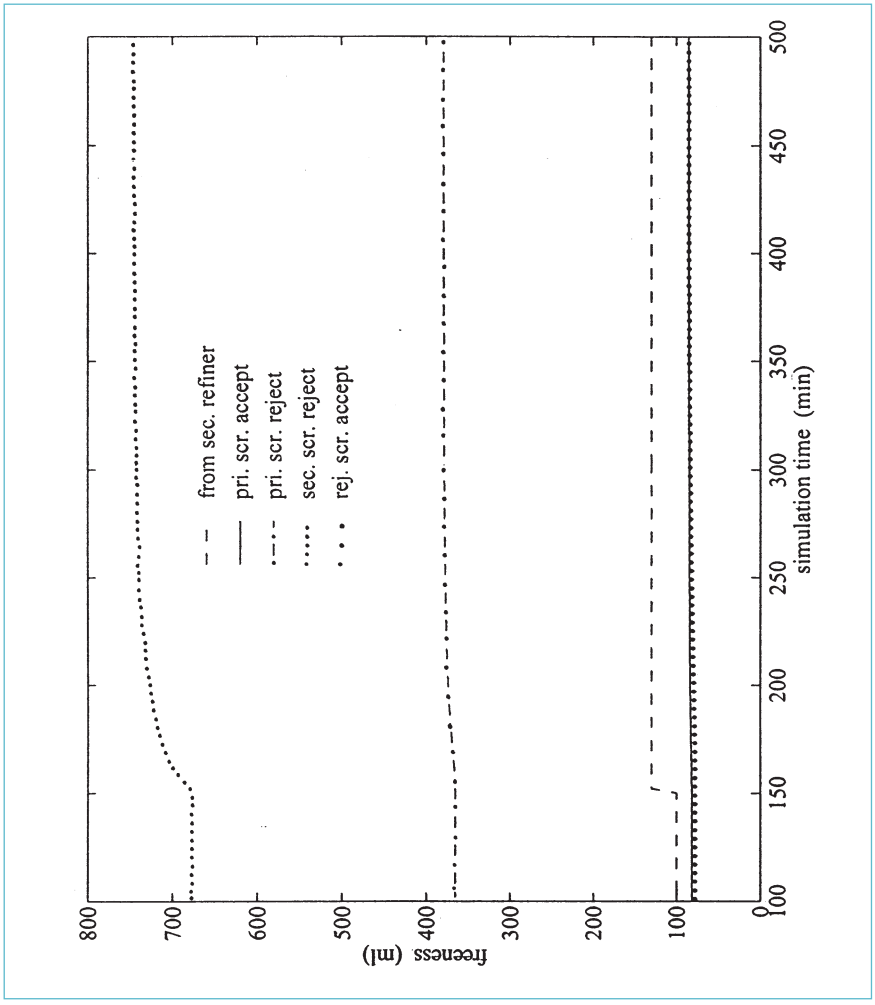
Figure 4 shows the dynamic response of the plant to a step change in shive content from the main line secondary refiner discharge. The system starts from steady state. After 150 min, the shive content from the secondary refiner discharge was changed from 1.0% to 2.0%; the other operating conditions remaining the same. The change in shive content showed up in the primary screen accept and reject after a delay of about 20 min, because of the latency chest. The shive content in the primary screen accept increased from 0.20% to 0.39%, while the reject line shive content increased from 1.27% to 2.47%. The secondary screen reject showed an increase

from 2.29% to 3.95% in shive content. Because of the transportation delays and the intermediate tanks, the response of the secondary screen reject was slow. The response of the reject screen accept was even slower than the secondary screen reject because of the loop between the reject refiner and the reject screen. The reject screen accept took about 250 min to reach 99% of a new steady state.

Dynamic responses to a change in feed consistency

Figure 5 shows the dynamic response of the plant to a change in consistency from the secondary refiner. When the consistency was changed from 4.5% to 5% at 150 min, the consistency in the primary screen accept and reject started increasing after a delay of about 20 min. The consistency of the primary screen accept increased from 2.0% to 2.2%, and the consistency of the primary screen reject increased from 5.1% to 5.6%. The response of the secondary screen and reject screen is slow because of the recycle loop; the accepts of the secondary screen and the reject screen took about 150 and 250 min respectively to reach their new steady state.

The effect of the change in consistency on the shive content at different locations was also simulated. When the consistency from the refiner chest was increased, the effect on the primary screen accept shive content was almost unnoticeable. However, there was a slight change in the shive content of the primary screen reject. The shive content in the primary reject was 2.56% before the consistency change and increased to 2.63% after the consistency change. The shive content in the secondary reject increased from 3.79% to 3.86% after the consistency change.



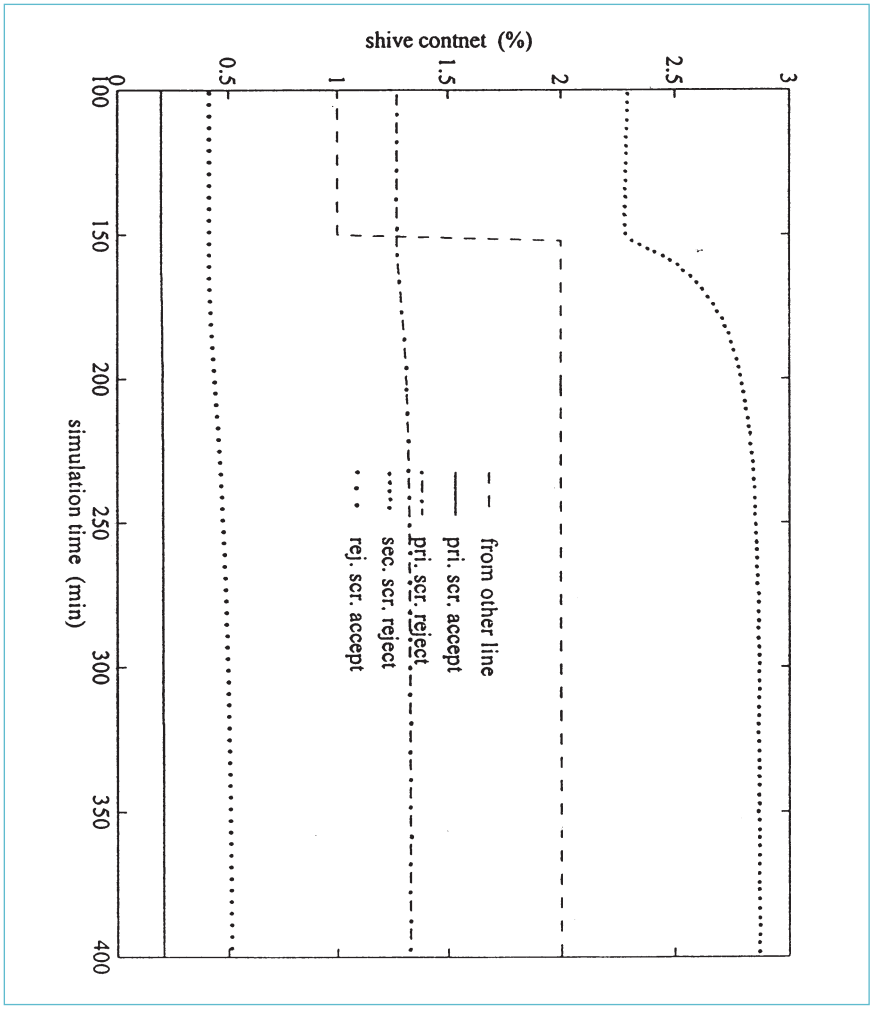
6. Responses to a step change in freeness from the main line refiner discharge.

Dynamic responses to a change in feed freeness

The dynamic response to a freeness change from the secondary refiner is shown in **Fig. 6**. A step change in freeness occurred after 150 min. The responses were quite similar to those of the shive content and consistency because the dynamic behavior of the system is dominated by tanks and transport delays. It should be noticed that a step change of freeness of 20 mL from the secondary refiner caused a change of 56 mL in the primary screen reject and a change of 16 mL in the secondary screen reject. The freeness of the primary screen and reject screen accept changed by 12 mL and 7 mL, respectively. In this simulation, we only studied the open loop performance of the process. A well-tuned freeness controller would further reduce the freeness variability of the reject screen accept.

Dynamic responses to a change in shive content from another line

The dynamic response of the plant to a change in shive content in the pulp from another refiner line is shown in **Fig. 7**. A step change from 1% to 2% in shive content in one of the other pulp streams feeding the secondary screen supply chest took place after 150 min. It can be seen that most shives were rejected by the secondary screen and treated in the reject refiner. The final pulp quality as indicated by the shive content in the primary and reject screen accept was barely affected; there was almost no change in the primary screen accept and a change of only 0.1% in the reject screen accept. It was also shown that the reject screen accept responded to the disturbance much slower than all the other streams. It took about 150 min to reach a new steady state. Here again, the dynam-



7. Responses to a step change in shive content from another line.

ics is mainly determined by the reject screen and reject refiner loop. When the shive content in the secondary screen reject increases, the shives start to accumulate in the loop between the reject refiner and reject screen if the refiner operating conditions are kept constant.

The dynamic response of consistency and freeness to a disturbance from another refiner line is similar to what has been shown for the shive content. Since the dynamics of the system is determined by the reject screen and reject refiner loop, the response of shive content, long fiber fraction, consistency, and freeness to a disturbance have a similar behavior.

Dynamic responses to a change in reject refiner specific energy

Figure 8 shows the shive content in pulp streams as affected by the reject refiner specific energy. At 150 min time, there was a negative step change in the specific energy of the reject refiner from 3.9 to 3.4 MJ/kg. The shive content after the reject refiner immediately responded with a jump followed by a slow change. The effect was also seen in the reject screen rejects. More shives from the reject screen were recycled to the reject refiner. This effect kept growing since the system acted as a positive feedback system. It would eventually reach a new steady state, but after a long time period. In some cases, the shives in the reject refiner and reject screen loop could build up.

In practice, the screen plant operator who would have reduced the reject refiner specific energy as shown above, would have no choice but to reverse his decision by increasing the specific energy of the reject refiner or decreasing the reject rate of the reject screen. The latter approach would apparently deteriorate the final pulp quality since more shives would be accepted by the reject screen.

Dynamic responses to a change in primary screen accept flow rate

Figure 9 shows the shive content in different streams along the process when the primary screen accept flow rate was changed by 7.6% from 5400 to 5810 L/min and the reject refiner motor load was kept constant. When the primary screen accept flow is increased by 7.6%, the reject rate of the primary screen decreases from 51% to 45%, and the shive content in the accept stream increases from 0.2% to 0.22%. Although the shive content in the secondary screen reject increased from 2.3 % to 3.1%, the total shives rejected by the secondary screens decreased by 5% from 1.64 to 1.56 because of the decrease in total reject flow. For the same refiner specific energy, the shive content in the reject screen accepts was reduced from 0.41% to 0.36%. It was also found that the shive content at the decker changed from 0.276% to 0.260%.

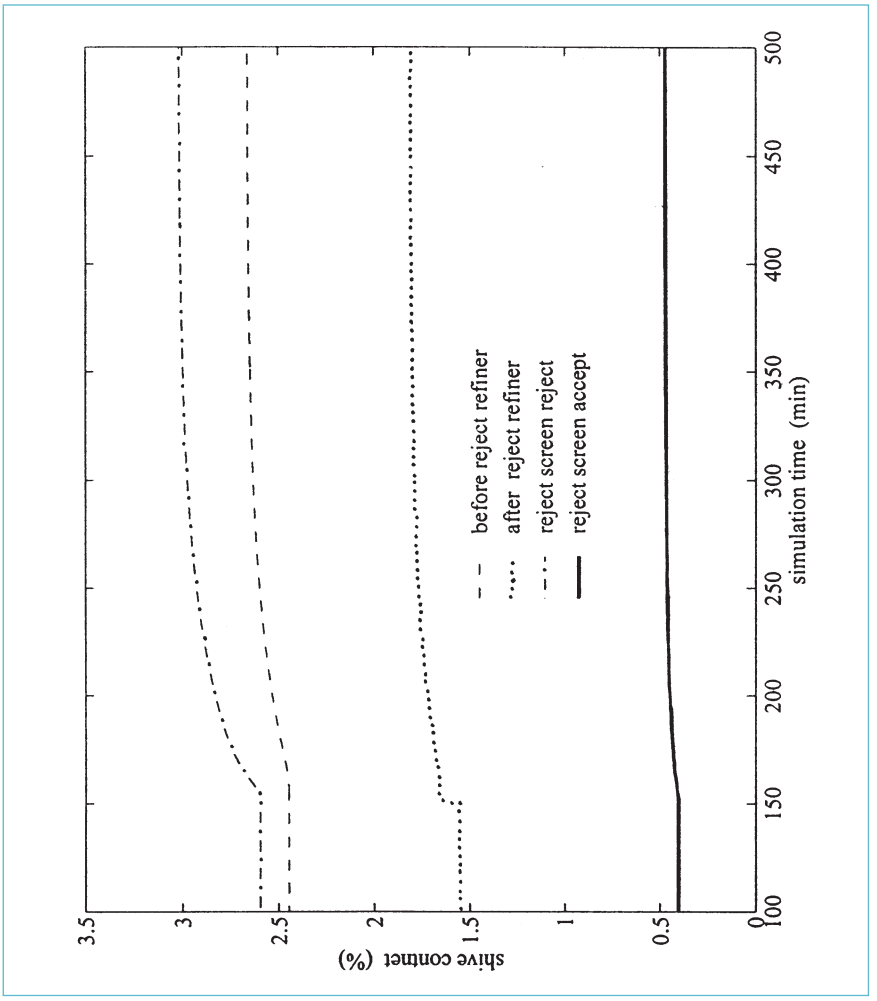
Pulp and handsheet properties along the process

Figure 10 shows the simulated pulp properties (freeness, long fiber fraction, and shive content) at different locations along the process. The shive content is much higher in the secondary screen reject. However, after refining, the shive content is reduced to a level of about 0.38%.

It was also found that that the same pulp quality can be achieved at the decker under different operating conditions. This warrants further studies on the optimization of the screening and reject refining systems.

The multiple linear regression models developed by Qian and Tessier (*6*) were used to relate the fiber characteristics (freeness, shive

content, and long fiber fractions) to the handsheet properties (tensile index, burst index, tear index, and scattering coefficient). **Figure 11** shows the tensile index, tear index, burst index, and specific scattering coefficient at different locations of the process. The reject stream from the secondary screen has a low tensile, tear and burst index, and a low specific scattering coefficient. This is because of the high freeness and high shive content at this point. The pulp at the outlet of the decker has a low freeness and a low shive content. Although the long fiber fraction at the decker is lower than in the pulp entering the latency chest, it has been fibrillated in the reject refiner, resulting in an improvement of the handsheet properties. Tensile, tear, burst, and specific scattering coefficient of the pulp at the decker are higher than for the pulps entering the screening and refining plant.



8. Effect of the reject refiner specific energy on shive content.

RESULTS

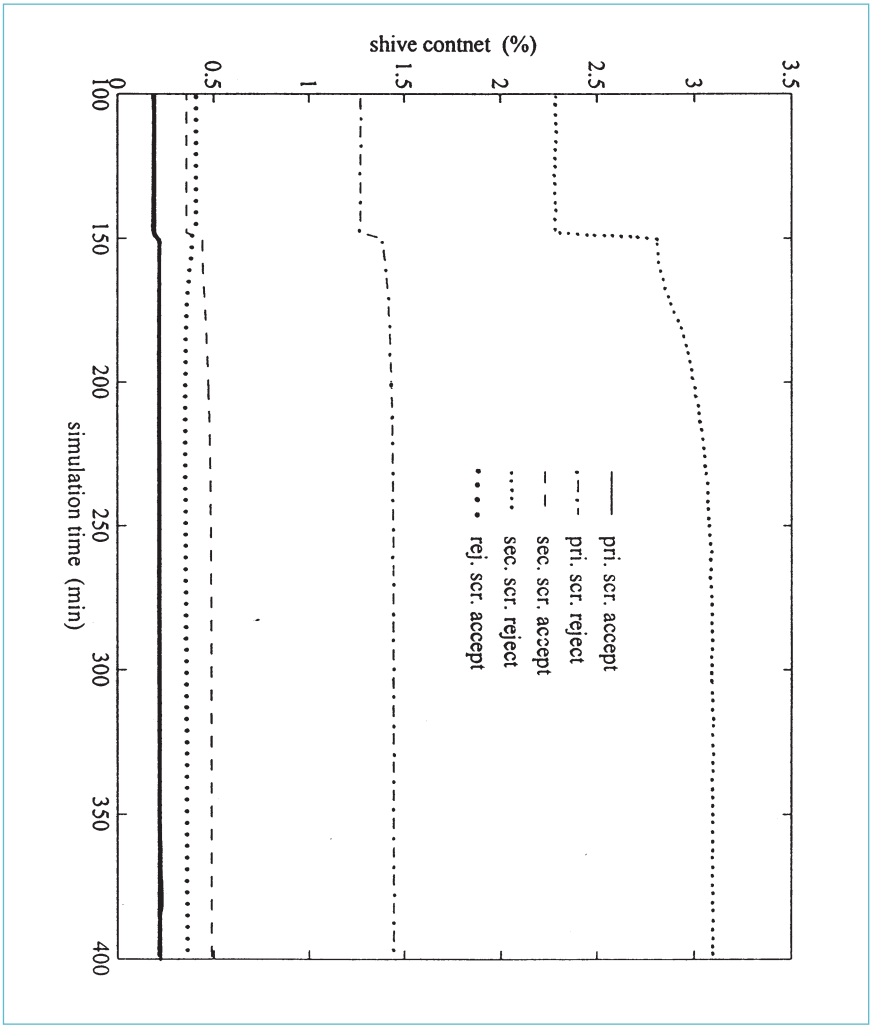
Although the above simulations were developed for a 325-metric ton/day pulp processing plant, the dynamic simulator can easily be modified to incorporate changes in process configuration or operating conditions, and other scenarios can be investigated.

The simulations showed that a proper operation of the reject screen and reject refiner and a full coordination of reject screen and reject refiner are crucial in controlling the decker pulp quality. A low level of specific energy in the reject refiner would probably cause shives to become a "dead load." While the reject screen reject rate could be modified to eliminate the problem, pulp quality would be sacrificed as more good fibers will be sent to the reject refiner and be unnecessarily shortened. On the other hand, a higher specific energy than necessary would reduce the pulp strength and waste energy.

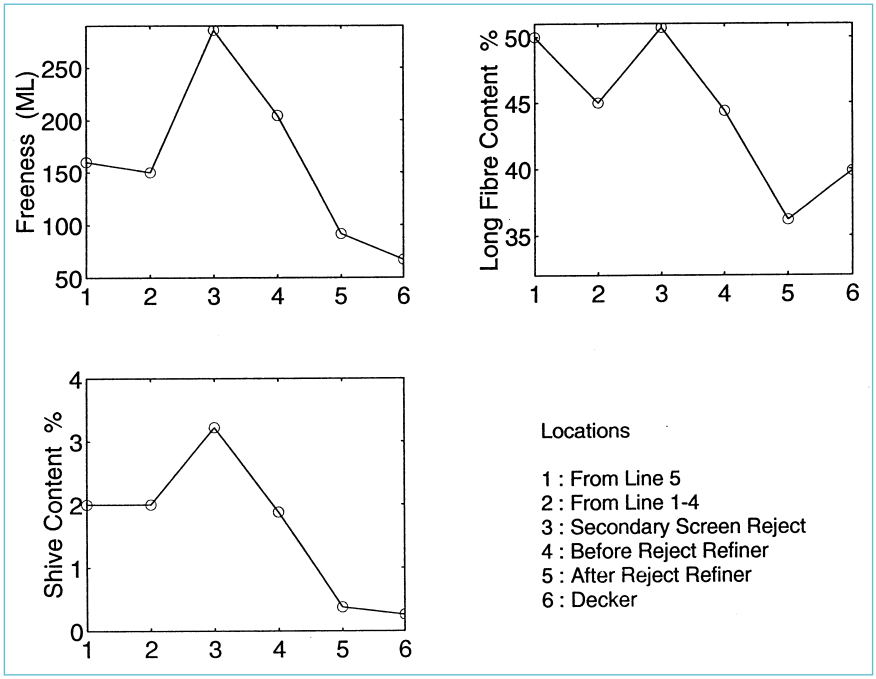
We also learned that in the operation of a screening and reject refiner process, localized control of each operation unit does not necessarily achieve the best performance of the whole process because of the interactions between the different units. For example, increasing the screen reject rates produces cleaner pulp, but more stock needs to be circulated through the process. In doing so, higher capacity screens, larger tanks, and bigger pumps are needed, translating into higher capital cost and energy consumption. Operating strategies must find the best compromise between cost reduction and product quality. The optimization of the process involves not only material flow rates but also the knowledge of how the properties of the product change as operating conditions are changed. The models in this work predict the pulp properties from the operating conditions and can be used when optimizing process operations.

CONCLUSION

Mathematical models for the pulp processing process in a CTMP plant have been developed. In the models, pulp consistency, shive content, long fiber fraction, and freeness are used to describe the pulp properties along the process. The dynamic responses to the variations in properties of pulps entering the process were simulated. In this process, the dynamics are dictated by the tanks, the transportation delays, and most importantly by the recycling loops. Simulations of the impact of the manipulated variables on the pulp properties exiting the process were also carried out. Under normal operation, a small change in consistency does not have significant effect on the shive content, fiber fractions, and freeness of the pulp at the decker.



9. Effect of primary screen accept flow rate on shive content.



10. Pulp properties.

For the operation of the screens, however, consistency is an important variable that should be carefully controlled because higher consistency may cause the screen to blind while a low consistency will reduce the screen efficiency. The reject rate of each screen should be used to control the final pulp properties. In practice, it may be difficult to control them independently due to the limitation of the surge tank volumes. The reject refiner specific energy is critical since it has the most important impact on the final pulp properties.

The relationship between pulp properties and handsheet properties were also used to predict the handsheet properties along the pulp processing process. It was found that pulp strength and light scattering coefficient was improved through screening and reject refining. The light scattering coefficient was increased from about 675 cm^2/g for the unscreened pulp to 750 m^2/kg for the screened pulp at the decker. The tensile index increased from 28 to 37 Nm/g, the burst index from 2.1 to 2.6 $kPa \cdot m^2/g$ and, the tear index from 6.2 to 6.5 $mN \cdot m^2/g$.

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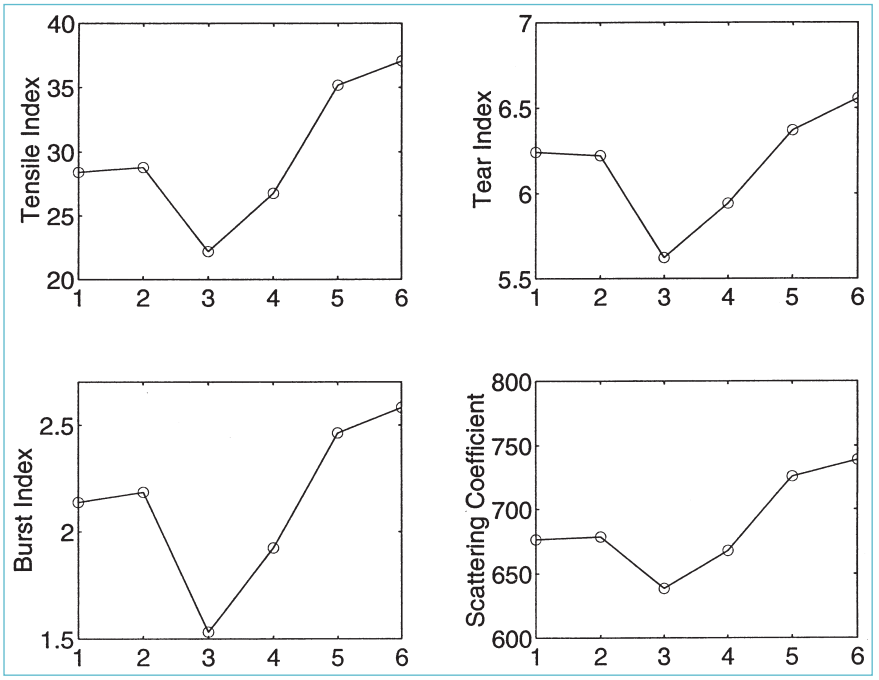

11. Handsheet properties.

NOMENCLATURE

$C_{in,i}$ = *inlet consistency of stream i*
C_f = *feed consistency*
C_o = *outlet consistency*
C_r = *reject consistency*
CSF_a = *accept freeness*
CSF_f = *feed freeness*
$CSF_{in,i}$ = *inlet freeness of stream i*
$CSF_{LC,o}$ = *freeness after latency removal*
CSF_o = *outlet freeness*
$CSF_{PF,i}$ = *inlet freeness of the plug flow region*
$CSF_{PF,o}$ = *outlet freeness of the plug flow region*
CSF_r = *reject freeness*
CSF_d = *drop in freeness across the latency chest*
D = *consistency drop*
$F_{in,i}$ = *inlet flow of stream* i
LF_f = *feed long fiber content*
LF_r = *reject long fiber content*
P = *passage ratio*
P_a = *accept flow rate*
P_f = *feed flow rate*
P_r = *reject flow rate*
R = *reject rate*
R_v = *reject ratio*
SV_f = *feed shive content*
SV_r = *reject shive content*
T_{rej} = *reject thickening factor*
t = *time*
V = *volume*
β_{LF} = *screen quotient for long fibers*
β_{SV} = *screen quotient for shives*
t = *dead time*