Dynamic modeling of a paper machine, part I: programming and software development

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ABSTRACT: The development of models that accurately predict the performance of a paper machine is valuable to operators trying to optimize paper production and to others wishing to obtain a better understanding of the process. In this study, a dynamic modular paper machine simulator package was developed using Matlab® with Simulink®. Structuring the simulator as a set of modular blocks means that the variety of configurations that can be found on today's paper machines can be modeled by assembling the blocks in different ways. The use of a dynamic model allows the user to see the effects of system changes as they occur, in addition to the steady-state results.

Application: This work can be used to aid in the development of simple models for the simulation of complex dynamic systems.

The manufacture of paper is a complex dynamic process involving an extensive matrix of variables. Each of these variables plays an important role in the ever-intensifying quest for better productivity, as fierce competition cuts into profit margins.

Computer simulations can be a valuable tool for optimizing processes, designing wastewater closure strategies, and helping to visualize a complicated process. Steady-state models are simple to create and provide a view of what the final process state will be given a set of parameters, but offer very little understanding of the steps that occur between the start and finish of the simulation experiment. The dynamics of the papermaking process are much harder to model than the steady-state responses, and for this reason are often overlooked. As computer processing speeds have increased, it has become possible to simulate the dynamics of a paper machine with all of its components and recirculation loops. Disturbances can have long-lasting effects on the products of the papermaking process as they work their way through the many recirculation loops.

Orccotoma, Paris, and Perrier [1] have shown the utility of a modeling approach for quantifying the effects of a disturbance on a paper machine and determining its controllability. Dynamic simulations of the wet end of a paper machine have been used to evaluate the results of disturbances due to web breaks [2] and the dynamics of fines distribution in the white water network [3]. Simplified models have been used by Bonhivers, Perrier, and Paris [4, 5] to test an algorithm for managing white water tanks.

Another challenge faced by paper machine model developers is to enable the model to simulate different machine configurations. Paper machines are made up of many components which are configured on an individual basis to meet the needs of each production process. Because of the vast number of possibilities for component addition and configuration, most models are limited to the machines for which they are designed. By breaking the model down into smaller components and simulating these using basic modular blocks which can be linked to simulate an entire paper machine, a simulator package has been developed which can represent a large variety of machines with the same basic set of modular blocks. Most dynamic models that have been proposed to date focus on one small part of the papermaking process (e.g., the headbox or the forming zone) [6-10]. These dynamic models can be incorporated into existing or new blocks within the library to make their advanced modeling capabilities available in a new context.

The basic modular blocks in the simulation contain many operations and equations, all using parameters and incoming variables to determine the outgoing variables. By looking at the operations and equations that are used in the simulation, the user can see how the incoming variables and parameters are used to calculate the outgoing variables and thus gain a better understanding of the simulation and the papermaking process. In the same way, the more informed user can better configure blocks and set parameters to represent the particular machine being modeled and determine which parameters should be adjusted to optimize the simulation.

METHODS AND MATERIALS

Model programming

The simulator package was developed using the Simulink® and Matlab® software developed by Mathworks, Inc.,

BLOCK INPUT AND OUTPUT PORTS				
TYPE	**1**	**2**	**3**	**4**
LABEL	(*a)	(*b)	(*c)	PROPERTY NAME
j ** Properties contained in signal	water flow rate fiber flow rate fines flow rate dirt flow rate filler flow rate chem 1 flow rate chem 2 flow rate	water flow rate fiber flow rate fines flow rate dirt flow rate filler flow rate chem 1 flow rate chem 2 flow rate table width machine speed	water flow rate fiber flow rate fines flow rate dirt flow rate filler flow rate chem 1 flow rate chem 2 flow rate machine speed	contains a single property as labeled (including but not limited to any property in type 1, 2, or 3 input/output)
**flow rates (lb/min), table width (inches), machine speed (ft/min)				

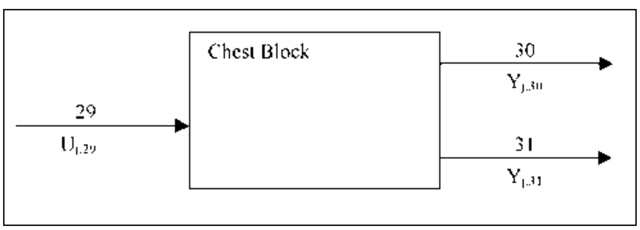
I. Block input and output signal types.

which was chosen due to its dynamic capabilities and relative ease of use. Blocks are constructed and added to a library of blocks, which is then used to construct a model. The models constructed for this study used both the blocks we developed and those built into Simulink. To make this model usable by the largest possible number of users, it was developed with those blocks and models that come with the student version of Matlab. However, the simulations will also run readily on the commercial version of the software.

The blocks use input and output ports to receive information from and pass information to other blocks within a model. After a block is placed in a model, the output from that block is connected to the input of the next block in the model to establish which output ($Y_{j,k}$) should be used for the input ($U_{j,k}$) of the next block (where j represents signal properties and k is the signal location number). Currently there are four types of input and output signals that are used to link the blocks in the paper machine simulator library (**Table I**). Information sent to any particular input port must come from a corresponding type of output port (i.e., type 1 output ports must be connected to type 1 input ports). Each of the blocks in the library also requires the user to set the operating parameters for that block before the simulation is run. These parameters will be used when evaluating functions within the block during the run.

Chest block

The chest block (**Fig. 1**) simulates a well-mixed chest and can be used to simulate a machine chest, white water chest, seal pit, or similar process units. **Table II** shows the inputs,



1. Chest block flow diagram.

CHEST BLOCK			
	DESCRIPTION	TYPE	SYMBOL
INPUTS	Incoming flow	1	$U_{j,29}$
OUTPUTS	Primary flow	1	$Y_{j,30}$
	Overflow	1	$Y_{j,31}$
	DESCRIPTION	**UNITS**	**SYMBOL**
STATES	Mass of water in the chest	lb.	$X_{1,cst}$
	Mass of fiber in the chest	lb.	$X_{2,cst}$
	Mass of fines in the chest	lb.	$X_{3,cst}$
	Mass of dirt in the chest	lb.	$X_{4,cst}$
	Mass of filler in the chest	lb.	$X_{5,cst}$
	Mass of chemical 1 in the chest	lb.	$X_{6,cst}$
	Mass of chemical 2 in the chest	lb.	$X_{7,cst}$
	Total mass in the chest	lb.	$X_{8,cst}$
PARAMETERS	Maximum primary flow rate from the chest	lb/min	$Q_{max,cst}$
	Chest level when maximum primary flow rate is reached	lb.	$M_{Qmax,cst}$
	Minimum primary flow rate from chest	lb/min	$Q_{min,cst}$
	Chest level when minimum primary flow rate is reached	lb.	$M_{Qmin,cst}$
	Maximum chest capacity	lb.	M_{cst}
	Length of the primary flow pipe to the next block in the model	ft.	pl_{30}
	Effective cross-sectional area of primary flow pipe	ft.^{2}	pa_{30}
	Length of the overflow pipe to the next block in the model	ft.	pl_{31}
	Effective cross-sectional area of overflow pipe	ft.^{2}	pa_{31}

II. Chest block input, outputs, states, and parameters.

outputs, states, and parameters used by the chest block.

Initially, the eight states used by the chest block are all set to zero. These initial settings will be used to calculate the first set of output values. The chest block adds the incoming mass and subtracts the outgoing mass of each constituent and the total flow from the corresponding continuous state (see Equation 1).

$$\frac{dX_{x,cst}}{dt} = U_{j,29} - Y_{j,30} - Y_{j,31} \quad \text{for } [x,j]=\{[1,w],[2,f],[3,n],[4,d],[5,a],[6,c1],[7,c2]\}$$
$$Q_{29} = \sum_{j=w,f,n,d,a,c1,c2} U_{j,29} \tag{1}$$
$$\frac{dX_{8,cst}}{dt} = Q_{29} - Q_{30} + Q_{31}$$

The flow rates of the primary flow and the overflow are dependent on the mass of stock in the chest and the user-defined parameters for flow rates and chest levels. The primary flow rate(Q_{30}) from the chest will be zero until the total mass in the chest is equal to the level at which the minimum primary flow rate is reached. At this point, the primary output flow from the chest will start at the rate of $Q_{min,cst}$. While the value of $X_{8,cst}$ remains between $M_{Qmin,cst}$ and $M_{Qmax,cst}$, the change in the primary flow rate between the minimum and maximum flow rate will be linearly proportional to the change in the chest level, between the chest level when the minimum primary flow is reached and the chest level when the maximum primary flow is reached. When the value of $X_{8,cst}$ becomes greater than $M_{Qmax,cst}$ the primary flow rate from the chest will remain equal to the maximum primary flow rate. When $X_{8,cst}$ exceeds M_{cst}, the chest will begin to overflow at the overflow rate (Q_{31}). See Equation (2) for calculations of primary flow and overflow rates.

$$Q_{30} = \begin{cases} 0 & \text{when } X_{8,cst} < M_{Qmin,cst} \\ \dfrac{(X_{8,cst} - M_{Qmin,cst})*(Q_{max,cst} - Q_{min,cst})}{M_{Qmax,cst} - M_{Qmin,cst}} + Q_{min,cst} & \text{when } M_{Qmin,cst} \le X_{8,cst} \le M_{Qmax,cst} \\ Q_{max,cst} & \text{when } X_{8,cst} > M_{Qmax,cst} \end{cases} \tag{2}$$
$$Q_{31} = \begin{cases} 0 & \text{when } X_{8,cst} \le M_{cst} \text{ or } Q_{29} \le Q_{30} \\ Q_{29} - Q_{30} & \text{when } X_{8,cst} > M_{cst} \text{ or } Q_{29} > Q_{30} \end{cases}$$

When there is no mass in the tank, both $Y_{j,30}$ and $Y_{j,31}$ are set to zero. Otherwise, the flow is calculated based on the chest block states, the total primary flow rate, and the total flow rate to the overflow as calculated above. See Equations (3) and (4) for the calculations used to determine the total flow rates for the primary flow and the overflow.

To account for the time that it takes for the primary flow and the overflow to travel from the chest to their destination blocks, a transport delay is applied to each of the flows. The transport delays td_{30} and td_{31} for the primary flow and the

$$\begin{aligned} &Y_{j,30} = 0 \quad \text{for } j=w,f,n,d,a,c1,c2 && \text{when } X_{8,cst} \le 0 \\ &Y_{j,30} = \frac{X_{x,cst}}{X_{8,cst}} * Q_{30} \quad \text{for } [j,x]=\{[w,1],[f,2],[n,3],[d,4],[a,5],[c1,6],[c2,7]\} && \text{when } X_{8,cst} > 0 \end{aligned} \tag{3}$$

$$\begin{aligned} &Y_{j,31} = 0 \quad \text{for } j=w,f,n,d,a,c1,c2 && \text{when } X_{8,cst} \le 0 \\ &Y_{j,31} = \frac{X_{x,cst}}{X_{8,cst}} * Q_{31} \quad \text{for } [j,x]=\{[w,1],[f,2],[n,3],[d,4],[a,5],[c1,6],[c2,7]\} && \text{when } X_{8,cst} > 0 \end{aligned} \tag{4}$$

overflow respectively are calculated based on the flow rate and pipe dimensions for each flow (see Equations (5) and (6)). The values of the constituents in $Y_{j,30}$ and $Y_{j,31}$ that are calculated at time t are not sent to the next block until $t+td_{30}$ and $t+td_{31}$, respectively.

$$td_{30} = \frac{pl_{30} * pa_{30} * 62.4}{Q_{30}} \tag{5}$$

$$td_{31} = \frac{pl_{31} * pa_{31} * 62.4}{Q_{31}} \tag{6}$$

Flow regulator block

The flow regulator block simulates a device that splits a flow, such as a stuff box. This block separates the input signal into two output signals, primary and secondary. The primary output will be equal to the input until the input exceeds the user-defined parameter value for the primary flow rate. If this happens, the excess will be sent to the secondary output.

Starter flow block

The starter flow block sends components to its output stream at given rates for each flow component for a designated time (time-driven) or at a given rate for the total flow until a set mass for each component has been used (mass-driven). This block is useful for initializing the model and can be used in combination with the transport delay block from the Simulink library to introduce disturbances to the system. There are no inputs to a starter flow block and all functions are controlled by user-defined parameters.

Dilution chest block

The dilution chest block simulates a mixing chest where make-up white water is taken from a well-mixed chest to bring the flow rate of the primary input up to the desired level for the primary output as defined by the user. White water is sent to the chest via a secondary input and the overflow from the chest is removed from the secondary output.

A second version of the dilution chest block has a level control on the chest, which sends a controller signal to a block with flow control, based on a mass balance around the block. The incoming white water is thus controlled to maintain the desired level in the chest.

Screen block

The screen block can be used to simulate pressure screens, centrifugal cleaners, and other screening devices. The screen block can also be used to model a saveall by accepting the rejects flow and discarding the accepts flow. Accept and reject flows are based on the input flow rate, mass retained in the screen, and user-defined screening quotients and reject ratios.

Headbox block

The headbox block simulates the action of a hydraulic headbox with a tapered header. The headbox block splits the incoming stock stream into the stock-to-wire flow and the recirculation flow and adds components representing sheet width and machine speed to the stock-to-wire flow signal.

Forming section block

The forming section block is used to model one or more parts of the forming section and can be placed in a model flowsheet between the headbox and the couch roll. The stock that enters the forming section block in the incoming sheet is divided into the outgoing sheet and the effluent flow, based on user-defined retention values for each stream component (Rt_s) and a specified outgoing sheet consistency.

As machine speed and sheet width do not change over the forming section, these parameters can be passed directly from the input to the output.

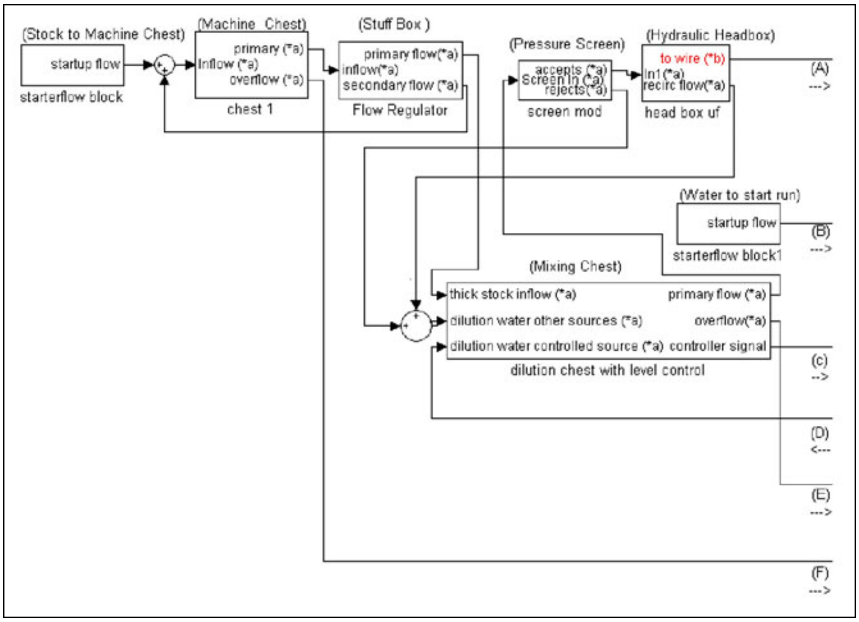
Selective flow mixer

The selective flow mixer combines three input flows to achieve a desired output flow rate from the mixer. The mixer uses all or part of the first inflow, then the second, and then the third, until the user-defined flow rate for the primary output has been reached. The excess flow will then be sent to the secondary output.

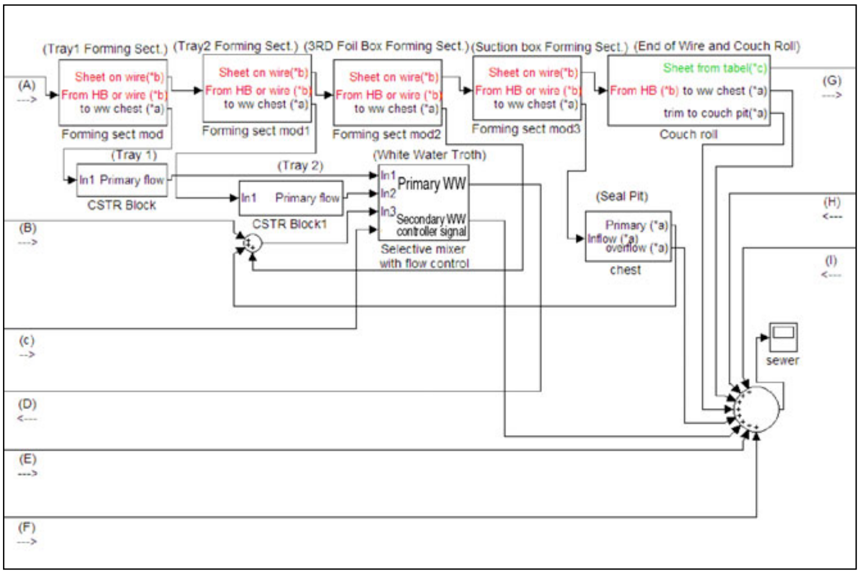
A selective mixer block with flow control is also available. This modified version has an additional input port for a controller signal, which is used in place of the user-defined flow rate to determine the primary output.

Couch roll block

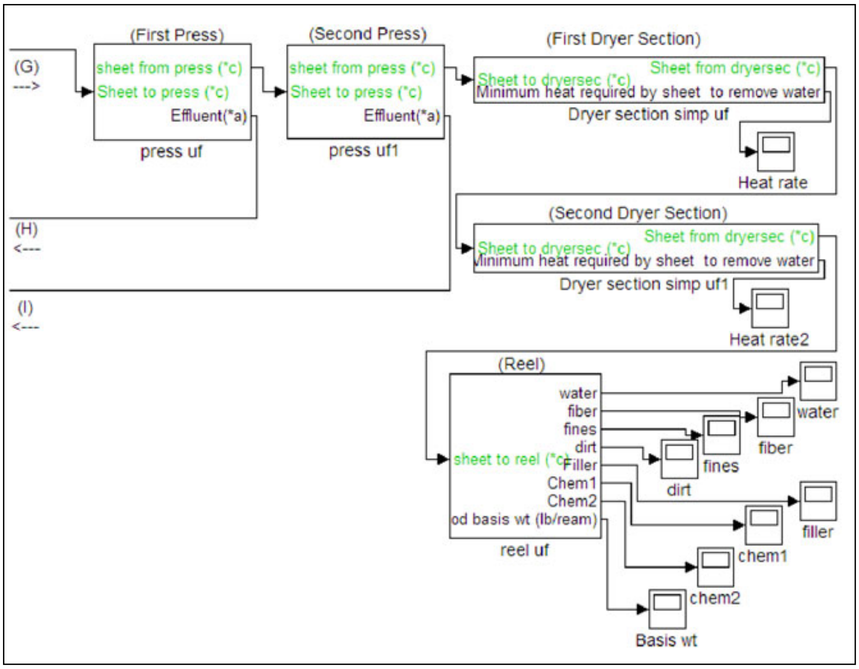
The couch roll block serves as the last stage of the forming section. It incorporates equations to simulate the last part of the forming section and the removal of trim. Mass flow rates in the effluent output from the couch roll block are calculated based on the incoming sheet properties, retention values, and the user-defined exit consistency, in the same way as effluent flow rates were calculated in the forming section block. The constituents of the incoming sheet that do not go to the effluent will be trimmed based on the sheet width coming from the previous block and the user-defined trim width. The trim is sent to the trim output stream and the remainder of the sheet goes to the sheet output stream.



2. Walters pilot plant PM1 simulator (part I).



3. Walters pilot plant PM1 simulator (part II).



4. Walters pilot plant PM1 simulation (part III).

Press section block

The press section block simulates the removal of effluent from a sheet by pressing. The block will split the flow of each component of the incoming sheet into the outgoing sheet and the effluent flow, based on user-defined consistency values for the sheet and the effluent. The speed of the press (sp_{pres}) is calculated based on the speed of the previous block and a user-defined press draw value.

Dryer section block

The dryer section block removes water from the incoming sheet to obtain the desired moisture content in the outgoing sheet. The speed of the dryer section is calculated based on the speed of the previous block, which is received with the input, and the user-defined draw value from the previous block.

Reel block

The reel block separates the incoming sheet signal into each of its components and calculates the oven-dry basis weight of the sheet at the reel. The user can choose from six options for ream size (17 x 22 in. 500 sheets, 1000 $ft.^2$, 24 x 36 in. 480 sheets, 25 x 38 in. 500 sheets, 24 x 36 in. 500 sheets, and 3000 $ft.^2$), which are all converted to $ft.^2$ in the model.

CSTR block

The continuous stirred tank reactor (CSTR) block represents the actions of a well-mixed chest with a primary flow equal to the inflow after the operating level has been reached. The inflow will fill the chest, which starts empty and without an outgoing flow. When the chest operating level is reached, there will be a primary output flow from the chest equal to the inflow and containing constituents at the same concentration as the mass in the chest.

PM1 simulator

A model is constructed using blocks from the paper machine simulator library and the blocks already existing in the Simulink user library. The model was designed to simulate the paper machine in the C.E. Libby pilot plant in Walters at the State University of New York College of Environmental Science and Forestry (SUNY-ESF) in Syracuse, which will henceforth be referred to as PM1.

The PM1 model starts with a mass-driven starter flow block, which sends the initial mass of the thick stock components to the machine chest, simulated by a chest block. The flows to the machine chest are combined in the chest and stored until they are needed. The primary flow from the machine chest is sent to the stuff box. The machine chest being simulated is not designed to have an overflow, and therefore the overflow output port is terminated and the pipe length and cross-sectional area parameters are set to an arbitrary value of one (see **Figs. 2** and **3** for schematics).

The PM1 stuff box, which regulates the flow of thick stock to the mixing chest, is simulated by a flow regulator block. The incoming flow to the stuff box comes from the machine chest primary output flow. The primary output flow from the stuff box is sent on to the mixing chest, and the secondary output flow is sent back to the machine chest (Fig. 2).

The mixing chest is simulated by a dilution chest block with level control. The thick stock input port of the dilution chest block receives its flow from the stuff box primary output. The dilution water from a controlled source comes from the white water trough, while the dilution water from a noncontrolled source comes from the pressure screen rejects and the headbox recirculation flow. The white water flows to the mixing chest are combined and stored until they are needed. The forward flow from the mixing chest is sent to the pressure screen. When the mass stored in the mixing chest exceeds its capacity, the surplus will overflow. The overflow from the mixing chest is sent to the combined sewer. The controller signal of the dilution chest block is sent to the white water trough (Figs. 2 and 3).

The PM1 pressure screen is simulated by a screen block. The screen block receives its incoming flow from the mixing chest primary output flow. Accepts from the pressure screen are sent to the hydraulic headbox, while the rejects are sent back to the mixing chest. The line from the screen to the mixing chest was shut off during this particular simulation, and therefore the reject ratio was set to zero (Fig. 2).

The PM1 hydraulic headbox is simulated by a headbox block. The headbox block receives stock from the screen accepts flow.The stock-to-wire output flow from the hydraulic headbox is sent to the tray 1 forming section, while the recirculation flow is sent back to the mixing chest (Figs. 2 and 3).

The PM1 wire section is simulated by four forming section blocks and a couch roll block.The sheet starts at the tray 1 forming section, is passed to the tray 2 forming section, then to the third foil forming section, then to the suction box forming section, and finally to the couch roll block. The effluent from the tray 1 forming section is sent to tray 1. The effluent from the tray 2 forming section is sent to tray 2. The effluent flow from the third foil forming section is sent to the white water trough. The effluent flow from the suction box forming section is sent to the seal pit (simulated by a chest block); the primary flow from the seal pit then goes to the white water trough, while the overflow goes to sewer. The effluent flow from the couch roll is sent to the combined sewer along with the sheet trim. The sheet, after passing through each forming section and the couch roll block, continues from the sheet output of the couch roll to the first press (Figs. 2, 3, and **4**).

Trays 1 and 2 are both simulated by CSTR blocks. Tray 1 receives its incoming flow from the tray 1 forming section effluent and sends its primary output flow to the white water trough. Tray 2 receives its incoming flow from the tray 2 forming section effluent and sends its primary output flow to the white water trough (see Fig. 3).

The PM1 white water trough is simulated by a selective mixer block with flow control. The first input of the white water trough receives flow from the tray 1 primary flow. The second input of the white-water trough receives flow from the tray 2 primary flow. The third input of the white-water trough receives flow from the third foil forming section effluent and the primary output flow from the seal pit (simulated by a chest block), as well as a signal from a time-driven starter flow block, which initializes the trough at the start of the simulation. The white-water trough also receives a controller signal from the mixing chest, which controls the flow rate of the primary flow from the white-water trough. The primary output flow from the white-water trough is sent to the mixing chest, while the secondary output flow is sent to the combined sewer (Figs. 2 and 3).

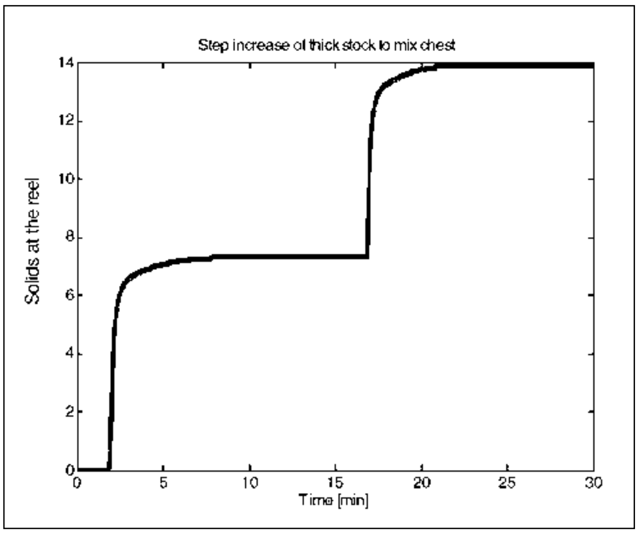
The PM1 press section consists of two presses, each simulated by a press section block. The first press receives the incoming sheet from the couch roll block. The sheet from the first press is sent to the second press, while its effluent is sent to the combined sewer. The sheet from the second press is sent to the first dryer section, and its effluent is once again sent to the combined sewer (Figs. 3 and 4).

The PM1 dryers are simulated by two dryer section blocks. The first dryer section receives the sheet from the second press. The outgoing sheet from the first dryer section is sent to the second dryer section, and the heat flow rate is sent to a scope block. The sheet from the second dryer section is sent to the reel block, and the heat flow rate is sent to a scope block (Fig. 4).

The reel block receives the sheet from the second dryer section. Within the reel block, the incoming sheet is broken down into water, fibers, fines, dirt, filler, chemical 1, and chemical 2 flow rates, and the ovendry basis weight at the reel is calculated. Each of the output ports from the reel block is connected to a scope block (found in the Simulink library) where it can be viewed as a function of time (Fig. 4).

RESULTS

After constructing the model for the PM1 simulation, it was necessary to set the user-defined model parameters. The parameters for the simulation were calculated based on information obtained during the spring 2002 paper run for the Papermaking Processes course (PSE 468) at ESF and with measurements made on the paper machine. The PM1 simulation was run until steady state was achieved, and the values at the reel were noted. The mass flow rate of water was 0.11 lb/min, the fiber flow rate was 7.35 lb/min, and the ovendry (o.d.) basis weight was 39.80 lb/3000 ft^2. This value, while referred to as fiber, is actually composed of fiber, fines, and filler in this simulation. The flow rate of fiber at the reel, obtained from measurements taken during the run, was 7.41 lb/min. The calculated values show a deviation of less than 1% from the measured values. The simulated consistency of the white water to the mixing chest was 0.033%, while the measured value was 0.039%. This lower value for the consistency to the mixing chest in the simulation is most likely the cause of the low simulated fiber flow rate at the reel. To show more accurately the dynamics of the solids at the reel, the flow rate of thick stock to the mixing chest was doubled (**Fig. 5**). The first effects of



5. Solids flow rate at reel with a doubling of thick stock flow to mixing chest at 15 min.

this increase takes approximately 2 min. to reach the reel, and approximately 6 min. are needed to reach steady state. The results of our evaluation of the dynamic capabilities of this simulation will be discussed in a later report.

CONCLUSIONS

The blocks in the paper machine simulator library described here simplify the operations which take place in the various parts of a real paper machine. These modular blocks can be updated and further developed on an individual basis to increase the capabilities of the model, provided they contain compatible inputs and outputs.

Using the simplified blocks, a more complex system such as PM1 can be constructed. This construction of the model in modular block form allows the user to reconfigure the machine in a variety of ways, allowing for greater versatility when modeling different systems. Changes can be made to the model configuration as well as to the user-defined parameters, enabling the user to evaluate the results of various actions without the cost or time necessary for a trial paper run.

Future work on this simulation package will include further development of the blocks in the simulator library to include more advanced mass balances as well as energy balances. While the mass balances in and around the sheet are important for the production of a viable sheet, the energy used by the paper machine is important not only to quantify machine limitations, but also to calculate the energy costs of production. Further development will also include the addition of blocks for pulping operations, stock preparation, and converting operations, with the intent of providing a package which can model a fully integrated paper mill. **TJ**

Submitted: June 19, 2006
Revised: September 12, 2006
Accepted: September 14, 2006

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AUTHOR INSIGHTS

The development of models that enhance the optimization and understanding of various paper machines is important to industry and to the research community. This work has resulted in the development of a simple set of models that can be configured to represent a wide variety of systems.

Most previously developed paper machine models are steady-state. The models developed in the course of this work are dynamic and can more fully describe the state transitions brought about by disturbances and operating changes.

The most difficult problems encountered in this work were first, how best to represent the signals that would be sent from one process block to another to convey not only material flows but also process information, and second, how best to account for the time that the stock is in transit from one operation to the next. This latter problem was addressed by applying a time delay to the signal, based on pipe dimensions or sheet speed.

This work confirmed our belief that simplified model blocks, each describing the operation of one small part of a paper machine, could easily be configured and modified to represent a wide variety of systems. Mill personnel can use these models to simulate dynamic paper machine mass balances and then optimize machine parameters using the simulation, avoiding the cost and complexity of on-machine trial runs.

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Future work will involve expansion of the model library to include pulping and converting operations as well as energy balances.

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