Enhancing grade changes using dynamic simulation

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ABSTRACT: This report describes the development of a dynamic simulation model of a 3-ply paperboard production process. The simulation model consists of stock preparation and proportioning, short circulations, wire and press sections, and 75 drying cylinders, including the steam and condensate system. We also modeled the functionality of the automatic grade change program used on the machine. Physical, first principles models were used whenever possible. We used historical data to extensively validate the simulator. The simulator has been used as a test bench to find better values for automatic grade change parameters. The new simulator-tested parameters have been used on the full size machine with good results.
Application: Simulator helped to understand the grade change dynamics in a multilayer board machine, and to re-tune the automatic grade change program.

Paper and board machines must often produce many grades to meet different customer specific needs. To avoid large storage, mills have to change grades frequently. Grade changes (GC) greatly affect machine production efficiency, so mills make all possible efforts to minimize GC production losses. Careful production planning helps a lot. Some paper machines may even eliminate the losses with a production cycle where basis weight changes are so small that acceptance limits of the grades overlap. However, the minimum basis weight change between grades may be 20 g/m^2, with simultaneous changes to fiber furnish type, filler content and type, color, and so on.

Dynamic simulation has had a major role in many grade change studies. In 1988, Miyanishi et al. [1] demonstrated the effects of machine chest volume, first pass retention, and dry broke ratio in GC. They also showed the effect of increasing filler loading in the initial period of the GC in which filler type is changed.

Historically, GCs have been accomplished manually by machine operators. Many studies deal with the question how to automate the associated operations. The basic idea of automatic grade change (AGC) is simple: ramping of manipulated variables with preplanned targets and mutual coordination. However, it is challenging to tune the system to give good performance simultaneously for all quality variables, and many approaches have been suggested to overcome this problem. Ihalainen and Ritala presented an idea to numerically optimize the actions in GCs by using dynamic simulation [2]. Murphy et al. proposed a dynamic coordinator to reduce the basis weight and moisture content upsets during GCs [3, 4]. Thick stock flow was used as a coordinating actuator. Mori et al. suggested non-linear control curves for two variables: thick stock flow and steam pressure [5]. Additionally, Mori et al. presented a new iron plate drying model that enables fast calculation of steady state moisture and temperature profiles for the drying section. They tuned the model before each GC using on-line measurements. After the tuning, the model is able to accurately predict steam pressures for the new grade. For a successful GC, it is very important that the new grade's target values are reasonably good, and the most difficult to predict are steam pressures. Many other papers concern the different estimation methods [4,6,7].

The traditional AGC methods switch the machine's quality controls off when performing grade changes. Approaches to perform GCs under feedback control have been considered, also. Välisuo et al. suggested use of model predictive control with non-linear models [8]. Recently, Kuusisto et al. have discussed the same subject [9]. They emphasize the importance of moisture dynamics in the use of multivariable predictive control in AGC. The moisture model must handle the complicated dynamics because of the changing machine speed, paper basis weight, and ash content, but it is still be easily commissioned. A totally different approach in speeding-up GCs has been presented in papers that introduce new papermaking concepts with considerably faster transient dynamics than before [10].

In this paper, we present our experiences in using dynamic simulation to improve GCs on a Finnish multi-grade, multi-ply board machine. Our approach has not been to develop a new algorithm or a control strategy, but to enhance the operation of the mill's present AGC system. The structure of the simulation model and the main calculation principles are described. Simulation results are shown and discussed. Finally, the way to use the simulator at the mill is presented before looking to future work.

PROBLEM FORMULATION

The board machine we used produces liquid packaging boards having basis weight area of 170-350 g/m². The machine has three fourdrinier wires, one of which is equipped with a top wire unit. The machine has three press nips in the press section. Five two-tier dryer groups with The model includes these five groups, and the following two steam groups before the on-line coating. The machine speed varies between 200 and 450 m/min.

The mill averages one GC per day on the machine. For many years, a specific automatic grade change program has assisted operators at the mill. The following control variables that are included in the AGC:

- wire speed
- thick stock flows for three layers
- slice opening of the three headboxes
- jet-wire ratios for three headboxes
- steam pressures in steam groups 5 and 7

The AGC program calculates targets for the thick stock flows and the two steam pressures. Pressures in other steam groups are following the pressures in the 5th and 7th group with given ratios. The AGC also suggests typical grade operating values for the wire speed, slice openings, and jet-wire ratios, though the operator may change them if necessary. When the GC begins, the AGC coordinates the mutual delays and handles ramping of the variables. This coordination is pre-planned by giving a start delay, maximum stepping rate, and a stop delay for each variable in the GC. Additionally, there is an option to synchronize or not the ramping of each variable with the others.

Operators select which of the variables are controlled automatically by the AGC. They usually let the automatic program handle all variables except the slice openings, which they most often adjust manually. All operators use the AGC and consider it as a useful tool. On the other hand, the general feeling has been that the operation could be improved to give shorter GC times and to reduce moisture fluctuations during the GCs. The AGC's steam pressure prediction for the new grade has been at a satisfactory level, so that part of the AGC was not included in this study.

Large, unwanted excursions in the web moisture content have been one of the main concerns in GCs on the machine. Clearly, the moisture bounds up or down when the machine speed starts to change and again just after reaching the target speed. The headbox dynamics during the speed change is the dominant reason for this kind of moisture disturbance [3, 4]. Historically, this occurs in most GCs, but the amplitude of the disturbance varies from case to case. An intuitive reaction is that the phenomenon could be eliminated through better timing. However, it is very challenging to try to figure out the right actions needed to fix such a fluctuation using just a mind model. In multi-ply machine, the number of tuning parameters of the AGC is remarkable. Different ideas compete and conflict. This kind of "opinion engineering" is quite a fragile base to start experimenting on the real machine. The simulator allows us to play with different ideas before anything is done on the machine.

MODELING

The process model covers the board making process from pulp chests to the end of the base board drying. The model was built using the APROS platform [11]. It is a general purpose modeling and dynamic simulation tool. The extension of the platform on pulp and paper mill applications is called Apros Paper (APMS).

Simulation models are built based on the Piping and Instrumentation Diagram (P&ID) and equipment functional descriptions. High fidelity is achieved by using first principles of physics to describe process operations whenever possible. Conservation of mass, energy, and momentum is used in solving pressures, flows, and temperatures in piping networks. Validated and tested model algorithms for process equipment, instrumentation, and automation are integrated under the executive control of an advanced graphic user interface. The user graphically builds a model that looks analogous to the corresponding flowsheet in the P&IDs. The simulation model is configured while the flowsheet is being drawn and parameters are set. The model structure can be changed any time and the model can be expanded without need to recompile or link the program.

Most of the required parameters, such as pipe diameters, tank volumes, nominal flows, and heads for pumps, were derived from P&IDs. Pipe lengths were calculated from piping drawings and some were estimates. Equipment elevations from a reference level were obtained from layout drawings. Some of the parameters—such as cylinder diameter and shell thickness, or number and dimensions of pipes inside a condensator—were obtained from construction drawings. Others, such as pressure drops in pressure screens, were obtained from measurement data. General engineering knowledge is also useful when specific information of a piece of equipment, such as pressure drops in valves, is not easily available.

Mass preparation and short circulation

Refining, mass proportioning, and the short circulation of each layer form a large thermohydraulic pressure/flow network that is modeled by connecting model objects for pipes, pumps, valves, tanks, etc. The incoming stocks to the chests before refining form the starting point for the model. Three fiber components, filler, and water are carried along in the system. Ideal mixing was assumed in tanks, but wire pits were divided into several ideally mixed volumes. Refiners, pressure screens, and centrifugal cleaners also take part in the pressure/flow network. Screens were defined to have constant separating ratios. Refining does not change pulp properties in the model, though this feature would further broaden the scope to cases where refining is changed noticeably for the new grade. It would, however, require many experiments to capture the effects of refining quantitatively (e.g. water removing in the wire, wet press, and drying sections), so we decided to take the first step without modeling any refining effects.

The headbox is the last part of the pressure/flow network before the web model starts. Only the jet-wire ratio controls directly regulate the speed of each head box feed pump in our model. That was all that we needed as head box controls to match the dynamics with the measurements. We neglected machine cross direction in this model. For the machine direction, the web is described with the user-defined number of elements moving with the machine speed. The calculated web properties are moisture content, temperature, basis weight, composition, and thickness.

Wire and press section

In the wire section model, webs from three separate wires are interconnected into one and the compositions of the layers are averaged. We have used constant values for retention of various fiber components and still obtained very good correspondence to measured values, e.g. headbox consistencies. This is because of the relatively high grammage of the grades produced. Filler plays a minor role because its content is very low in all grades. Therefore, no extra effort was taken to explain retention changes in this phase.

Dewatering on the wire part was modeled in a straightforward way, as well. Our first approach was to use constant dewatering ratios in all wire model components. As an example, the dry solids content of the web and total mass flow to the press section change with consistency in a headbox changes. Another approach was to use constant dry solids content of the outgoing web in the last part of the wire. Then a change in a head box consistency does not change the dry solids content, but the total flow into the press section is still free to change. This approach seemed to work well. That may be because the operators control the dry line position with the slice opening, thus keeping the dry solids content in a certain range. If the effect of the slice opening on the dry solids content is not known accurately, it may be better to keep the dry solids content constant. In this study, the slice openings, before and after each simulated GC, could be taken from the corresponding historical data.

The decreasing permeability model [12] was used to describe water removal in each of the three press nips:

$$\frac{z}{z_0} = \left(1 + \frac{4Anz_0^n I}{\nu W^2}\right)^{-1/n} \qquad \text{(Eq. 1)}$$

Where:

z = outgoing moisture ratio [kg H_20/kg d.p.]
z_0 = ingoing moisture ratio [kg H_20/kg d.p.]
I = press impulse = press load/speed [(kN/m)/(m/s)]
n = compressibility factor
A = specific permeability [g/m]
W = basis weight [kg/m^2]
ν = kinematic viscosity of water [m^2/s].

McDonald and Amini recommend determining the model parameters, compressibility factor, and the specific permeability, by pressing handsheets in a laboratory press [12]. Unfortunately, we were not able to do this. Instead, we used some earlier measurements to obtain the parameters and evaluated the result qualitatively.

Drying section

We modeled the drying section of the base board production, including the steam and condensate system. The drying section has 75 steam-heated cylinders in the model. Steam headers bringing the steam from the power plant start the model in the steam side. The condensate return flow to the power plant forms the other model boundary. The piping network of the steam and condensate system was modeled using the homogeneous two-phase flow model of the simulation platform. The drying cylinder and free draw models previously reported by Niemenmaa [13] were used and partially developed further in this study. The main calculation principles of the drying model are presented. **Figure 1** shows a view from pictures of the 2nd steam group.

Heat transfer in cylinders

To calculate the heat transfer coefficient from steam inside the cylinder through the condensate layer to the inner surface of the cylinder, we used the theoretical expression of Appel and Hong [14]. The modeled drying section includes cylinders with turbulence bars, and in those cases a constant coefficient has been used instead. The cylinder shell is radially discretized into three parts. The one-dimensional heat conduction model is used in calculation of heat flow through the cylinder wall. The heat capacity of the cylinder heads has been considered, also. **Figure 2** shows an example of a drying section profile for cylinder inside steam, inner surface, outer surface, and web temperatures after each cylinder and web moisture content.

Evaporation from paper

The following approximation of the Stefan equation expresses the evaporation rate $\dot{m}/A$ from paper to air [15]:

$$\frac{\dot{m}}{A} = \alpha \cdot C \cdot \ln\left(\frac{p_{tot} - p_{va}}{p_{tot} - p_{vp}}\right) \quad \text{(Eq.2)}$$

Where:

α = paper-to-air heat transfer coefficient
p_{tot} = air total pressure
p_{vp} = vapor partial pressure on paper surface
p_{va} = vapor partial pressure in surrounding air
C = constant

Differences in felting are taken into account by the paper-to-air heat transfer coefficient. Below the critical moisture content, the evaporation front has moved inside the paper surface. The evaporation reduction is obtained by using sorption isotherms:

$$p_{vp} = \varphi(T_p, z) \cdot p_0 \quad \text{(Eq.3)}$$

Where:
$\varphi(T_p,z)$ = sorption isotherm of paper
T_p = paper temperature
z = paper moisture ratio
p_0 = vapor partial pressure for free water

For wet paper the function $\varphi(T_p,z) = 1$. In the hygroscopic region, where the paper moisture is less than the critical moisture content, the function $\varphi(T_p,z) < 1$, and approaches zero as paper moisture decreases. Sorption isotherms for various paper grades have been published [16]. Vapor partial pressure for free water is calculated using Antoine's equation and the vapor partial pressure in air is solved using the given air humidity and air total pressure in dryer pockets. Air humidity and pressure are assumed to be constants during GCs. The incremental change in the paper moisture content can be solved by mass balance when the initial moisture content and the evaporation rate $\dot{m}/A$ are known.

The heat and mass transfer between outer cylinder surface, paper, and air in the hood are solved explicitly by the cylinder and free draw models, and are added as source terms into the continuity equations of the steam and condensate system. The calculation of the heat and mass transfer is discretized into several machine direction steps in the cylinder and free draw models. The number of partitions (20 in this study) is determined by the user.

A single layer web model is used. The state of the web in each position in the machine direction is described by average temperature and moisture. In practice, there are gradients in paper thickness direction in moisture and temperature. Thickness-dependent resistance for the heat and mass transfer is approximated in the model by the same type of evaporation reduction factor used to model evaporation through a pigment coating [15].

Control system

We modeled the control system in parallel with the process modeling and included 74 control loops in the model.

The functionality of the AGC program was modeled in detail using the basic automation components of the simulation platform. Thus, the AGC model calculates the target values for the new grade and handles the GC operations for situations where the parameter values are changed from the mill values. **Figure 3** shows the user interface of the AGC in the simulator graphics.

MODEL VALIDATION

When a simulator is used in what-if studies, its success depends on model fidelity and the users knowledge of the model's limitations. The focus of the simulation study was on finding better values for those AGC parameters that define the mutual coordination and rates of the ramps. To be able to do that, the simulator must confidently predict the effects of the simultaneous ramps of the various operating variables on critical variables such as moisture and basis weight. In addition, the model of the AGC must function like the real one to enable what-if studies with new parameter settings. The parameters that we focused on are equal for the entire operating area, so the new values must suit well for changes between all produced grades. Accordingly, the simulator validity must cover the whole operating area of the machine. This is a major motivation for using a mechanistic modeling approach in this kind of study instead of identification of linear black-box models.

Our main emphasis in validation runs was naturally placed on dynamics during GCs. GCs produce good data for model development and validation in general because of the large transients in so many variables [17]. A large amount of validation data can be easily collected without additional experimentation. At this mill, the DCS automatically collects a large data set from every GC. In fact, we did not make any machine bump tests or additional measurements in this project because of the modeling and validation.

Most of the time spent in validation went into tuning the drying section model. In addition to the measurements taken by the DCS, we had an opportunity to use a report of a recent study where temperature measurements of paper, cylinder surface, and dryer pockets (moisture, also) were taken in the drying section by hand. Simulated drying section profiles, as in Fig. 2, agreed well with these measurements. Additionally, it would have been very interesting to see how the simulated moisture and temperature profiles reflect reality in a dynamic situation. The model of the steam and condensate system needed a lot of attention as well because of the noticeable amount of details measured, and thus verified.

Another time-consuming task was to adjust the AGC model to perform GCs in the simulator just as the actual AGC performs on the machine. We found differences that occasionally appeared between simulations and mill data. We determined that the differences come from the fact that some operators were using the AGC in a slightly different ways than we did in the simulations. By using the simulated GCs as reference, we could filter out such actions in using the AGC that were undesirable for best result. For example, for the calculation of the new target values, some operators let the AGC calculate them far too early. The best way is to use the mode of automatic target updating. Then the final calculation occurs just before the GC is initiated. In conclusion, as time passed since initial training, the automatically handled grade changes were not as good as they should have been. Once we identified these faults, the operators were advised of the optimal and consistent use of the AGC.

Simulation example

Figure 4 presents an example of a GC selected from the historical data and then repeated with the simulator. Measured values are drawn with black, and gray curves show the corresponding simulation. Time scale is presented in seconds; total time is 25 min. Speed (see upper left picture) has been changed from 355 to 290 m/min. Thick stock flows of top and bottom layers have practically the same values (upper right picture). The absolute change in the steam pressure is rather small in this case. The moisture and basis weight controls are switched on at 600 s. In this GC the slice opening controls have been included in the AGC (middle right picture). The three jet-wire ratios have been ramped to new values, as well, though not shown in the figure.

Overall, the simulation model showed very good agreement with the measurements. As in many of the previous GC studies, the biggest challenge in modeling is to capture the moisture dynamics accurately. One problem was to get the modeled moisture to correspond to the measurement before each GC. The only workable solution was fine-tuning the drying model for each GC case. Without accurate models to explain the effect of refining and furnish type, this kind of tuning is needed. The tuning occurs automatically when the model state (machine speed, thick stock flows, wet press loads, etc.) is simulated to correspond to the old grade situation. Still, the following three problematic phenomena were identified concerning the model accuracy:

- After a large moisture excursion, the simulated moisture returns to the normal level earlier than the measurement. This can also be seen in the bottom right picture of Fig. 4. Cylinder surface and hood air measurements during GCs would help to determine whether the difference come form the drying section model. The key reason could be in the modeling of wire or press section, also.
- Another feature we noticed relates to the amplitude of simulated moisture peaks. The peaks have often been smaller than those measured. **Figure 5** shows an example of this. Even so, the form of the dynamic behavior fits well to the measurements.
- Furthermore, the final moisture level does not exactly equal the measured level (Fig. 4). Even if the initial moisture was tuned to fit actual measurements, this happened from time to time. It seemed to be very difficult to tune the model so that the final moisture never differs from the measured level.

UTILIZATION

After gaining confidence that the simulator can consistently repeat the GCs made on the real machine, we started the what-if experiments. The above-mentioned inaccuracy in moisture dynamics did not hinder us from studying effects of various tuning parameters of the AGC.

Whenever a new GC was taken for further studies, we used the following procedure:

- Select an interesting GC for a base line data (e.g. one from that day's machine run).
- Open the data into a spreadsheet. The target file has been configured so that the set points that define the state before the GC, and the new grade targets that are not calculated by the AGC, are automatically picked up.
- Run the model state to correspond to the old grade in the selected base line data. This is most easily done with a script file. At the same simulation run the drying model is automatically fine-tuned so that the sheet moisture content before the grade change is exactly correct (otherwise the calculated new targets for the steam pressures would not be the same as in the historical data).
- Simulate the GC, usually done as a batch run, although the simulation speed is about 4 times the real time (600 MHz PC). The simulator writes values of pre-defined variables into a file.
- Compare the simulated data with the historical data. The spreadsheet file is used here as an already configured template for the comparison.

After this procedure, if the result seems reasonable, ideas (new or old) can be tested using this new GC as a reference for the performance. It is easy to design a series of simulation batch runs with different parameter values and check what happens to the performance.

Our first simulations concentrated on speeding up the GCs simply by increasing the ramping rates of those variables, which most often limited the total ramping time. One by one, higher rates were tried and the effects on the performance analyzed. The positive impact on GC time was very clear from the basis weight point of view. The moisture fluctuations seemed to get somewhat worse in the amplitude, but they settled down faster. The simulated maximum and minimum moisture values were not so extreme as to cause web breaks, so we were encouraged to tune the actual AGCs ramping rates faster as well. For example, the ramping rate of the machine speed was originally 8 m/min^2. We increased the rate in three steps. In the GC shown in Fig. 4, the rate is 12 m/min^2; in Fig. 5, it is 20 m/min^2. Fig. 5 shows comparison of simulated and measured variables in another GC, with a new set of AGC parameters, both in the machine and in the simulator. The simulator accuracy remained same yet the GC dynamics had speeded up markedly.

Figure 6 shows the same GC as in Fig. 5, but with simulated results only. The light gray curve is the same as in Fig. 5. The dark gray curve shows the same GC using the original AGC parameters (e.g. machine speed ramping rate 8 m/min^2). It is clear that because of the faster ramping, the basis weight reaches the target value earlier and the moisture fluctuation is squeezed into a smaller time window.

The trials with different AGC parameters are continuing at the mill. Now the focus is to find better mutual timing for the ramps in order to decrease the moisture fluctuations during the GCs. For example, changes to start delays of steam pressure and thick stock flow ramps are being studied. When good candidates for the parameters are found, the performance is tested with a large group of GCs to cover the whole area of operation. At the mill, statistics concerning every GC before and after the first parameter changes have been collected. Thus, quantitative information is gained for later evaluation of each step taken in the AGC tuning.

FUTURE WORK

The model development continues. The scope of the model will not be extended, but we are seeking ways to increase the accuracy, especially concerning the moisture dynamics. To achieve more accuracy, we probably need to make extra measurements on wire, press, and drying sections. We must also consider bump tests with the machine.

The developed model offers a platform for troubleshooting, related to GCs or other issues within the simulator's scope. The existing tool can be used to quickly check GC developments and explore new ideas. The model can also be used for operator training and support.

Another project where the model will be used aims at increasing the drying capacity of the machine. Effects of additional dryers, such as air impingement drying units, into the production capacity are studied. Also, use of the impingement dryer in moisture control during GCs is investigated. The development of a model for air impingement drying has been reported recently [18].

CONCLUSIONS

The 3-ply paperboard production process was modeled from the pulp chests to the drying of base board. The model was verified with dozens of grade change runs selected from the mill's historical data. Modeling and the validation phase helped us to understand the interactions during grade changes. Additionally, we were able to spot some weaknesses in operational practices concerning the use of the AGC program.

For a multi-ply process, figuring how the AGC parameters should be changed to speed up grade changes and simultaneously remove unwanted moisture fluctuation is a demanding task. The simulator helped to cut the problem into pieces. It offered a way to visualize the problem and compare the solution candidates. A procedure was developed to simulate grade changes and hunt for better AGC parameter values. It is no longer necessary to only rely on intuition in tuning the process. The parameter changes were carried out to the actual AGC with good results. We have also found new applications for the model, in addition to the ongoing grade change development. **TJ**

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AUTHOR INSIGHTS

The mill had interest in dynamic simulation: methods, tools, accuracy of modelling, and usability at the mill site, potential for practical problems. The subject was selected because it has continuously been a topic that more knowledge and understanding is needed for.

The models and the simulation environment have been developed during many years, and Kaukopää mill is one of the actively involved partners of VTT Industrial Systems' simulation team. Also grade change development has been an active research topic also earlier. GC in a multiply, multigrade machine is a complicated problem, and it can be approached from many different directions. Our starting point was to re-tune the existing system, and learn in doing that. To enable this, the first step was to verify that the model can reflect the real world accurately enough. Compared to other research related to GCs, our approach has maybe paid more attention to model the existing system and study it thoroughly before making any suggestions to change it.

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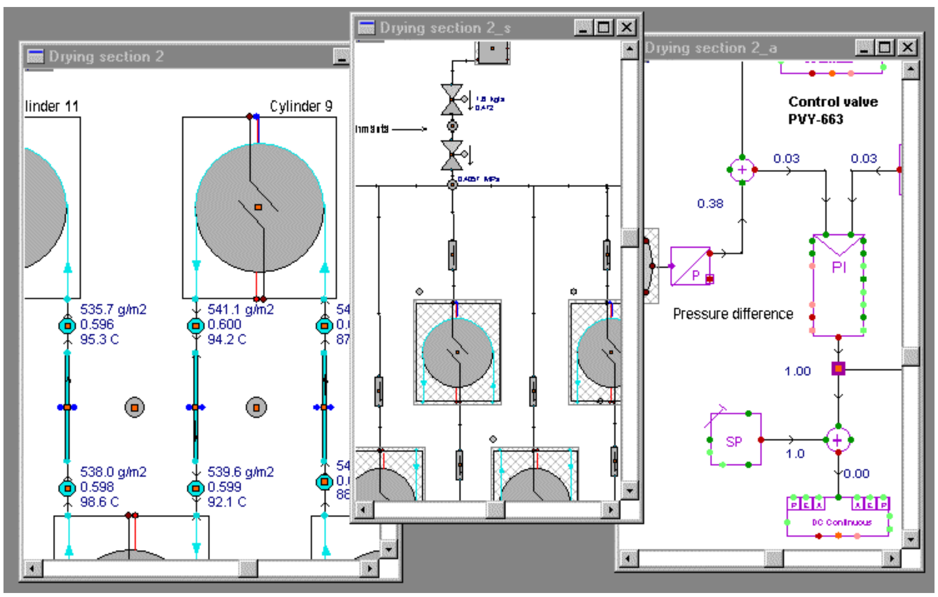
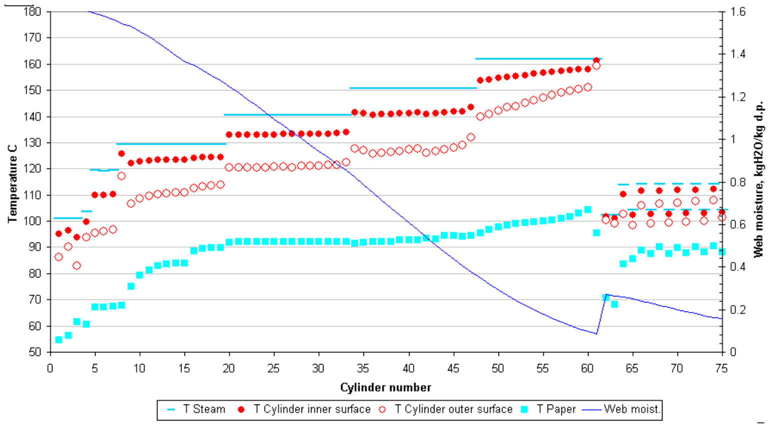
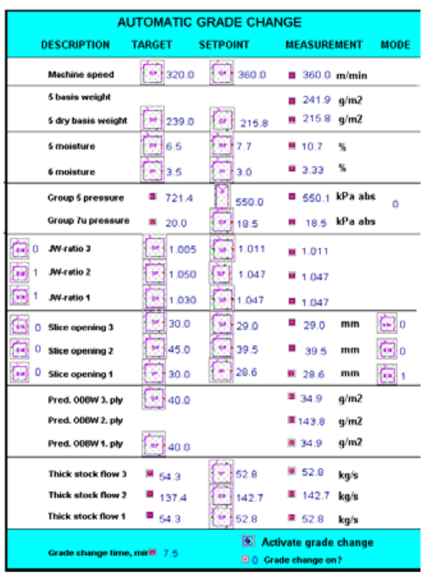


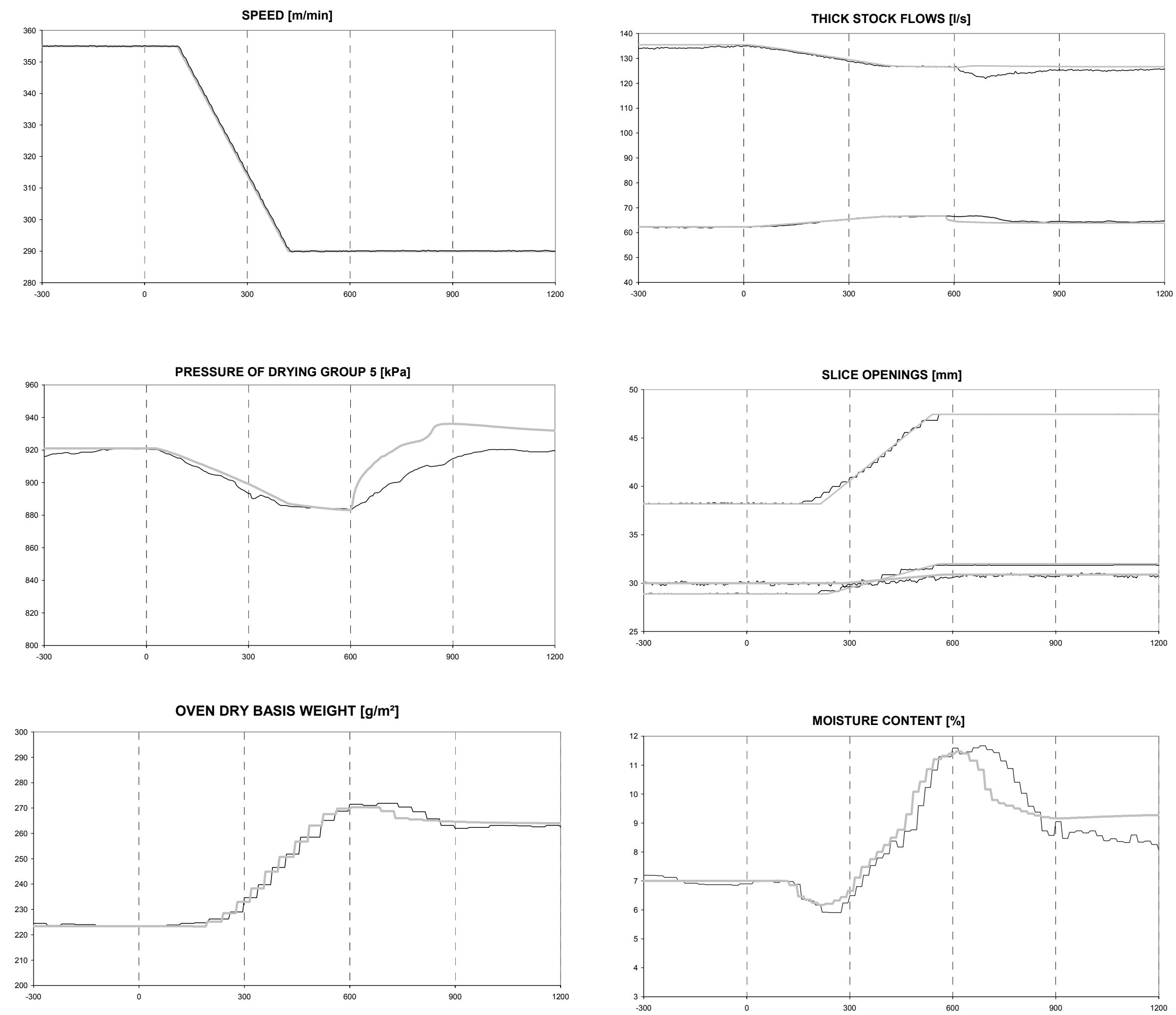
1. The graphical specification of the model for each steam group is divided into three pictures: the web side, the steam and condensate system, and the related controls.



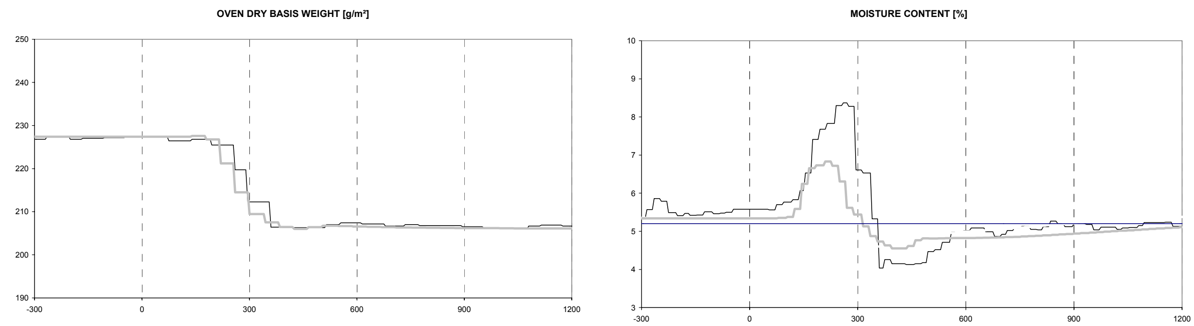
2. An instantaneous profile from the drying section model. Temperatures (°C) of the cylinder inside steam and inner and outer surfaces, and web temperature and moisture content (kg H_2O/kg d.p.) after each cylinder are presented as a function of cylinder number.



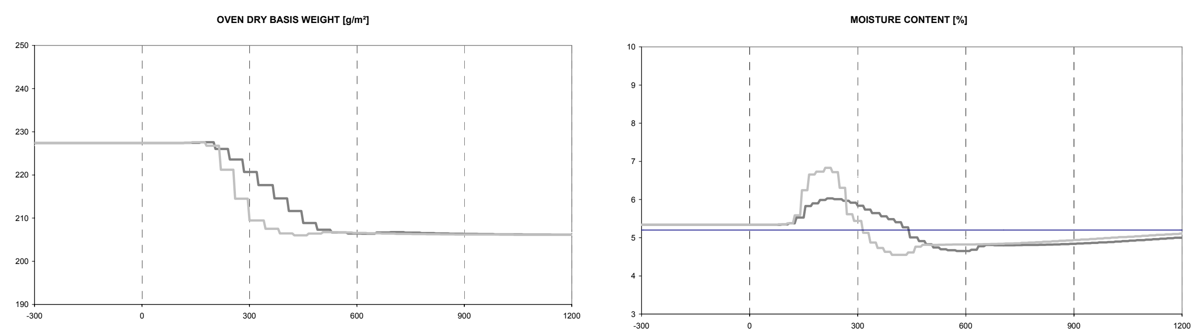
3. The AGC display in the simulator graphics resembles the main picture of the AGC package in the mill DCS. Values in the three main columns are targets for the new grade, current set points and measurements.



4. Measured (black) and simulated (gray) variables in a GC: machine speed, thick stock flows of three layers, slice opening of three headboxes, steam pressure in 5th steam group, oven dry basis weight, and moisture content before the size press. Time scale is in seconds.



5. Measured (black) and simulated (gray) variables in another GC: oven dry basis weight and moisture content. The AGC parameters that define the ramping rates have been changed from the case in Fig. 4.



6. Simulated values in the same GC as in Fig. 5. Light gray curves are the same as in Fig. 5. Dark gray curves correspond to oven dry basis weight and moisture in the case that no changes would have been made to the AGC parameters.