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Experiences building and validating a large-scale dynamic paper machine model

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Abstract

Building and validating a dynamic model of a five layer paper-board machine is a nontrivial undertaking. Karlstad University in collaboration with Stora Enso have developed a dynamic model of a 5-ply board machine producing packaging board at Skoghall, Sweden. Three models were developed in decreasing order of complexity. First a detailed dynamic model of the short circulations was built using Simons IDEAS, which is a special purpose dynamic simulation package intended for the pulp and paper industry. This full model contained a comprehensive differential and algebraic equation set so consequently quickly became too unwieldy for the intended uses of troubleshooting, aiding retro-fits and model-based control studies. A slightly simplified version of this model was re-engineered in Simulink, dropping the algebraic constraint equations and implementing the transport delays in a more elegant manner. Finally transfer function models, suitable for online control and optimisation tasks were identified from production data with a structure given by semi-rigorous reasoning. All three models were adjusted and subsequently validated against almost one year of plant operating data.

This paper highlights the difficulties in validating a large industrial system with widely varying time constants, dubious transducers and the ubiquitous noise. We also discuss the necessary, but delicate, task of performing model reduction; 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 performance of the adaptive IMC controller for the basis weight in the finished board.

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1 Computer aided modelling for chemical plants

The renewed interest in modelling in the chemical process industries, at least in Scandinavia, can be explained by (1) the now ubiquitous PC in the control room and on the engineers desk, (2) adequate computing power, coupled with the often underestimated attractive user-interface. The result is that users, with automated modelling tools and little training, are encouraged to construction complex models and experiment with "what-if" scenarios in a wide variety of industries and applications. A review of general modelling for the process industries is given in [16].

Nonetheless the tackling of realistic industrial problems by the non-specialist is still an open problem. 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, [7, 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.

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

Given the unique characteristics and special requirements of the pulp and paper industry and taking into consideration the typical user for a simulator, the ideal modelling and simulation software should assist in a number of tasks such as the construction of the model (to avoid high index problems, algebraic loops, needless discontinuities), subsequent simplification (model reduction) hiding the solution algorithm from the model, and changing the algorithm (perhaps using symbolic manipulation if necessary) if the requirements change.

Furthermore we would like to see the tool allow a graceful upgrading from static to dynamic models, linear to nonlinear, lumped to distributed parameter all computed rapidly to encourage experimentation with the model within an open architecture with good communications to external programs, particularly the distributed control system.

We favour the block diagram approach since it is natural for chemical engineers used to a unit operations thinking. This also allows vendors to supply libraries of equipment (such as GL&V/Celleco[1], a vendor that supplies cleaners and disk filters, produces their own library of equipment models for FlowMac[2]) but be reticent about what is 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.

2 Models of paper machines and approach systems

Simulations, while not common, are being increasingly used in the pulp and paper industry. An industry-wide overview of modelling with particular attention to control is given in [17, 8]. Studies such as [4] using Cadsim and Papdyn or [9] is perhaps typical of steady-state investigations. Dynamic models are less common being considerably more expensive to develop and validate. Input-output dynamic models are commonly used in control studies such as [1, 18, 11], which typically use standard system identification techniques such as ARX, partial-least squares or splines,[6], to build blackbox models. The well recognised disadvantages of purely heuristic models prompt the development of models based on first principles such as mass, energy and momentum balances, [13]. The drawbacks of these more fundamental models are that they become increasingly unwieldy and harder to validate. Many studies such as [12] are essentially unvalidated or alternatively [3], where a 284 state model of a paper dryer, was validated by comparing with a single time constant from a publication 36 years earlier! Combinations of blackbox models such as neural networks and first principle models is a natural extension, [19].

To a large degree the underlying software tool dictates much of what the model is capable of. Steady-state simulators such as WinGems[3] 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 used as such.

The dynamic simulators currently fall into two camps; those with a academic heritage (SpeedUp, [14]; gProms, [15]; Omola, [2]; Dymola/Modelica [5]) which tend towards strong underlying numerical routines and often innovative thinking but intended for very general purpose modelling, and those with an industrial heritage (FlowMac, IDEAS, Entech[4]) which concentrate on the effort into building a

[1]http://www.crosswinds.net/ celleco/
[2]http://www.papermac.se
[3]http://www.pacsim.com/
[4]http://www.entechcontrol.com/index.htm

high quality library of unit operations, typically restricted to certain industries.

3 Process description and modelling hierarchy

Skoghall mill, located in central Sweden, produces board products (5 layered board) in two board machines; KM7 and KM8. 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 the short circulations with the intention to model the water, fibers and fines. This paper only discusses the short circulation model for KM7 (denoted by an asterisk in Table 1.)

Table 1: Board machines and models used in this project

	KM7 ('76)	KM8 ('96)
Prodn.	230,000 t/yr	320,000 t/yr
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

The three grades given in Table 2 were chosen as representative of the 30 different grades of board products produced by KM7. These are used as nominal operating points.

Table 2: Nominal grades chosen as representative operating conditions for KM7

Basis Weight, g/m^2	*Machine Speed*, m/min
350	295
262	412
230	489

3.1 Hierarchical simulation tools

During the course of this investigation, it was found necessary to use three levels of simulation (using two different simulators) since no single product satisfied all the demands. At highest level we used IDEAS (Integrated Design Engineering with Advanced Simulation)[5] from Agra-Simons which is a dynamic simulator built on top of Extend from ImagineThat![6] targeted originally at the pulp and paper industry, [10]. Our original intention was to use this product exclusively for the modelling task, but in practice it proved too 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. However the largest problem was that the execution speed was only 2 to 3 times faster than real time which was too slow for the intended controller design studies. It also took some experience to both scale the problem and find reasonable initial conditions so the solver could get started.

These problems necessitated that we re-engineer the model, but without the time-consuming algebraic equations to solve the pressure-flow network in SIMULINK. This model retained the nonlinearities and most of the physically meaningful components such as vessel sizes, pipe lengths, pump characteristics etc and the dynamics associated with the transducers, particularly the scanning frame for moisture and basis weight.

From this still complex nonlinear dynamic SIMULINK model of the stock preparation and wet-end of the machine we could develop still simpler models suitable for model based control studies. These models are best considered as grossly simplified fundamentally based models rather than totally blackbox models.

4 Validation

A complete validation of the IDEAS model is a challenging task, so we separated the require-

[5] http://www.simonstech.com/
[6] http://www.imaginethatinc.com

ments to: (1) validating the steady-state conditions of flows and concentrations (consistencies) where measured of 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. Finally we built simple transfer function models suitable for model based control tasks using the now validated Simulink model as our truth model. Fitting black-box transfer function models to production data without any physical based reasoning failed to capture the nonlinearities and varying deadtime of the true plant. Consequently these models could not be extrapolated to grades not used for the identification.

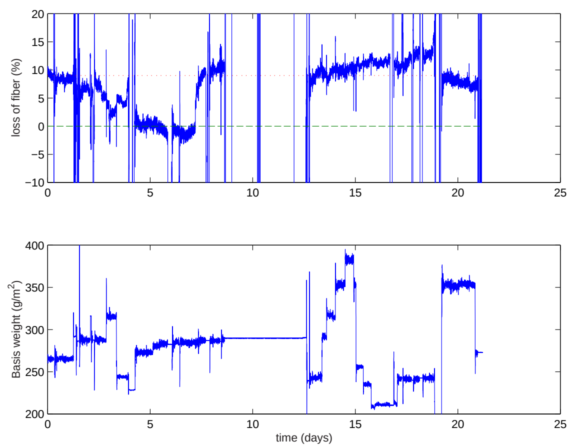

Figure 1: Production over 3 weeks showing (a) Fiber loss and (b) Basis weight

4.1 Steady-state validation

Even though IDEAS is a dynamic simulator, its principle use was to fine tune the steady-state values of the flows and concentrations of fiber around the approach system which is a complex interconnected system with hydrocyclone cleaners and recycle. Since the model is physically based, ideally there should be few parameters to be regressed, but 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.

Fig. 1 shows the total fiber balance over almost 3 weeks. Due to trimming of the sheet and cleaning losses, we expect the fiber loss to be about 9%. This figure gives an indication of the quality of the overall model.

4.2 Dynamic validation

The main dynamics of the board machine are due to the deadtime through the press and dryer sections, unusual filtering due to the scanning frame for moisture and basis weight measurements and the recirculation of fibers from the wire through the short circulation and dilution water.

Typical operating conditions are appropriate for establishing system gains while grade changes can give some dynamic information. However during a grade change, where the machine speed is ramped under manual operation, only the gain is substantially changed, which makes it difficult to resolve between the deadtime and time constants. Dynamic studies are better done by adjusting the thickstock flow, preferably staggered in different layers during the period just prior to a shut down, when we have the opportunity to change inputs without concerns with off-specification production.

Fig. 2 shows the results of the model prediction and measured basis weight for a series of bump tests in thickstock flow in the top, middle three, and bottom layers of the board. During these tests, the machine was disturbed by other factors (such as water added to tanks running low) which were accounted for in the model. Two scanning frames were used: one in a fixed position on the sheet and one scanning across the sheet. The fixed position scanner, due to its position, is sensitive to the excessive moisture, and due to an erroneous internal filter was sensitive even to the cross-profile, so consequently delivered unreliable readings and is only included for comparison in Fig. 2.

It is known from past tests that the lip opening, the moisture readings in the scanning frame and the flow rates are relatively accurate, but the consistency readings suffer from a bias, especially at low concentrations, and since they are located before the machine chest, do not give an accurate reading of the consistency in the thickstock just prior to the input to the wet end of the machine. Therefore the main adjustments

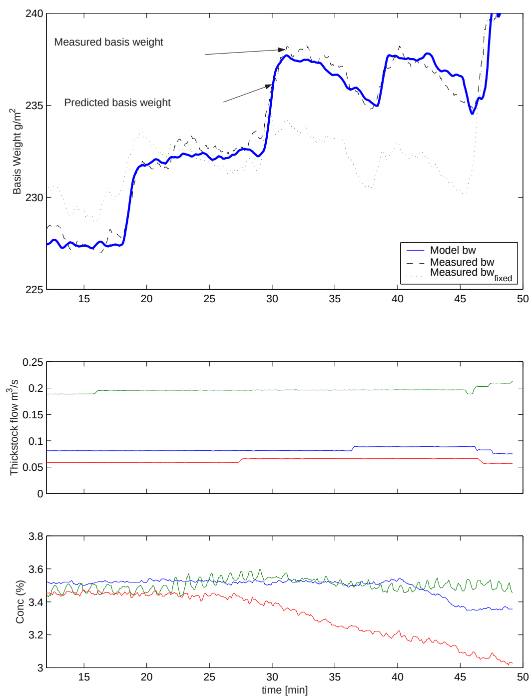

Figure 2: Model predictions compared to measured basis weight (upper plot) due to changes in thickstock flow and concentrations in the three plys (lower plots).

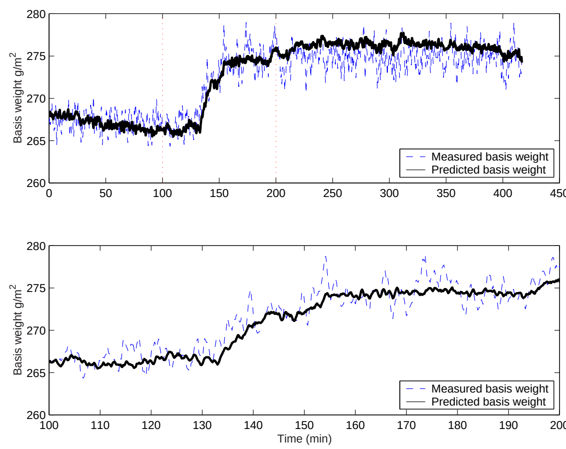

Figure 3: Model validation using the model from Fig. 2 against data from normal production. The lower plot shows a zoomed version of the grade change in the upper plot.

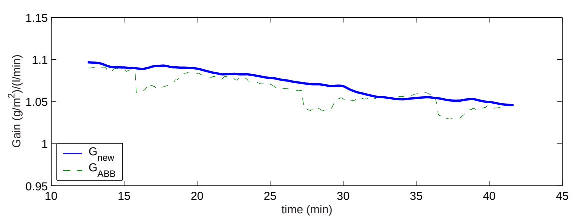

Figure 4: Simplified model gain comparisons between the original (dashed) and improved model gain (solid).

to the model are parameters in the consistency transducers (particularly a bias term) and minor adjustments to the time constants of the flow between the mixing and machine chests. The fitted model is validated by comparing model predictions against the logged basis weight during a grade change in normal operation in Fig. 3.

4.3 Control-type model comparisons

A comparison of the adaptive gain used by the simplified model and what is currently implemented on the ABB DCS is given in Fig. 4. Note that the updated model gain both better fits the validated full model, and is smoother, a characteristic we would expect given that the machine speed is not varying during this test.

5 Improving the model based control scheme

The internal model-based control (IMC) scheme using the model validated in §4.3 can be compared to the current model-based control scheme implemented by the ABB engineers in the DCS. Fig. 5 illustrates the (simulated) benefit in using the improved model-based controller with an appropriate gain scheduler to correctly handle the nonlinearities in the plant for small grade changes at the low, medium and high basis weights chosen as nominal operating points in Table 2.

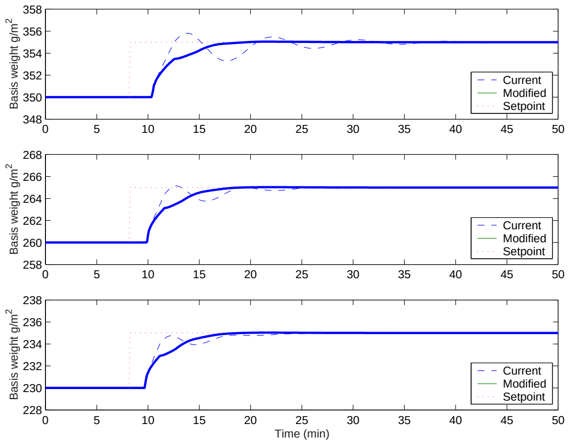

Figure 5: Improved controller model comparisons. 5g step changes at high (top), medium (middle) and low (bottom) basis weights.

6 Conclusions

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. Due 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.

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