Large-scale dynamic paper machine models

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Abstract

Optimising industrial operations, building soft-sensors and model-based controllers and even fine-tuning controllers is much easier with a good plant model. Karlstad University in collaboration with Stora Enso have initiated a project to develop a series of dynamic models for two 5-ply paperboard machines at Skoghall, Sweden. One aim is to better predict paper properties which requires modelling the entire machine, the other is to model only the short circulation with the intention of closer control of fines and faster grade changes.

Because the full machine models quickly become unwieldy, smaller 'mini-models' were constructed for control-type investigations. To reduce the computation burden further, analytical solutions for the pressure-flow balance are proposed. All models were validated against almost one year of plant operating data.

This paper highlights the difficulties in modelling a large industrial system with widely varying time constants, dubious transducers and the ubiquitous noise. We also contrast different simulation tools used at the various levels of model hierarchy and finally the paper demonstrates the use of simplified models to improve the operation of the board production.

INTRODUCTION

This paper is focused towards the modelling of paper and board machines with the intention to improve production by better control and possible design modifications. The increased awareness of the benefits of simulation in the process industries has spawned a number of specialty and general purpose simulators over the last decade. Aided by the continuing improvements in affordable computational power, a serious commitment by developers to 'user-friendliness', and strong improvements in the underlying numerics of the solvers. The result is that ordinary users, with these automated modelling tools, are encouraged to construction complex models and experiment with "what-if" scenarios in a wide variety of industries and applications, sometimes even to dangerous extremes.

Models of paper machines and approach systems

The tackling of realistic industrial problems by the non-specialist is still an open problem, [1, 2]. Building a dynamic model of a complex system such as a 5 layer paper board machine investigated in this study is a nontrivial undertaking and for a variety of reasons, partly economic perhaps, the pulp and paper industry was until recently poorly served by the standard chemical process simulators, [3, p1141]. The reasons for this are partly explained by the unique characteristics of this industry that makes little use of a large physical property database of say hydrocarbons, or a comprehensive thermodynamic library, but does need data on components such as pulp fiber types, fines, clay additives, non-Newtonian flow models, and correlations of paper properties such as bending stiffness, tear strength and brightness, [4, Chap 21]. Experience has shown, [5, 6], that while the understanding of hydraulics is good, it is lacking in the areas of drainage, bonding, paper property prediction and the effect of chemical additives.

A study such as [7] using CADSIM and PAPDYN is a typical steady-state investigations. Dynamic models are less common being considerably more expensive to develop and validate. Data-driven input-output dynamic models are commonly used in control studies such as [8–10], which typically use standard system identification techniques such as ARX, partial-least squares or splines,[11], to build blackbox models.

The disadvantages of purely heuristic models prompt the development of models based on first principles such as mass, energy and momentum balances, [12]. The drawbacks of these more fundamental models are that they become increasingly unwieldy and harder to validate. Many studies such as [13, 14] are essentially unvalidated or alternatively [15], where a 284 state model of a paper dryer, was validated by comparing with a single time constant from a publication 36 years earlier! Validated models such as [6, 16, 17] are less common.

PLANT DESCRIPTION

Skoghall mill, located in central Sweden, produces board products (5 layered board) in two board machines, KM7 and KM8 schematically depicted in Figure 1. A project initiated by Stora Enso, Skoghall and Karlstad University with the intention to improve operation resulted in the construction of 4 dynamic models as shown in Table 1. Two of the models are of the entire machine from stock preparation to reel with the intention of modeling paper properties, in particular bending stiffness and tensile stiffness index. The other two models, with a time resolution of seconds, are of just the short circulations with the intention to model the water, fibers and fines. This paper only discusses the short circulation model for KM7, [6] and the full model for KM8, [18], (denoted by an asterisk in Table 1.)

Unlike the KM8 model developed originally for machine re-design and the development of new paper board grades, the KM7 model of the short circulation is intended for control and operation optimisation studies and models the pressure and flow variations in the short circulation. These type of operations span a much tighter time span, necessitate better fidelity at higher frequencies and track more complicated nonlinear dynamics.

The plant is characterised by substantial conveyor runs and recirculations contributing to large deadtimes, structural discontinuities (such as tanks running dry), poor placement of transmitters increasing the time delay further. The investigations of interest deal with unusual cases such as poor mixing, plugging of screens with pulp, air entrainment in piping runs, and haphazardly tuned controllers connected to poorly maintained oversized control valves.

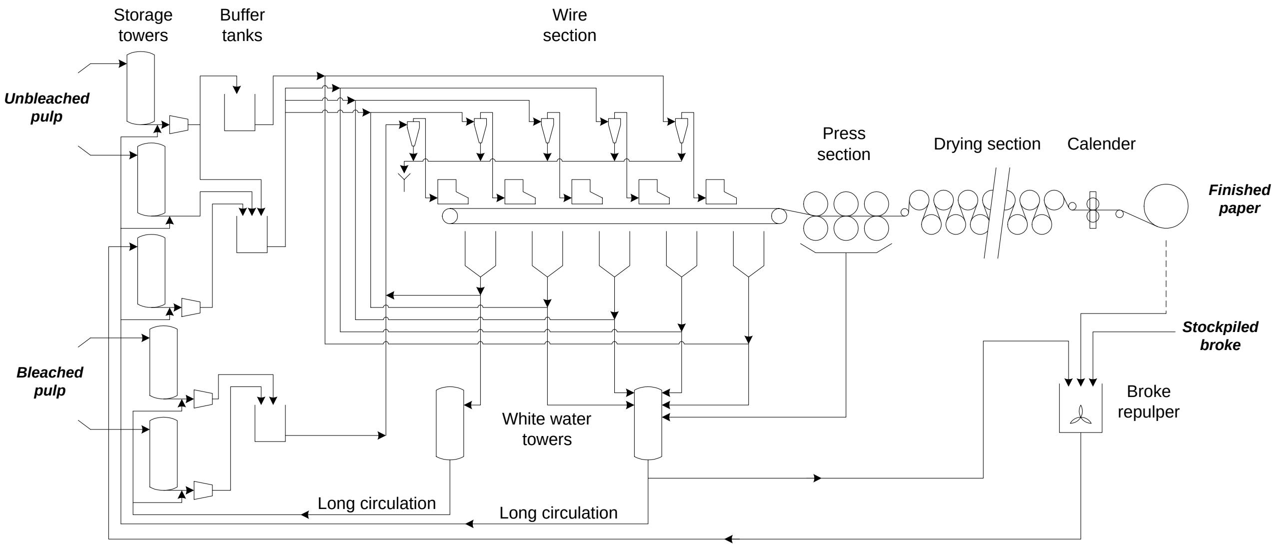

Figure 1: Simplified process flow diagram of board machines KM7 & KM8.

Table 1: Board machines and models used in this project

	KM7 (1976)	KM8 (1996)
Prodn.	230,000 t/yr	320,000 t/yr
Length	251 m	298 m
Width	5.4 m	8.1 m
Speed	540 m/min	800 m/min
Extent	Full machine	Full Machine*
What	Paper properties	Paper properties
Extent	Short circ.*	Short circ.
What	fiber, fines, bw	fiber, fines, bw

Choosing a simulation environment

To a large degree the underlying software tool dictates much of what the model is capable of. Steady-state simulators specifically directed to the pulp and paper industry such as WinGems or MassBal II tend to be used for retro-fitting and design tasks, whereas dynamic simulators are more suited for control and operations. While some packages (e.g. FlowMac) now have the capacity for dynamics of flows and levels, they are essentially steady-state flowsheeting mass balance models and are used as such.

The dynamic simulators currently fall into two camps: those with a academic heritage (SpeedUp, [19]; gProms, [20]; Omola, [21]; Matlab/Simulink, [6, 14, 22, 23] Dymola/Modelica [24]) which tend towards strong underlying numerical routines and often innovative thinking but intended for very general purpose modelling, and those with an industrial heritage (Flow-Mac, IDEAS, Entech's VisSim, [5], KCL-WEDGE, [25], VTT's APMS (advanced paper mill simulator) which concentrate on the effort into building a high quality library of unit operations, typically restricted to certain industries.

As no single product combined the necessary unit operations for board machines, (head-boxes, fan pumps, screens etc.), robust DAE solvers, [26], elegantly handle variable direction transport delays, exhibit ease of use (panning/zooming, printing large PFDs) and be able to produce documentation we decided to use three levels of simulation running under two different simulators. This was unfortunate since the original intention was to minimise the amount new software the plant engineers would need to use.

At highest level we used IDEAS (Integrated Design Engineering with Advanced Simulation) from AMEC Technologies Inc. which is a block-orientated dynamic simulator built on top of Extend from ImagineThat! targeted originally at the pulp and paper industry, [27]. Fig. 2 gives an indication of the size of the model for KM8. The block diagram approach is natural for chemical engineers used to a unit operations thinking and also has the advantage that it enables vendors to supply libraries of equipment (such as GL&V/Celleco) but be reticent about the exact details contained in these blocks. The downside of the 'closed box' approach is that the solver engine (and user) cannot extract the necessary information such as gradients (Jacobians/Hessians, infeasible regions etc.) to use equation-based schemes currently favoured by the simulation community.

Ideas proved slow, employed suspiciously crude numerical integration routines, hiccuped on discontinuites, and for a product that we expected to be strong in the internals of blocks that are of interest in the pulp and paper industry, some are surprisingly thin in intellectual property. It also took some experience to both scale the problem and find reasonable initial conditions so the solver could get started.

But from our personal experience problems start appearing in modelling noise and (the associated problems in integrating stochastic differential equations), the rapid explosion in complexity and the under exploitation of symbolic manipulation (automated or human) to cast the problem into a better posed problem perhaps by separating the linear parts from the nonlinear or choosing good tear variables. We also regularly observe excessive stiffness in the differential equations due to an ill advised choice in state variables, under-utilisation of results from modern numerical analysis (such as sparse problems, adaptive integrators, DAE solvers

Figure 2: The process flow diagram of KM8 in Simon's IDEAS.

etc) and often poor implementation of unusual events such as deadtimes, hystersis and other discontinuities.

Model Validation

A complete validation of the IDEAS model is a challenging task, so we separated the requirements to: (1) validating the steady-state conditions of flows and concentrations where measured by the DCS with those predicted by the full-scale IDEAS model, then (2) using these flow values as constants in the SIMULINK we fine-tuned the dynamics. Given that the model is fundamentally based, in principle there should be few parameters to regress. In practice we needed to adjust vessel mixing and pipe friction parameters, cleaner efficiencies, and wire retention values to match the experimental steady-state values of concentrations and flows, and the sporadic laboratory sampling at points not measured online. Using periods just prior to machine shut-downs, we could step-test the plant without incurring a significant economic penalty. This data was used to validate the plant dynamics. Finally a fiber mass-balance over a period of weeks gave some indication of the quality of the steady-state model. Further details regarding the validation are discussed in [28].

IMPROVING PRESSURE-FLOW CALCULATIONS

Simulation speed is still the overriding user concern according to one simulation vendor, [29]. In the pulp and paper industry, it is the computation of the hydraulics that limit the integration speed rather than say thermodynamic calculations. The problem is particularly noticeable in the dynamic simulation case where the flow calculations are to be computed at every integration time step based on the instantaneous pressures around the piping network. The developers of a high fidelity dynamic simulator for paper machines found it necessary to simplify considerably the calculations for pressure drop since the time required to solve the Colebrook equation was prohibitive, [5]. Our own experiences showed that using Simon's IDEAS we could only manage simulation speeds of around 3 to 5 times faster than real time on a 300MHz PC which was too slow for the proposed control-type investigations. This section attempts to alleviate the need for simplification, avoid the requirement of a chart, and to improve the reliability of the algorithm by avoiding solving nonlinear algebraic equations using generic routines such as Newton-Rhapson without overly compromising solution speed.

Previous attempts to improve the method have either reworked the data to produce approximate explicit functions, [30, 31], or assumed constant friction factors in the turbulent region, [32], or despite the claim for an analytical solution, [33], used iteration in some form. However while neither the Colebrook equation

$$\frac{1}{\sqrt{f}} = -2.0 \log_{10}\left(\frac{2.51}{\mathrm{Re}\sqrt{f}} + \frac{e/d}{3.7}\right) \tag{1}$$

or the Moody friction-factor chart is suitable for direct incorporation into a simulator, we can re-work Eqn. 1 into

$$\frac{1}{\sqrt{f}} = 0.8686\,\mathrm{W}\left(\frac{\exp\left(\frac{e/d\,\mathrm{Re}}{8.0666}\right)\mathrm{Re}}{2.1802}\right) - \frac{e/d\,\mathrm{Re}}{9.287} \tag{2}$$

which is explicit in friction factor f. Eqn. 2 involves Lambert's $W(x)$ function, [34], which is defined implicitly as the function that satisfies $W(x)\,e^{W(x)} = x$. Various algorithms have been published for the numerical calculation of Lambert's function, but most have concentrated only on the principle branch, [34, 35]. Nearly all of them establish a good starting guess using some sort of approximating function, which is subsequently refined using a Newton or Halley iteration. The symbolic toolbox for MATLAB provides a complete numerical routine for Lambert's $W_k(x)$ function which in turn calls the MAPLEV implementation. This method is accurate but slow and overly general since it is defined for all branches.

A second common iterative calculation in pressure/flow problems is where the flow velocity in a pipe is given by

$$v = \sqrt{\frac{2gdh_L}{Lf}} \tag{3}$$

with the Swamee and Jain equation for smooth pipes,

$$\frac{1}{\sqrt{f}} \approx -1.8 \log_{10}\left(\frac{6.9}{\mathrm{Re}}\right) \tag{4}$$

This is a coupled system of two nonlinear equations in v and f and could be solved using a multivariable Newton solver. In practice, even using the values from the previous iteration as initial estimates, and using competently written numerical routines, this is not always successful. MATLAB's general purpose multivariable root finder, `fsolve`, from the OPTIMISATION TOOLBOX was particularly sensitive to initial conditions, while a multivariable Newton showed less sensitivity. Using two nested univariate solvers (such as `fzero` in MATLAB) proved robust, but slow.

Inserting Eqn. 4 in Eqn. 3 gives the velocity as

$$v = \sqrt{\frac{2gdh_L}{L}}\, 1.8 \log_{10}\left(\frac{\rho v d}{6.9\mu}\right) \tag{5}$$

or explicitly

$$v = -\frac{9\sqrt{2g}}{5\log_e(10)}\sqrt{\frac{dh_L}{L}}\,\mathrm{W}\left(-\frac{23\sqrt{2}\log_e(10)}{12}\frac{\mu L}{\rho d\sqrt{Lgdh_L}}\right) \tag{6}$$

again in terms of $W(x)$. Lambert's W function returns real values for arguments in the interval $[-1/e, \infty)$ and for negative arguments, it exhibits two branches as shown in Fig. 3. Since

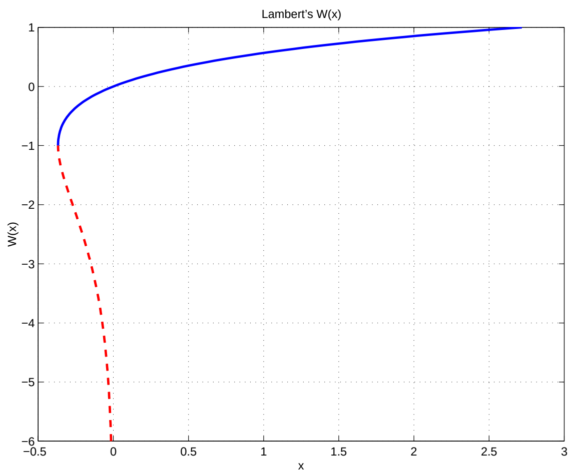

Figure 3: Lambert's $W_k(x)$ function showing the principle branch, $k = 0$, (solid) and the $k = -1$ branch (dashed).

the argument of Lambert's function $W(x)$ in Eqn. 6 will always be negative for physically meaningful piping problems, we must first establish which branch of $W(x)$ contains the solution that makes physical sense. Choosing the wrong branch will lead to Reynolds numbers that are laminar. We know that an increase in head will lead to an increase in velocity, or $dv/dh_L > 0$. The solution for velocity, Eqn. 6, is in the form

$$v = -\alpha\sqrt{h_L}\,W\left(\frac{-\beta}{\sqrt{h_L}}\right) \tag{7}$$

where α and β are positive constants (given simply by comparing Eqn. 7 to Eqn. 6 but whose values are unimportant for the following development.) Differentiating Eqn. 7 with respect to the head loss h_L gives

$$\frac{dv}{dh_L} = \frac{-\alpha}{2\sqrt{h_L}}\frac{W\left(\frac{-\beta}{\sqrt{h_L}}\right)^2}{\left(1 + W\left(\frac{-\beta}{\sqrt{h_L}}\right)\right)} > 0 \tag{8}$$

For Eqn. 8 to be positive, the denominator term $1 + W\left(\frac{-\beta}{\sqrt{h_L}}\right)$ must be negative, or

$$W\left(\frac{-\beta}{\sqrt{h_L}}\right) < -1 \tag{9}$$

which implies the $k = -1$ branch for W_k as seen in Fig. 3. This branch is not computed in the commonly available algorithms for Lambert's function and the reliable numerical computation is the topic of an upcoming report.

MINI MODELS

For some applications smaller models (mini-models) are preferable. Often these simplified models are created simply from the input/ouput data generated by the rigorous model. The problem is that unless special attention is paid to the structure, they may fail to capture the known nonlinearities of the plant. Fig. 4 compares a linear 2-input/1-output ARX model to basis weight data collected from KM7 where the model was regressed using data until $t = 12.5$ hours. After that fitting period, the model diverges from the measured basis weight data.

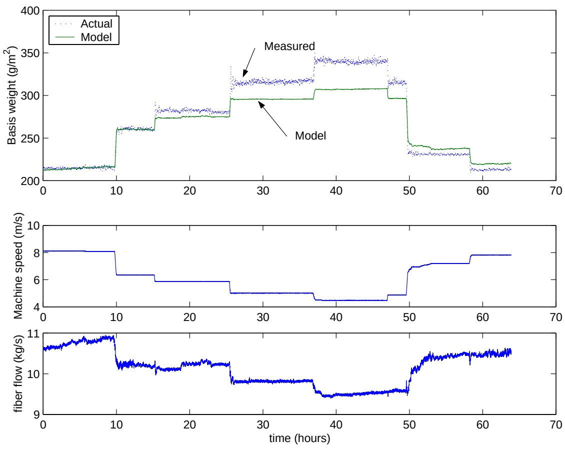

Figure 4: A linear ARX model to predict basis weight using machine speed and thickstock fiber flow fails to account for machine nonlinearities.

Figure 5 shows the preferred approach where the entire plant from Fig. 1 is simplified for the purposes of predicting the response of a key chemical additive to the board. This simplification was generated using physical knowledge about the plant. Figure 6 compares the simplified model (dotted line) to the full rigorous model. There is a difference, but we have chosen to regress the parameters to capture the steady-state gain and the first bump preferentially rather than minimising the say the total error.

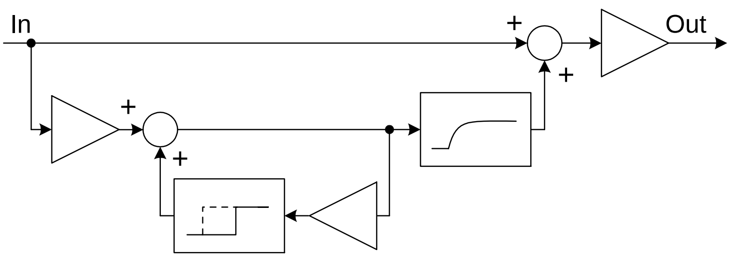

Figure 5: Simplified block diagram model of KM8.

Basis weight is a key quality variable measured online using a radioactive scanning device described in [36]. For control purposes one normally assumes a first-order plus deadtime response from the basis weight valve to the basis weight measurement. Since the machine

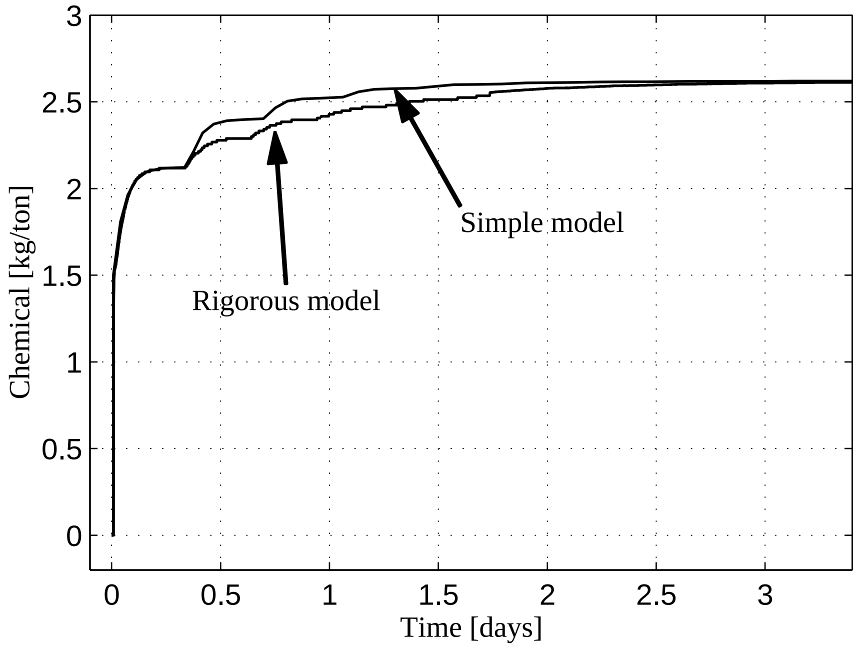

Figure 6: Step response of chemical additive on KM8 with a simplified linear model superimposed.

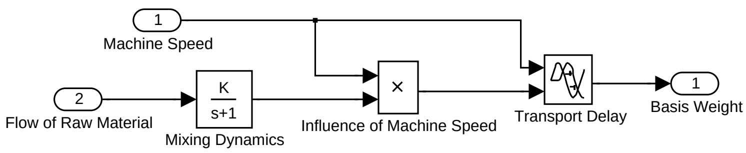

Figure 7: A diagram of a simplified model to predict basis weight

speed is varied when producing different paper grades to keep the dryers running at their optimum, the loop becomes nonlinear. To capture this nonlinearity we include a variable gain representing the influence of machine speed and variable transport time through the machine . Fig. 7 shows a simplified model incorporating these changes.

The mini model shown in Fig. 7 captures the main basis weight dynamics. However, there are some features that the model is unable to capture. As shown in the process flow diagram the short circulation includes several recycle loops. These recycle loops is contributes to a stair shaped response when subjected to a step input. Since the proposed model is of first order it will not capture this phenomena.

CONCLUSION

A detailed dynamic model of the short circulation of a 5 layer board machine was developed using a three layer simulation approach and validated from both bump tests and typical operating data. The model is intended to be used for improving the grade change sequencing, enabling “what-if” scenarios to help solve various operational problems posed by the staff at the mill. This model constitutes part of a larger project involving 2 board machines and 4 models. Owing to the complexity, the model was built and validated in 3 parts. The resulting simplified models indicated substantial improvements when used as part of an internal model controller for grade changes.

Many simulated examples are not academically orientated, and could in principle, be investigated semi-analytically without resorting to running a full-scale simulation. However the illustrative power of simulation to demonstrate key concepts to operators should not be underestimated, nor should the ability to explore second-order effects that may not be self-evident to all but the most experienced.

Our experiences over two years of working closely with the operating company is that the industry were reluctant to act on the simulated results, except where the analysis (typically negative) reinforced their own pre-supposed ideas.

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