UTILIZATION OF DYNAMIC SIMULATION IN THE IMPROVEMENT OF A PULPING PROCESS

Jouni Savolainen[1], Petteri Kangas[1], Manne Tervaskanto[2], Timo Ahvenlampi[2], and Ville Hietanen[3]
[1]VTT Technical Research Centre of Finland,
P.O. Box 1000,
FIN-02044 VTT, Finland
[2]Department of process and environmental engineering,
Systems Engineering Laboratory, University of Oulu,
P.O. Box 4300,
FIN-90014 University of Oulu, Finland
[3]Metso Automation, Lentokentänkatu 11,
P.O Box 237, FIN-33101 Tampere, Finland

jouni.savolainen@vtt.fi (Jouni Savolainen)

Abstract

This paper present results of modelling and simulation studies at a CTMP mill (chemi-thermomechanical pulp). The aim of the study was to improve the quality of the screened pulp and in overall improvement of the screen room's runnability. Simulation, in addition to other advanced mathematical methods, was used as a tool in this. The simulation model presented in this paper is a combination of dynamic mechanistic conservation laws and empirical pulp quality models. The quality models integrated to the Apros Paper simulator were screen freeness (CSF) and screen shive fractionation models. Also the changes in freeness and in pulp fibre length distribution were modelled for the reject refiner. These quality models were semi-empirical models whose parameters were estimated based on data from several mill trials. The integrated process model was validated with logged process measurement data. The final use of the model was threefold. Firstly it was used to generate data for testing the applicability of a data clustering algorithm to fault diagnosis. Secondly the simulator was used as a test bench for the effects of process modification on the end product quality. Thirdly the model was used in the development of new DCS application. During the studies it was shown that a high fidelity dynamic simulation model could be used for several applications ranging from a test bench of process and control changes to data generation for new applications and all way to development of user interfaces.

Keywords: CTMP, screening, refining, dynamic simulation, pulp quality modeling.

Presenting Author’s biography

Jouni Savolainen. Savolainen works as a senior research scientist at VTT Technical Research Centre of Finland. He is also the team leader of the System Dynamics team at VTT, specializing in modeling and dynamic simulation of large scale systems. He received his Master’s degree from Helsinki University of Technology in 1999 and has been working at VTT since.

1 Introduction

1.1 Motivation and background

The motivation for the simulation studies presented in this paper was highly industry-driven. On one hand the case mill saw that the study could supplement their constant efforts to improve their process functionality and end product quality. On the other hand the study provided a possibility for a service provider to integrate a mill case to their business. The research motivation of this study was mainly in testing new simulator features as well as to gain experience in the utilisation of the simulation model in a real life case.

Simulation of pulping and screening of mechanical pulp has been done in the past from different practical and scientific viewpoints. Optimization of screen configurations has been studied for example by Olson et al. [1]-[6], Allison and Olson [7] and Gooding and Olson [8]. These simulations concentrated on optimizing the pulp fractionation in the screen room and were based on the passage ratios of pulp fractions of different fibre lengths [9]. Simulation based optimisation has also been done from the perspective of impurities removal using the shive removal efficiency (E_R or SRE) by Kubat and Steenberg [10] and Nelson [11]. The control aspects of screens and screen rooms have been studied for example by Khanbaghi et al. using dynamic pressure-flow models ([12] and [13]). Modelling of pulp ([14], [15], [16] and [17]) and paper quality ([18]) variables has also been of interest in the simulation community.

In this study the models included the first principles pressure-flow dynamics of the plant as well as empirical pulp quality models.

1.2 CTMP screening and reject handling process description

The process under study was the screen room and reject handling process of a CTMP-mill (chemi-thermomechanical pulp). The simplified process layout is shown in Fig. 1.

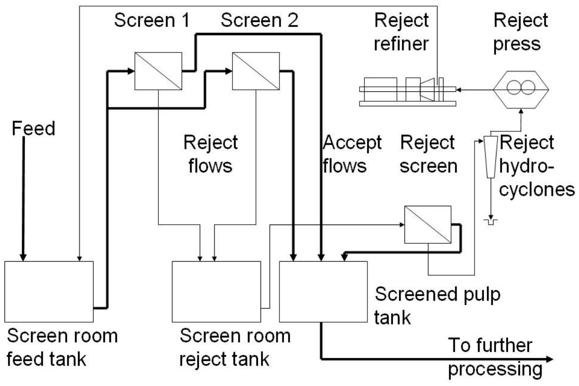


Fig. 1 Layout of the process under study

The feed flow entering the screen room consists of slurry of water and wood fibers. The fiber content of the entering slurry is roughly 5% per mass. Prior to the screen room the fiber resides in a large storage tower. The purpose of the screen room is to separate the fiber flow into two parts. This is done by the two parallel screens in the main flow line (bold line in Fig. 1). The accept flow is the part that has sufficient quality and can be further processed. The reject flow on the other hand cannot be passed further and need extra handling in the reject handling loop. For example the shive (long, coarse wood fiber) content might be too high and the pulp must be refined further. The reject flow is processed in a series of equipment. The first one is the reject screen which performs like the two main line screens. The reject flow from this screen is further purified at the reject hydrocyclone plant. The most coarse fraction of the pulp is removed from the process altogether at this stage. The flow continues from the hydrocyclones to the reject press which removes water from the flow increasing the fiber content to roughly 30%. This flow is then fed between the rotating plates of the reject refiner. It grinds the longer fibers into shorter ones thus refining the pulp quality. After a so called latency tank (not shown in Fig. 1) the pulp is fed back to the beginning of the main flow line.

The pulp produced at the CTMP mill is used as one component at the mill's paper board machines. The board machine produces paper board used by the food industry. This set strict quality requirements to the CTMP and thus creates a constant need to improve the functionality of the CTMP-mill. For example the shive content of the pulp should be kept low while maintaining a constant pulp freeness level (another quality measure defined in [19]). These requirements are somewhat contradictory making the process and its control challenging. Freeness is widely used as an indication of a pulp's suitability or quality. Because the freeness determination is often used for process control, it is desirable to measure this property on-line [20]. Freeness analysis is the most widely used technique for routine mechanical pulp characterization. Perhaps among the factors which also contribute to its popularity is its good reproducibility [21]. Mechanical pulps obtain their strength mainly from interaction between fiber surfaces and the fact that freeness is very sensitive to specific surfaces, therefore, explains its successful application to the strength characterization of mechanical pulps [21]. Freeness tends to be the most influenced by the fines content of the pulp and to a smaller extend by the degree of fibrillation and other fiber properties [22]. A shive on the other hand shive is often described as a fiber bundle, which is at least 3 mm long and 0.10 – 0.15 mm wide. At the laboratory the shive content percentage is normally defined using the Sommerville method, in which the mass of the pulp retained in the 0.15 mm screen surface is compared to the total pulp sample weight.

2 Modelling and simulation

2.1 Simulation system

The simulation software used in this study was the Apros Paper simulator developed by VTT Technical Research Centre of Finland. The software is a dynamic process simulator designed to be used in the modeling of pulp and paper processes. There also exist other Apros products for the simulation of conventional and nuclear power plants [23]. The uses of the simulator include process development, automation testing and operator training.

2.2 Modelling solutions and quality models

The process of Fig. 1 (plus the preceding storage tower) was modeled using the graphical user interface of the simulator by selecting and connecting the appropriate unit operation model blocks.

The input data for the model building was gathered from P&I diagrams, automation functional descriptions, pump curves, previous balance calculations done at the mill and pipe length measurements at the mill. Also a series of process experiments were done. Finally those values that could not be estimated from hard data were estimated based on general engineering know-how. Such things were for example some control valve characteristics and some model boundary conditions.

The flow model is based on the dynamical conservation laws for mass, energy and momentum. These are discretized with respect to place and time to yield a model solvable by a computer. The outputs of this calculation are the flows, pressures and temperatures of the whole process. This modeling technique was used for the main line tanks, flows, all screens and the hydrocyclones. The rest of the reject handling loop was modeled using a simplified pressure/flow solution. In this process area the pressures were not of interest and they could be approximated to be constant. The flows were solved by using simple mass balances.

The flow was divided into water and four fiber components whose concentrations were calculated throughout the process. The tanks in the process were modeled as ideal mixers. In the screens, reject press and hydrocyclones the calculation was divided into two parts. Firstly the total accept and reject flows were calculated by the pressure/flow solver. After this the fiber components were split into the exit streams using accept ratios defined by Eq. (1)

$$s_i = \frac{\dot{m}_{accept} x_{i,accept}}{\dot{m}_{feed} x_{i,feed}} \tag{1}$$

where

s_i	is the accept ratio of component i
m_j	is the total flow of the flow j, kg/s
$x_{i,j}$	is the mass fraction of component i in the flow j

The accept ratios for the fiber components were determined from the process experiment and kept constant during the simulations. The water component is not split using an accept ratio but it is split by the flow solver in order to preserve the mass balance.

The reject refiner was modeled as a combination of several basic blocks. In the refiner the flow is heated and some of the water vaporizes and is removed as steam. Furthermore the grinding in the equipment tends to break the longer fibers into shorter ones. Thus the component was modeled by first adding an external heat flow to the water-pulp slurry. The amount of this heat flow was calculated from the specific energy consumption of the refiner and the refiner production as shown in Eq. (2)

$$\dot{Q}_{refiner} = \eta \cdot SEC \cdot P \tag{2}$$

where

η	is the efficiency fraction of heat to enter the flow
SEC	is the specific heat consumption, kWh/ton
P	is the production, ton/h

The efficiency η was approximated from the mill data. SEC is an operator control parameter and was taken from the mill data as well. Production P is calculated from the simulated flows. After this heat addition the pressure of the flow was adjusted to range encountered by the flow between the refiner discs. From these the material properties calculation of Apros is able to calculate the amount of steam produced in the refiner as well as the temperature of the exiting pulp flow. The pulp fiber mass fractions were then altered using an empirical model obtained from mill trials data.

In addition to the above calculations a further calculation layer was added to the simulation system. This layer was used to calculate the pulp quality, measured by the freeness and shive content values. The freeness and the shive content were treated as being values transported with the flow but not affecting the flow themselves. They are thus called tracked variables. Their values were transported in the flow and altered by appropriate equipment models utilizing external model implemented in dll-libraries.

For example in the screens the freeness of accept and reject flow were calculated from the feed freeness, consistency and flows by Eqs. (3), (4) and (5).

$$CSF_a = CSF_f e^{-\theta RR_m} \tag{3}$$

$$CSF_r = e^{CSF_r'} \tag{4}$$

$$CSF_r' = \frac{\dot{m}_f Cs_f \ln(CSF_f) - \dot{m}_a Cs_a \ln(CSF_a)}{\dot{m}_r Cs_r} \tag{5}$$

where

CSF_j is the freeness of flow j, ml
m_j is the total flow of flow j, kg/s
θ is a tuning parameter
Cs_j is the consistency of flow j, %
RR_m is the reject mass ratio of the screen.

The consistency of a flow j is defined as in Eq. (6).

$$Cs_j = \left(\sum_{i \in \{fibercomponents\}} x_{i,j} \right) \cdot 100\% \tag{6}$$

where

$x_{i,j}$ is the mass fraction of component i in flow j.

The reject mass ratio is an operator controlled screen parameter defined in Eq. (7).

$$RR_m = \frac{\dot{m}_R Cs_R}{\dot{m}_F Cs_F} \tag{7}$$

A reference for equation (3) can be found for example in [14]. It has been widely used for screen freeness calculations ([24], [25] and [26]). Equations (4) and (5) can be derived from the so called mass weighted logarithmic average mixing rule reported for example in [15] and [27] and originally designed for groundwood pulp. In this study, the model was fitted to chemi-thermomechanical pulp using process experiments described later.

The most common index describing the effectiveness of screening is the shive removal efficiency, *SRE* (or E_r), introduced by Nelson in [11] and shown in equation (8). It defines the percentage of the component (in this case shive) removed during separation.

$$SRE = \left[1 - \left(1 - \frac{RR_m}{100} \right) \frac{S_A}{S_F} \right] 100 \tag{8}$$

where

S_A is the accept flow shive content, %
S_F is the feed flow shive content,%

SRE can be also presented as

$$SRE = \frac{RR_m}{1 - Q + QRR_m} \tag{9}$$

where

Q is screening quotient [11].

Q, which is also called the Q-index, describes the separation efficiency. Q-index has to be defined based on pulp samples analyzed in a laboratory.

The shive contents in the accept and reject flows of an individual screen can be calculated using the screen's *SRE* value, the feed shive content of the incoming flow and fiber mass flows:

$$S_A = \frac{(S_F(1 - SRE)Cs_F F_F)}{Cs_A F_A} \tag{10}$$

$$S_R = \frac{S_F \cdot SRE \cdot Cs_F F_F}{Cs_R F_R} \tag{11}$$

where

S_j is the shive content of flow j, %
Cs_j is the consistency of flow j, %.

The reject refiner's shive content model is calculated based on the reject refiner's specific energy consumption (*SEC*) and the shive content of the feed pulp. The input shive content can be calculated by using the shive content model of the reject screen's reject flow.

2.3 Process experiments

In the design of models and simulators for pulp and paper processes, accurate measurements are essential. Therefore mill samples and analyses using accurate laboratory devices are needed. Laboratory devices for consistency, freeness, shives and fiber length fractions measurements give information of the process itself and the modeling is more reliable and redundant using mill samples compared to purely data based methods using only measurement data. When using mill samples, the place and the length of storage of the mill samples is an important factor in the results of the analyses. The results of the analyses can be unreliable and incorrect if the samples are stored in the wrong place or for too long a period. Therefore good and experienced personnel for the laboratory analyzing process are essential.

In this study, the mill samples were taken from the screen room. The feed, accept and reject flows were analyzed in the screening phases and feed and refined flows were studied in the reject refining phase. Consistency, freeness, shive content and fiber length fractions were analyzed from these samples. The screen tests were performed using different production rates, volumetric reject rates and feed consistencies. In reject refining, changes were applied for the refiner's specific energy consumption. The samples were analyzed using accurate laboratory devises. The shives were analyzed based on a Sommerville-analyser and a BauerMcNett-analyser was used for fiber length fractions.

Using the mill experiments, the quality models described above for freeness and shives for the screens and reject refiner were constructed. The constructed quality models were implemented into the Apros simulator.

2.4 Model validation

Three different operation situations were used in the model validation. These cases were a) both screens running in a stable state, b) an increase in the production of the first screen while second is running in a stable state and c) a decreasing in the production of the first screen with the second screen out of operation.

The simulated validation period was 5000 seconds during which 32 different control loops (set-point, measurement and control output signals) were tracked and logged to a file. The validation runs were done in such way that the set-points of the controllers were fed into the simulator every 5 seconds. These set-point values were gathered from the process. Finally the simulated data was compared with measured data.

From these tests the following conclusions could be made. Firstly there are some errors in signal levels when comparing the measured and simulated data. These can be seen most clearly in control output values of the controllers. A cause for this can be wrongly parametrized control valves or pumps in the simulator. This can cause problems if controllers saturate in the simulator before they do at the mill. Secondly in the simulator there is less variation or noise in the results, see Fig. 2. This of course originates from the fact that a model is always a simplified version of real life. For example ideal mixing removes some of the variations, which can be seen for example in the consistency controllers. Thirdly the state of the process in the beginning of validation runs i.e. initial condition turned out to be rather difficult to obtain. Initialization of the model has to be done before the actual validation run is performed. In some cases the initialization run was not long enough and the model was in a slightly wrong situation in the beginning of validation run. The overall impression was that the model was accurate enough to be used for developing the new concepts.

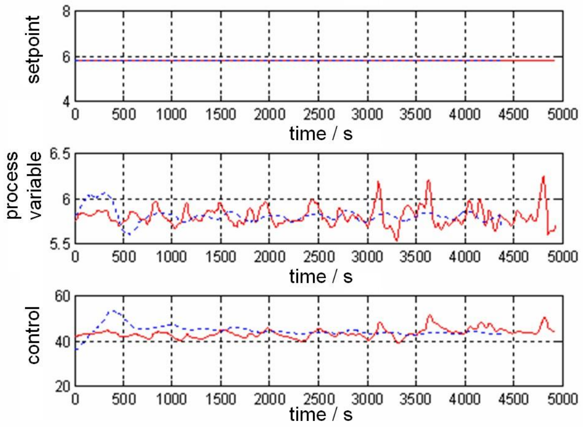


Fig. 2 Consistency controller simulation results. Set point on top [%], measurement on middle [%] and control output on bottom [valve opening]. Time scale is in seconds. Red is measured in mill, blue is simulated.

3 Use cases – description and results

3.1 Data generation for a fault detection application based on clustering

Validation of a fault detection application in real process environment is nearly impossible because the faults to be detected are unlikely to occur within a limited time period. Also generating real faults into the plant is too expensive and risky to be used as a validation procedure. Because of these reasons, simulation is widely used to solve this kind of problems. However to make the validation data to look realistic in the case of fault, a very detailed and accurate process model is needed. In addition to being able to reproduce normal operation results it is imperative that the simulator be able to replicate fault situations realistically. The simulator used in this study offers a wide range of predefined equipment faults and as the simulator is based on first principles models the reliability of the results was seen to be adequate.

The main objective of a fault detection system is to detect if something unexpected happens in the process. This means that the normal operation of the process has to be modeled with adequate accuracy. Normal operation of an industrial process is mathematically challenging because of changing conditions, non-linear behavior and constant changes during the plant's life cycle. Because of these reasons, the model structure used to describe the normal operation has to be multivariable, non-linear and adaptive.

Using dynamic simulation model as a residual generator is not a good idea, because in continuous online action even very small modeling error (noise) gets accumulated to the state of the model causing residual to increase without reason. To prevent the effect of accumulating modeling error, a stateless residual generator is used. The residual generator used in this study is based on a set of cluster centers. The cluster centre is an object consisting of location in multidimensional measurement space and internal variation (radius), which are defined by a clustering algorithm based on data collected from the process to be monitored. Several clustering algorithms are presented in the literature.

The set of cluster centers specifies a static, multivariable and non-linear model that describes what the data normally looks like. This set is then used as a reference to detect changes that are mostly caused by faults. This kind of model structure is good because it is open and easy to modify in case of known changes in the process. Each cluster centre also has a clear physical meaning, because they describe a known situation in the process.

Normally the measured process data is located close to the cluster centers in the multidimensional measurement space. The outcome of the fault detection system is residual which is defined as a distance between closest cluster centre and measured data divided by the radius of the closest cluster centre. Because of this definition the normal value of the residual is close to one rather than zero and trend should contain only noise. This is an important feature, because noise is always present and noise level depends on operation point. Less noise means smaller cluster radius and more accurate model. Any kind of regularity in the residual signal is originated from some of the input signals. The alarm limit can be dynamically adjusted, i.e. it is typically between 2.5 and 3 when the process operation point has been steady for awhile.

The process model described in earlier chapters was used to generate data for normal operational situations in the mill (e.g. full-production and half-production). This artificial data was used for training the normal operation for the fault-detection system. Training means setting the locations of the cluster centers by a clustering algorithm. Artificial data was used for training because it is important to minimize the differences between normal and fault situations. Because of modeling errors there are always small differences in signal levels between simulator and real process. Otherwise the fault detection system would detect the modeling errors rather than the fault.

After the training phase, several realistic malfunctions and faults were introduced into the simulator based on mill personnel interviews. These faults included for example increased backlash in a valve, a partly functioning consistency measurement and a wrong operation mode caused by operator. This data consisting of normal and abnormal situations was used to test if the fault-detection system can detect the fault and to figure out what kind of output it would give in such case.

In the following example the outlet valve of screen 1 is left open because of a mistake made by the operator. The system gives clear indication of the situation as presented in Fig. 3. The normal operation is presented in left half and fault situation is presented in the right half of the chart. The upper trend shows the code number of the currently closest cluster centre i.e. the operational point. In both cases there is first a start-up situation followed by a steady state situation. The fault is detected because the value of residual signal is higher than in the steady state situation.

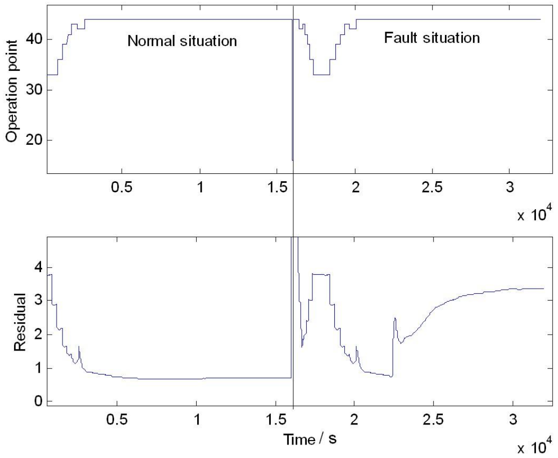


Fig. 3 Output of the detection system for the example case.

Detection system compares the vector of measured values to the location vector of the closest cluster centre. The result is a horizontal bar chart (Fig. 4) that tells the difference between each component of measurement and cluster location vectors. From this chart it is easy to identify the signals that are affected by the fault. In this case the fault detection system can tell that the consistency of screen 1 reject (signal 15) and input consistency of the reject screen (signal 61) are significantly lower than normally.

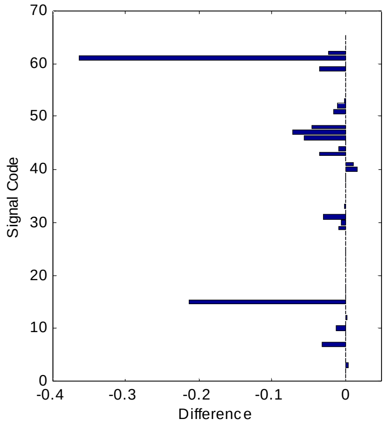


Fig. 4 Comparison of measurement and cluster location vectors.

In this case, the mistake causes reject consistency to drop as presented in Fig. 5 because a significant amount of the pulp goes to the outlet channel. In real case this kind of a situation could have major economical and possibly environmental effects, while the quality of the end product may not be affected at all.

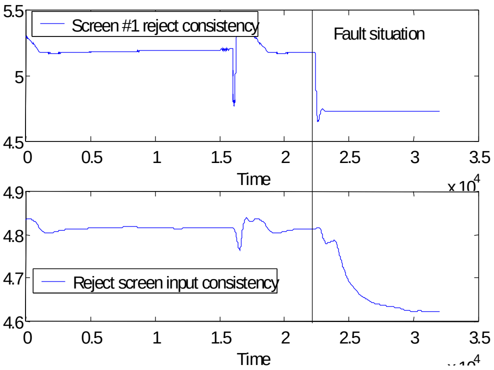


Fig. 5 Screen 1 reject and reject screen input consistencies.

3.2 Process piping modification

The process modification that was studied with the simulation model was the possible installation of a pipeline bypassing a storage tower preceding the screen room. The idea behind this modification was that by passing the storage tower might be worthwhile in cases when the tower is known to contain low-quality pulp. In this case this low-quality pulp could be mixed with good-quality pulp from the bypass line. With this arrangement the final product quality could be preserved.

Two production situations were studied. In the first one the storage tower was 50% full, both of the main line screens were in operation and the production was high. In the second test the tower was 80% full and the production was low with only one main line screen in operation. Other process parameters and boundary conditions were kept equal in both cases.

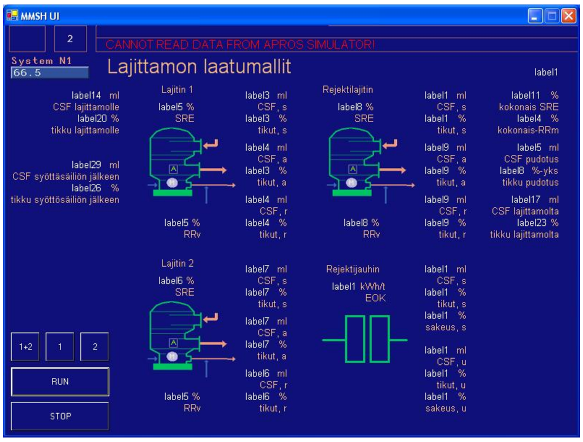
In the first case the model was first simulated for a while at a steady-state reference point. After this the quality in the tower was reduced and simulation was continued. After the low-quality pulp had spread throughout the screen room the bypass line was taken into simulation. Simultaneously the quality of the mass flowing into the bypass line and the tower was raised to a good-quality level. Finally the simulation was continued until the end product quality had returned to an acceptable level. This settling time was compared to a case where the bypass line was not in use. As a result it was found that using the bypass line the settling time was approximately half of the time of the no-bypass line case.

In the second case the model was started up from the same state as in the first case. After a while the second main line screen was shut down and the simulator was run to a new steady-state. Next the same steps were taken as in the first case. Also in this case it was seen that the end product quality settling time was shortened by the use of the bypass line.

Thus it can be concluded that the simulations showed that installing a bypass line would be beneficial. However further studies showed that the bypass line installation should have included a dilution tank. This kind of installation was deemed to be too expensive.

3.3 DCS application development

There are many different ways to keep the process in the state which produces acceptable pulp quality. However, the effects of different control actions can be more or less uncertain among process operators, especially in the case of many dependencies between process variables and long process delays which are typical in pulping processes. Therefore a need for pulp quality simulators exists. A process monitoring system should be reliable and quite simple to use by operators. Otherwise there is a risk that the system could even increase the difficulty of decision making in the process control and maintenance. It has been found important that the monitoring and simulation system can be viewed through the same user interface as the normal process control station. That is easier to implement, if the necessary calculations can be done with the process automation blocks. More demanding process and production chain simulations can be done and implemented to a PC environment. Although the developed system structure is quite generic, still some retuning of the models is normally needed when bringing them into new processes. Especially, this is the case when using detailed experimental or semi-experimental models, like in the case of CTMP freeness and shive content models. Adaptivity of the simulation system to time varying process conditions is a big question as well. Various adaptive methods to overcome the problem can be found in the literature and they might be used and implemented to the existing system in the future. When developing operator support systems operators should be involved in the development work already at the beginning of the process. That helps operators to accept the system and all the unnecessary features which do not give any additional information for the process maintenance are left outside of the system. In this study, the dynamic Apros simulator was also used in the DCS application development. The operator view was constructed for the Apros simulator. The selected features (quality models and indices) were tested with the simulator.


CANNOT READ DATA FROM APROS SIMULATOR!

System N1
66.5

Fig. 6 Operator GUI.

The GUI is a collection of some of the models and indices, which also have been implemented in the Apros simulator. The quality properties (freeness and shives) in the feed accept and reject flows and SRE (shive removal efficiency) were displayed on the screens. The input and output quality properties were displayed from the reject refining process. Also input and output qualities in the screening room were shown. The operator could simulate some different operations using the generated GUI. The operator can e.g. select 1 or 2 mainline screens (lower left corner in Fig. 6).

After the testing in the simulator, the quality models and indices have been implemented also into the mill's DCS displays.

4 Conclusions

This paper presented modelling and simulation work carried out at a CTMP-mill. The modelling included the pressure and flow dynamics of the mill's screen room as well as models for the pulp quality measures such as freeness and shive content. The developed integrated simulation environment was then used in three distinct uses cases.

The first use case concentrated on developing a new process monitoring and fault detection application. Validation of fault detection application showed that it is able to detect different kind of faults, human errors and malfunctions, which were artificially created into the dynamic process simulator. Because the simulator was also validated against the mill, it can be assumed that the fault-detection system will work properly when installed into the real mill. In the future, this kind of dynamic simulator can be used for testing several other fault detection systems. This study also showed that dynamic process simulator is an excellent tool to test the effects of a fault and develop more robust and fault tolerant control systems.

The second use case dealt with a more process oriented problem of determining the effects of a new bypass line. The same simulation model was used to analyse the effects of this process modification on the pulp quality.

Finally the third use of the simulator model was in the development and testing of a new control system display for the operators. Also some of the models included in the simulator were implemented to the control system for the operators to use.

In conclusion it was found out that a simulation model can act as a unifying framework for diverse practical applications. To this end the simulation model must be able to replicate the process in adequate accuracy and at a wide range of process operation points. This in turn requires that the model be based in most parts on first principles rather than being only an empirical correlation. Having a basis model based on physical laws allows then an additional empirical (quality) model layer to be used successfully.

5 Acknowledgements

The authors would like to thank the Finnish Funding Agency for Technology and Innovation (TEKES), Stora Enso and Metso Automation for funding this study.

6 References

[1] J.A. Olson. The effect of fibre length on passage through narrow apertures. Ph.D. Thesis. Univ. of British Columbia. 1996.

[2] J.A. Olson, N. Roberts, B. Allison, and R. Gooding. Fibre length fractionation caused by pulp screening. *J. Pulp Paper Sci.*, 24:393-397, 1998.

[3] J.A. Olson, and G. Wherrett. A model of fibre fractionation by slotted screen apertures. *J. Pulp Paper Sci.*, 24:398-403, 1998.

[4] J.A. Olson, B.J. Allison, and N. Roberts. Fibre length fractionation caused by pressure screening. Part II: Smooth-hole screen plates. *J. Pulp Paper Sci.*, 26:12-16, 2000.

[5] J.A. Olson. Fibre length fractionation caused by pulp screening. Part III: Slotted screen plates. *J. Pulp Paper Sci.*, 27:255-261, 2001.

[6] J.A. Olson, B.J. Allison, T. Friesen, and C. Peters. Fibre fractionation for high porosity sack kraft. *Tappi Journal.*, 84:66, 2001.

[7] B.J. Allison, and J.A. Olson. Optimization of multiple screening stages for fibre length fractionation: two-stage case. *J. Pulp Paper Sci.*, 26:113-119, 2000.

[8] R.W. Gooding, and J.A. Olson. Fractionation in a Bauer-McNett Classifier. *J. Pulp Paper Sci.*, 27:423-428, 2001.

[9] R. Gooding. The passage of fibres throygh slots in pulp screening. M.Sc. Thesis. Univ. of British Columbia. 1986.

[10] J. Kubat, and B. Steenberg. Screening at low particle concentrations. *Svensk Papperstidning*, 58:319-324, 1955.

[11] G. Nelson. The screening quotient: a better index for screening performance. *Tappi Journal*, 64:133-134, 1981.

[12] M. Khanbaghi, B.J. Allison, J.A. Olson, and J. Backström. A dynamic model of pressure screen hydraulics. *J. Pulp Pap. Sci.*, 27:124-129, 2001.

[13] M. Khanbaghi, B. Allison, and J. Olson. Modeling and control of an industrial pressure

screen. *Control Engineering Practice*, 11:517-529, 2003.

[14] X. Qian. Modelling and dynamic simulation of a CTMP plant. Ph.D. Thesis. Univ. of British Columbia. 1997.

[15] X. Qian, and P. Tessier. Dynamic behaviour of a pulp-processing reject refining plant. *Tappi Journal*, 83:1-10, 2000.

[16] M. Tervaskanto, T. Ahvenlampi, T. Harju, and T. Sippus. Modelling and simulation of chemi-thermomechanical pulp quality. In: *SIMS conference 2006*, September 28-29, Helsinki, Finland. 2006.

[17] M. Tervaskanto, T. Ahvenlampi, T. Harju, and T. Sippus. Shive content modeling and simulation in chemi-thermo-mechanical pulping. In: *Tappi Engineering, Pulping and Environmental Conference 2007*, October 21-24,, Jacksonville, FL, USA. 2007.

[18] G.L. Jones. Simulation of the Performance Characteristics on a TMP Mill. *Pulp & paper Canada*, 91:69, 1998.

[19] ISO 5267-2. International Organization for Standardization. 2001.

[20] G. Smook. Handbook for Pulp & Paper Technologists, 3rd edition. Angus Wilde Publications Inc.. 2002.

[21] F. El-Hosseiny, and J. Yan. Analysis of Canadian Standard Freeness. Part II. Practical implications. *Pulp & Paper Canada*, 81:67-70, 1980.

[22] C. Biermann. Handbook of Pulping and Papermaking, 2nd edition. Academic Press. 1996.

[23] E. Silvennoinen, K. Juslin, M. Hänninen, O. Tiihonen, J. Kurki, and K. Porkholm. The APROS software for process simulation and model development. VTT Publications 618. 1989.

[24] T. Hietanen, A. Ämmälä, J. Niinimäki, and T. Jussila. Pressure screening - prediction of production rate and pulp properties of accepted and rejected fractions. In: *4th International conference on pulp & paper industry*, New Delhi, India. 249-262, 1999.

[25] A. Ämmälä, and J. Niinimäki. Control of pressure screening by mass and volumetric reject rates. In: *Tappi Pulping Conference 2001*, November 7-10, Seattle, WA. 2001.

[26] M. Tervaskanto, T. Ahvenlampi, T. Hietanen, and U. Kortela. Modeling of compound pulp quality in thermo mechanical pulping. In: *IASTED International Conference on Modelling, Identification and Control*, February 11-13, Innsbruck, Austria. 283-287, 2003.

[27] H. Paulapuro. Prediction of quality parameters of groundwood pulp mixtures. *Paperi ja Puu*, 4:297-307, 1977.

ISBN 978-3-901608-32-2