4F3 – Predictive Control

Process Industry Case Studies
Dr Paul Austin

Outline Of Course

- Introduction to predictive control (PC)
- Digital state space control theory
- Unconstrained predictive control
- Predictive control with constraints
- Set-point tracking and offset-free control
- Stability and feasibility in predictive control
- Process industry applications of MPC - Dr Paul Austin

Outline Of Lecture

- 1. A brief history of MPC in the process industry
- 2. Some reasons for the success of MPC in the process industry
- 3. First case study: a paper recycle plant
- 4. Second case study: a paper (making) machine
- 5. Current practice in process industry applications of MPC

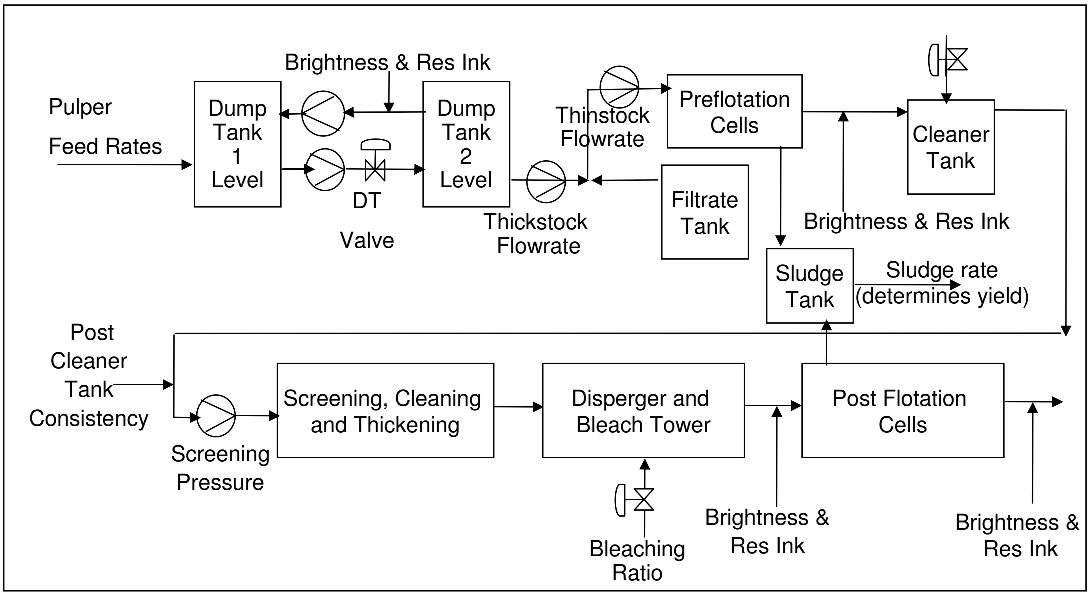
1. A (Very) Brief History of MPC in the Process Industry

- MPC was first developed by process control engineers in industry during the 1970s, mostly in oil & petrochem
- Devised to meet the needs of their processes
- Academics didn't become seriously involved till the late 1980s
- The huge performance improvements MPC was providing and its practical nature could not be ignored
- Early interaction between academics and industry practitioners not always cordial: robustness?! stability?!
- Academic scrutiny of MPC is now taking it into new spheres, well beyond its process industry origins
- Slow migration of MPC from oil & petrochemicals to other sectors of the process industry: paper industry

2. Some Reasons for the Success of MPC

- Naturally handles multivariable processes
  - A paper machine has many unused control variables because it has never been clear how to use them in a PID control law eg
    - Formation and drainage are jointly affected by the same input variables
  - Key quality variables are often controlled using a PID loop that adjusts just one of several variables affecting the quality variable eg
    - Recycled pulp brightness: controlled by one of many variables affecting it
- Offers optimal control subject to specified constraints:
  - profit can often be made by operating close to or at constraints
  - why control a tank level to a setpoint (as with PID) when what is required is to keep the tank from over-flowing or under-flowing
- Ability to run MPC with optimisers to determine optimum setpoints
- Process industry has slow processes, so even in the 1970s computers had time for the required calculation (MPC: Δ~20 sec)

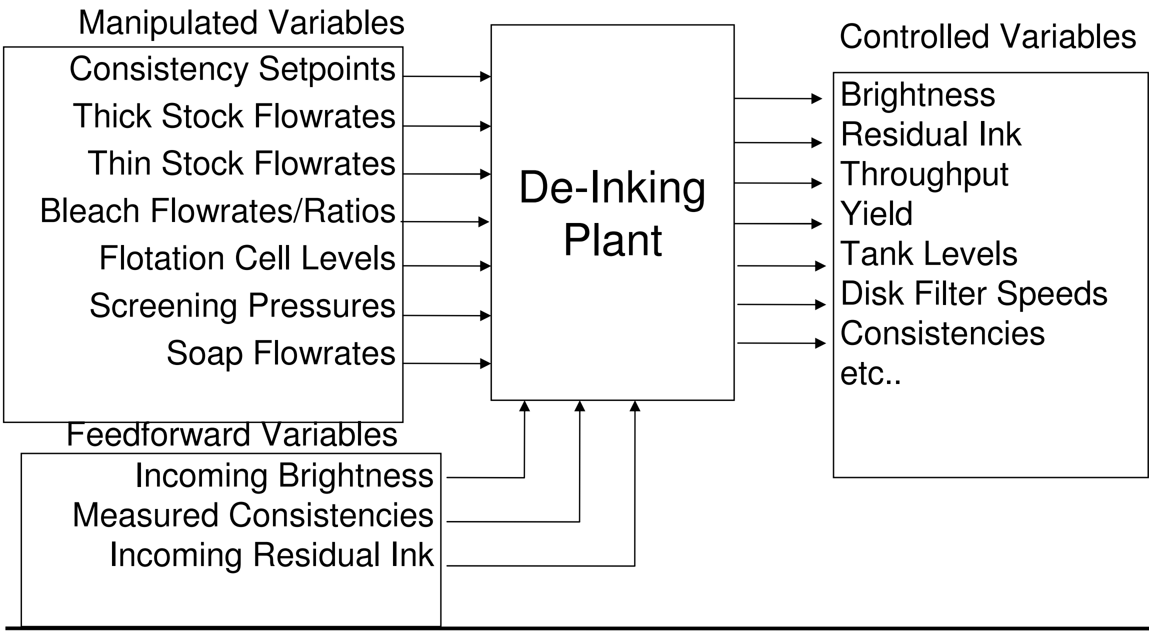
3. First Case Study: a De-Inking Plant



- Plant arranged mostly in two parallel lines to provide required volume
- Was designed to make 1250 air dry tonnes/day, now wanted more

Flotation Equipment in a De-inking Plant

Input - Output Representation of a Typical De-inking Plant



Cause-Effect Matrix: Step Response Models

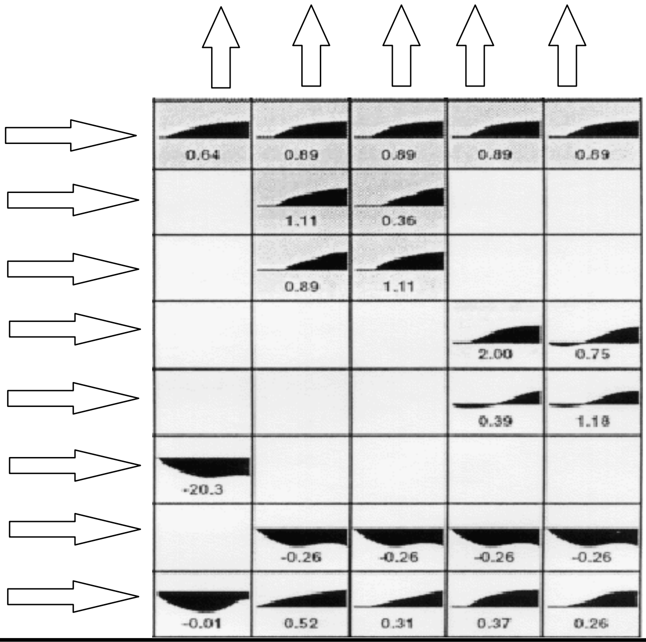
Outputs (Effect)

Controlled Variables (CVs)

Inputs (Cause)

Manipulated Variables (MVs)

Feedforward Variables (FVs)



- Need to define the required variables
- The MVs are usually setpoints to existing PID loops
- Must choose model order, type and length of delays
- Which elements are zero?
- Defining the variables and modelling is the crux of an MPC design

DIPs: Operational Objectives

- De-inking plants (DIPs) are usually required to operate:
  - to meet current brightness & eric (effective residual ink content) targets
  - with maximum plant throughput or with specified plant throughputs that may vary in time
  - at least cost in chemicals (bleach, caustic and silicate)
  - with best yield (fraction of dry weight into plant which becomes good pulp)
  - while observing certain constraints (differential pressure limits across screens & cleaners, mixing tank consistency limits, …)
- This requires tools that simultaneously combine control, optimisation and constraint handling functionality
- This is a very suitable challenge for MPC!

MPC Control of the DIP

- The MPC controllers implemented on the DIP have 34 MVs, 3FFs and 24 CVs
- With the conventional DCS-based control:
  - incoming brightness & eric variations were simply passed to the paper machine, perhaps a little attenuated
  - difficult to optimise yield, chemicals usage, throughput, brightness and eric
  - throughput control was manual with cascade controllers
- With the MPC system, operation of the DIP is optimised in real time, to meet the quality and economic objectives of the plant:
  - brightness variation is reduced, and brightness is controlled to target
  - brightness control in flotation works to make residual ink more constant – more brightness uplift (lower flotation cell consist'y) when feed br'ness is low
  - throughput can be controlled to setpoint, or maximised
  - yield can be improved, balanced against its effect on brightness and eric
  - chemical usage can be minimised

De-inking Plant APC System

Optimisation Scheme

Yield **Chemical usage** **Brightness** **Production** **Normal**

Pulper Controllers x 2

Manipulated Variables
- **Feed Rate**
- **Water Flows x 2**
- **Vat Level Valve**

Controlled Variables
- **Calculated Pulping Consistency**
- **Final Consistency**
- **Level**

WW Flotation Controllers x 2

Manipulated Variables
- **Polymer Flows x 2**

Controlled Variables
- **Polymer Ratio**
- **Outlet Solids**

Main Plant Controller

Manipulated Variables
- **Stock flows x 8**
- **Screen pressures x 2**
- **Bleaching ratio**
- **Production rates x 3**
- **Consistency loops and dilution valves**
- **Flotation cell levels x 6**

Controlled Variables
- **Tank levels x 5**
- **Final production**
- **Final brightness**
- **Flotation yield**
- **Disk filter speeds x 2**
- **Screening consistencies x 2**

DCS Displays: Summary Screen

Main Controller

ACTIVE

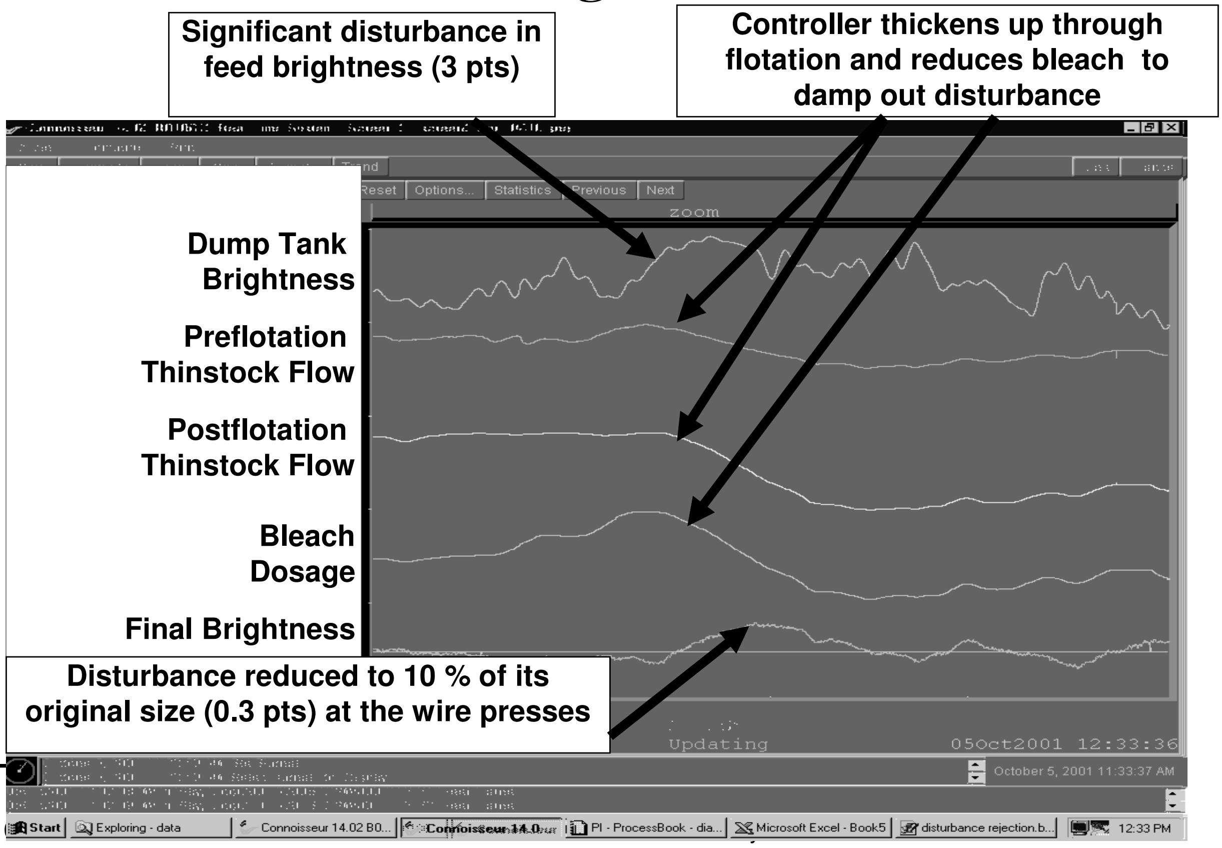
Controlled Variable		Status	Target	Value	Setpoint	Low Limit	High Limit
Flotation Yield	%	ON	92.00	92.00	92.00	90.00	99.00
Production	BDt/d	ON	1250	1256	1250	600	1300
Final Brightness	%ISO	ON	61.00	61.01	61.00	60.50	61.50

Plant Optimizer

ACTIVE

Normal	Chemical	Brightness	Yield	Throughput

Benefits: Good Brightness Control



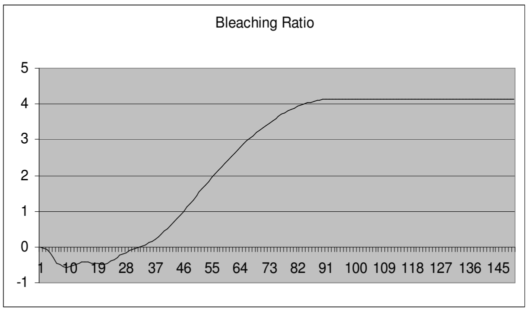
Benefits: Better Brightness Statistics

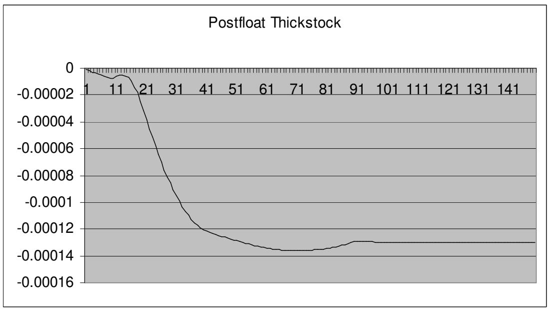
MPC can control brightness tightly:

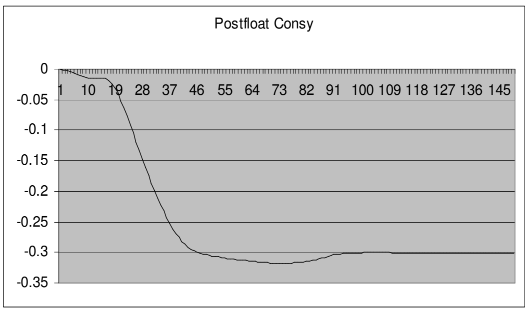
	Brightness Mean	Std Deviation	Run Length(Hours)
1	61.42	0.17	11.99
2	61.30	0.35	23.00
3	61.20	0.23	56.00
4	61.50	0.21	20.00
5	61.50	0.40	60.00
6	61.40	0.23	21.00
7	61.60	0.37	34.00
8	61.80	0.12	98.20
	Totals	**0.25**	**324.19**

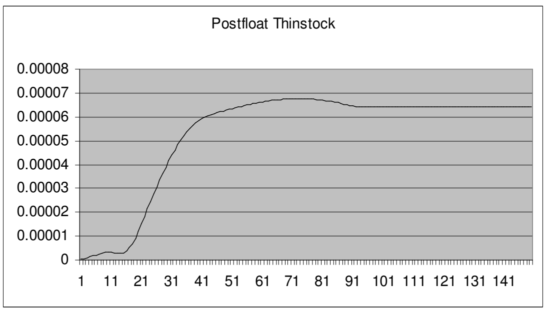
Under DCS controls, standard deviations of brightness were typically > 2 pts

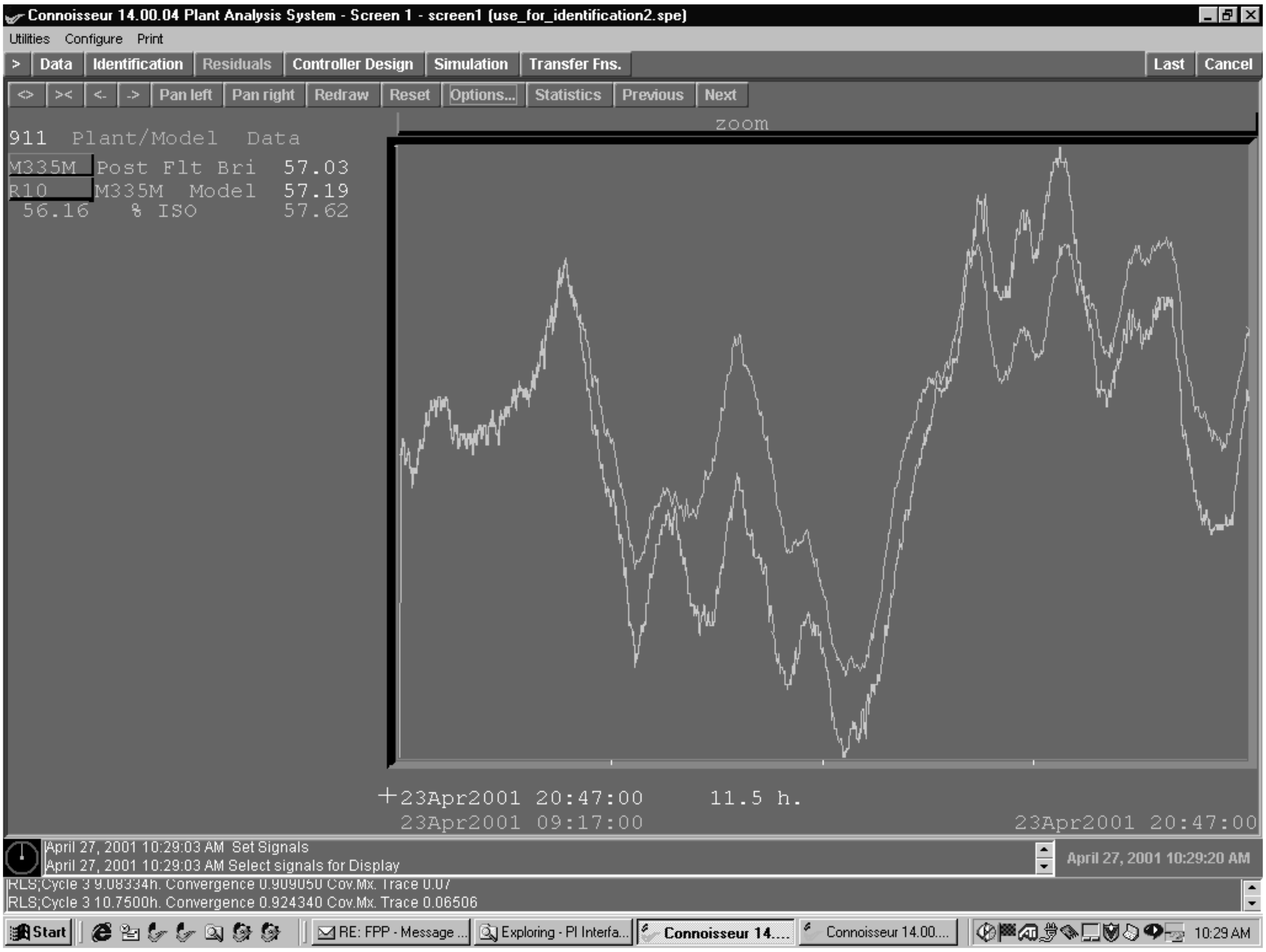
Some Typical Models: Postflotn Models to Final Brightness









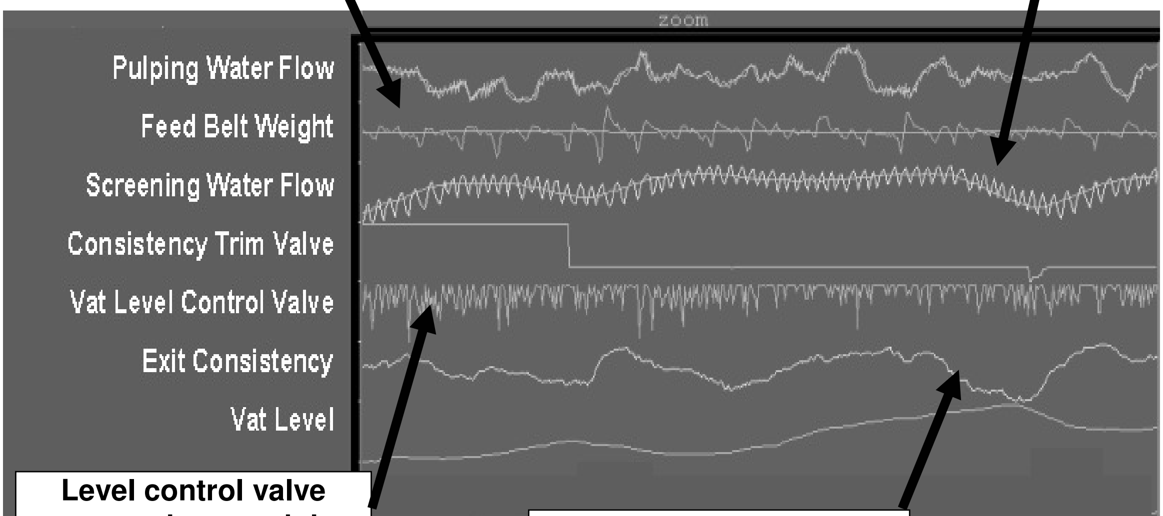


Benefits: Pulper Throughput Increase

Pulper running at 11% above design

Controller cuts back screening water as vat level increases

•Stable operation at 11% above designed throughput:



Level control valve saturated, so can't be used to control level

Exit consistency maintained within limits

•P... to 18% ab... controllers

Benefits: Throughput Control

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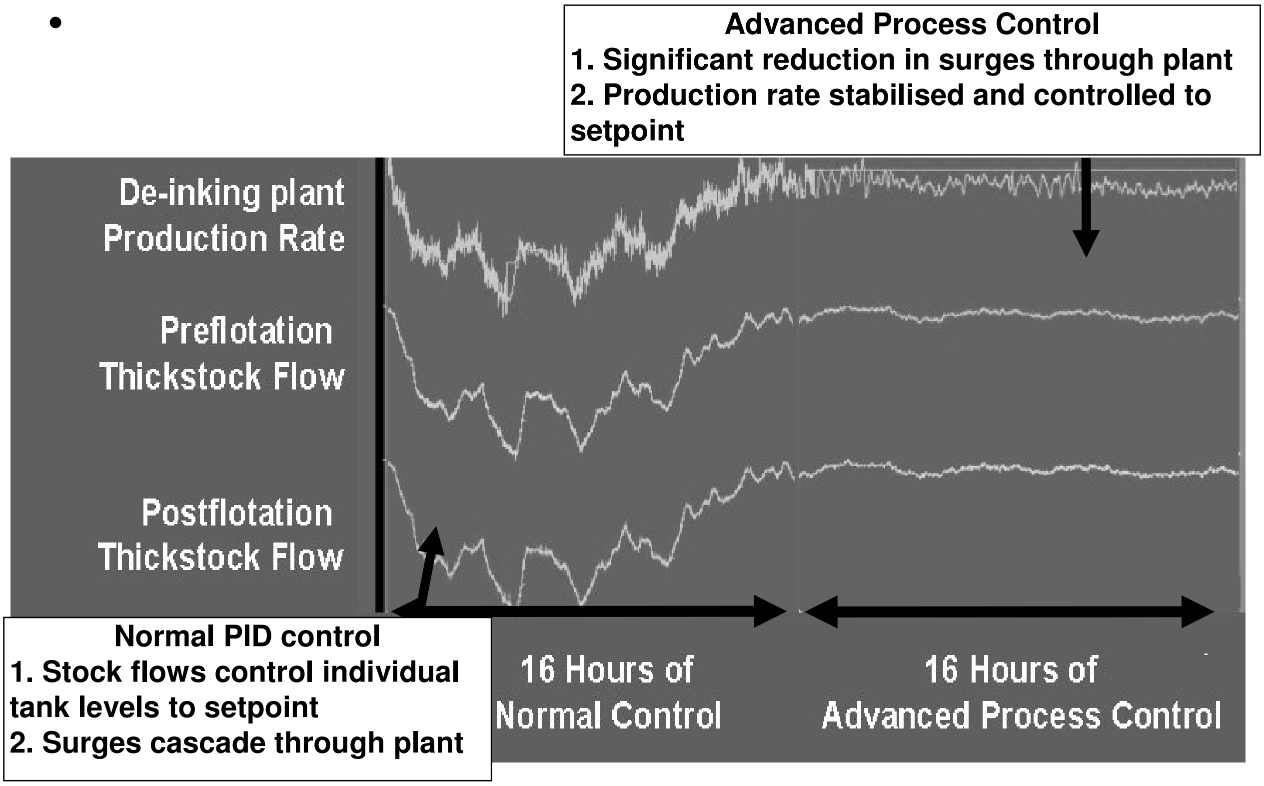
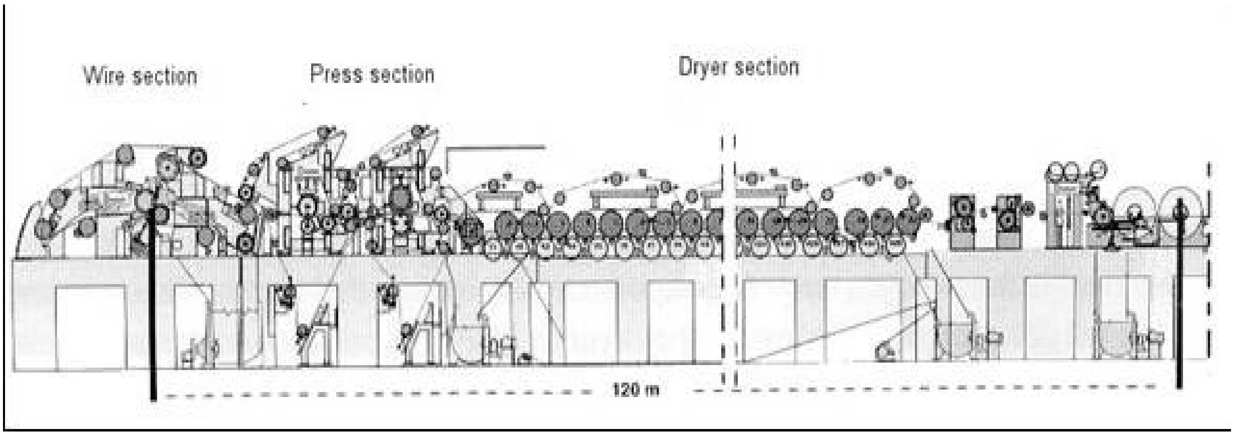


Summary of APC Benefits for Operation of the DIP

- Significant Reductions in Variability of Key Variables
  - Final brightness: variations previously ranged over 3.0 pts, now <0.6 pt, standard deviation < 0.35 pt. Could now reduce brightness target
  - Residual ink: range of variation reduced to <40 ppm
  - Cleaner and screening consistencies much steadier: reduced backwashing
- Significant Economic Savings (>£1.6 million/yr)
  - Improved yield: >1.5%. Online yield control shortly to be implemented
  - Greatly reduced chemicals usage: 25% less peroxide, 30% less caustic and 20% less flocculent polymer (water treatment)
- Improved Plant Stability, Operability and Throughput (£heaps!)
  - Much better control of throughput: 5% - 10% extra, or more
  - Significant reduction of surges on start up and during production changes
  - Improved operability: active constraints visible, loops can be kept 'on control', better management of bottlenecks, eg cleaning tank level
- Flexible Plant Optimisation based on the demands of the day

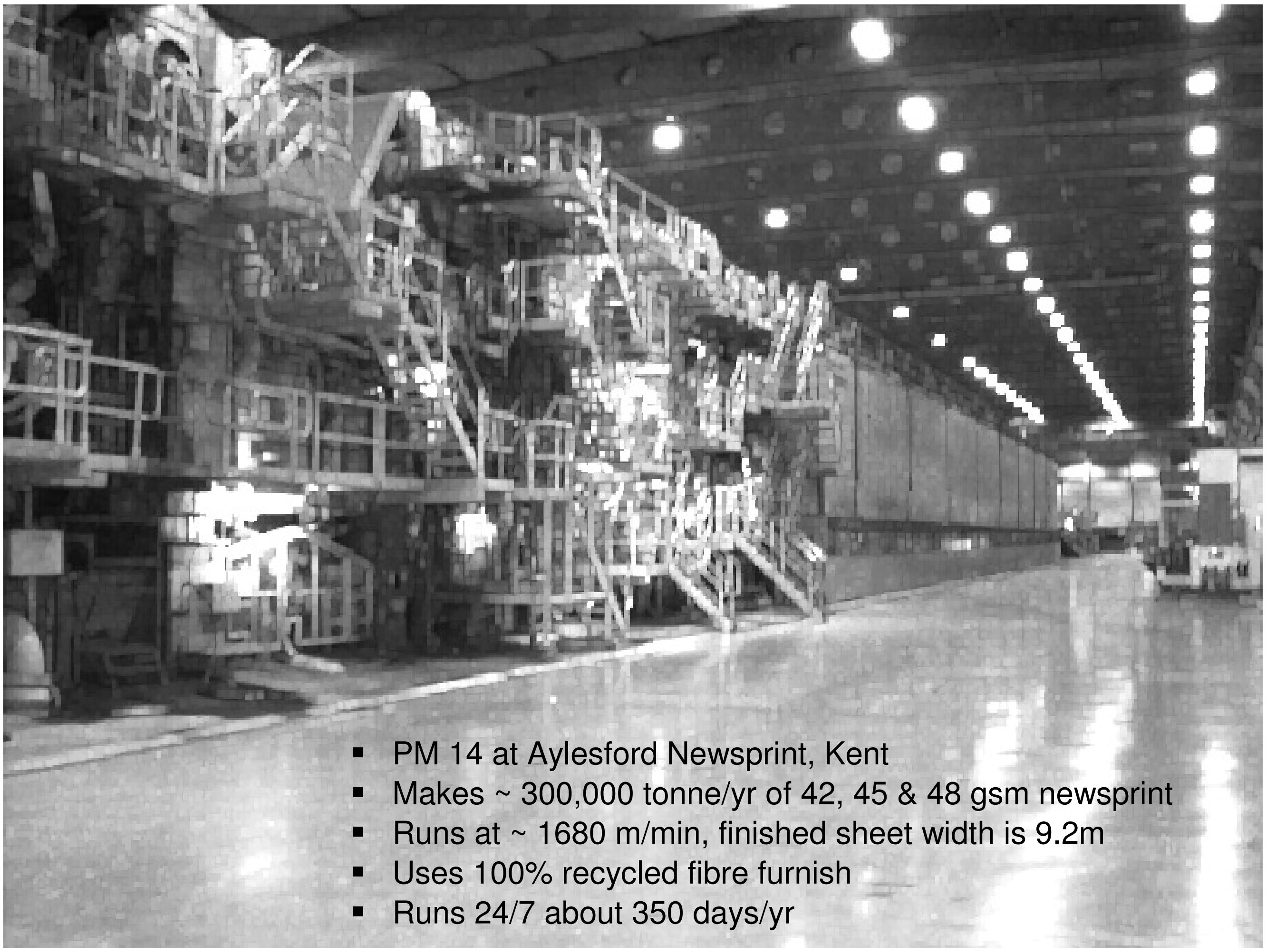
Second Case Study: Paper Machines



- Paper machine speed: typically between 600 m/min and 1800 m/min
- Length: typically 150 m with 500 m paper inside: 15 secs to 30 secs in m/c
- Fibre concentration: 0.7% at headbox, ~ 95% at the reel (lots of water to remove!)
- Grades: 18 gm per sq. metre (tissue) to 45 gsm (newsprint) to 350 gsm (board)
- Quality variables: weight, moisture, caliper, porosity, opacity, formation, shade…
- Constraints: pump speeds, fibre concentrations, chemical addition rates, water and stock flowrates, vacuums, pressures, machine drive speeds, steam pressures

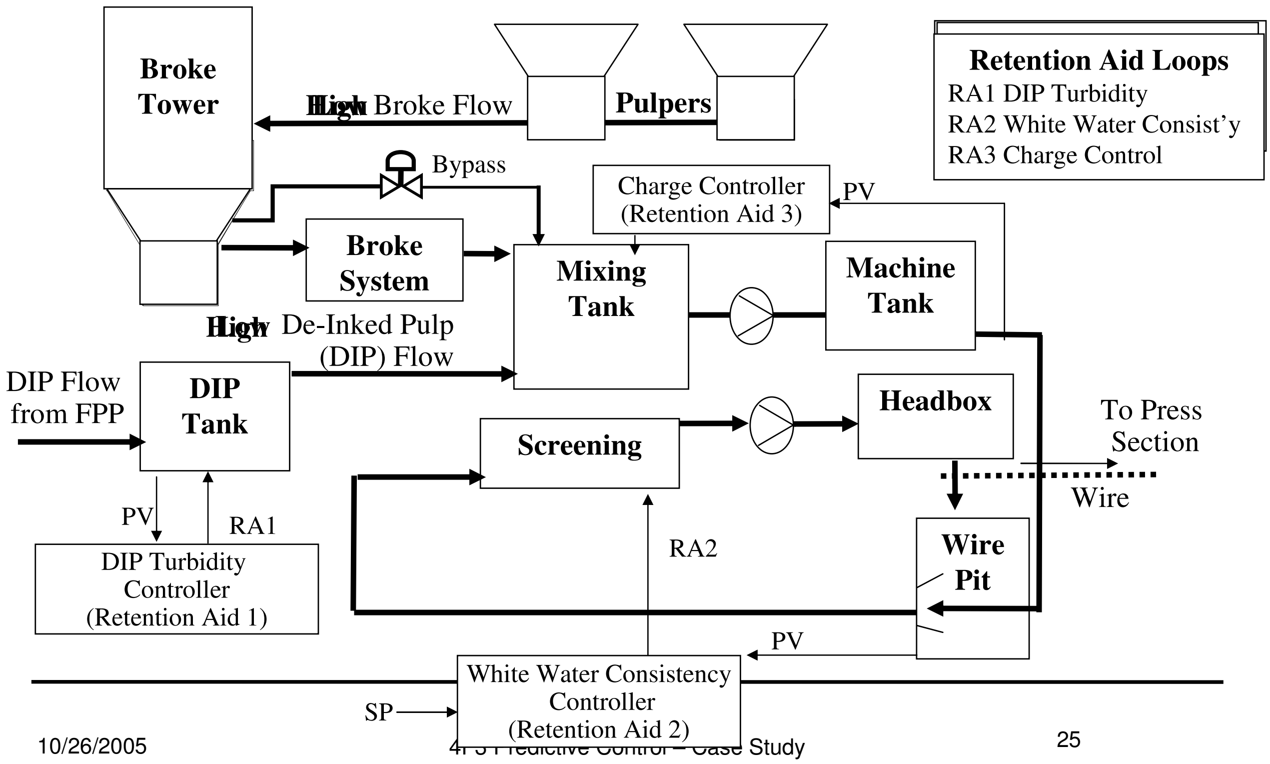
Paper Machines: Operational Objectives

- Meet MD (Machine Direction) quality criteria. Make paper of uniform:
  - weight, moisture and caliper - separate CD (Cross Direction) controls exist
  - formation, porosity, opacity + brightness, luminance, shade
- Maximise m/c efficiency and production, minimise off-spec production
- To assist in these objectives, MPC can:
  - improve wet end stability, especially against effects of varying broke and recovered fibre addition rates - steadier white water consistency (fibre content and filler (ash) content), retention and paper filler (ash) content
  - improve control of drainage to minimise moisture variation at the press
  - reduce the variation in draw (resulting from stretch in a wet sheet)
  - improve drying efficiency, reduce dryer bottleneck: increase production
  - reduce the variation in MD profiles: weight, moisture, caliper, formation …
  - improve grade change control
  - optimise machine operation: maximise usable production



- PM 14 at Aylesford Newsprint, Kent
- Makes ~ 300,000 tonne/yr of 42, 45 & 48 gsm newsprint
- Runs at ~ 1680 m/min, finished sheet width is 9.2m
- Uses 100% recycled fibre furnish
- Runs 24/7 about 350 days/yr

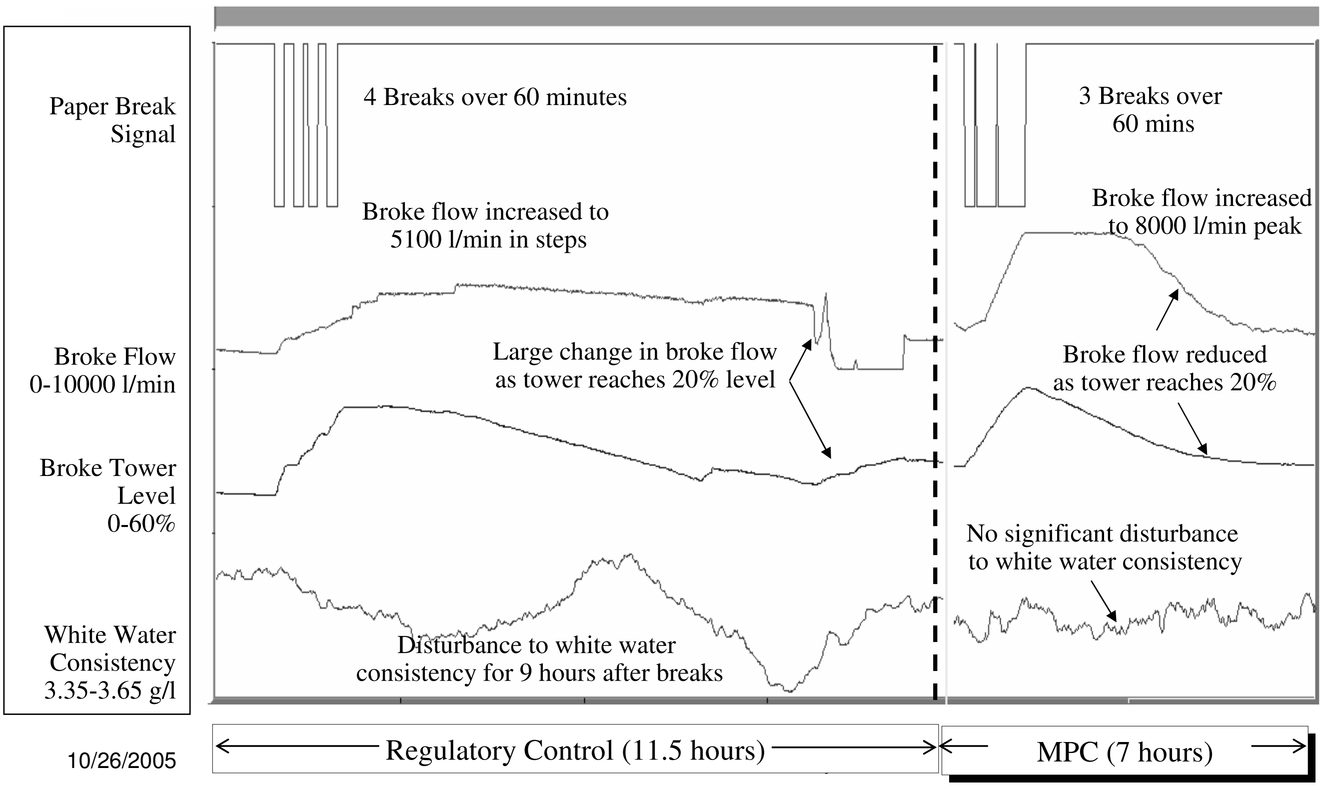
Newsprint Machine: The Wet End & Retention Control



Newsprint Machine Wet End APC: Controller Objectives

- Stabilise the operation of the wet end:
  - Steadier control of white water consistency (concentration of fibre in the water falling through the sheet) and headbox consistency
  - Control of charge and turbidity within a given range, using retention aids 1 & 3
  - Minimise usage of flocculent chemical, consistent with achieving required first pass retention (fraction of fibre staying in the sheet, rather than falling through in the white water)
  - Ensure good sheet properties are maintained: formation, opacity, porosity,…
- Provide effective control of the broke system
- Optimisation of the setpoints for the DIP, recovered fibre and broke consistency control loops => better headbox consistency control

Newsprint Case Study: Controller Performance Evaluation 1



Newsprint Case Study: Controller Performance Evaluation 2

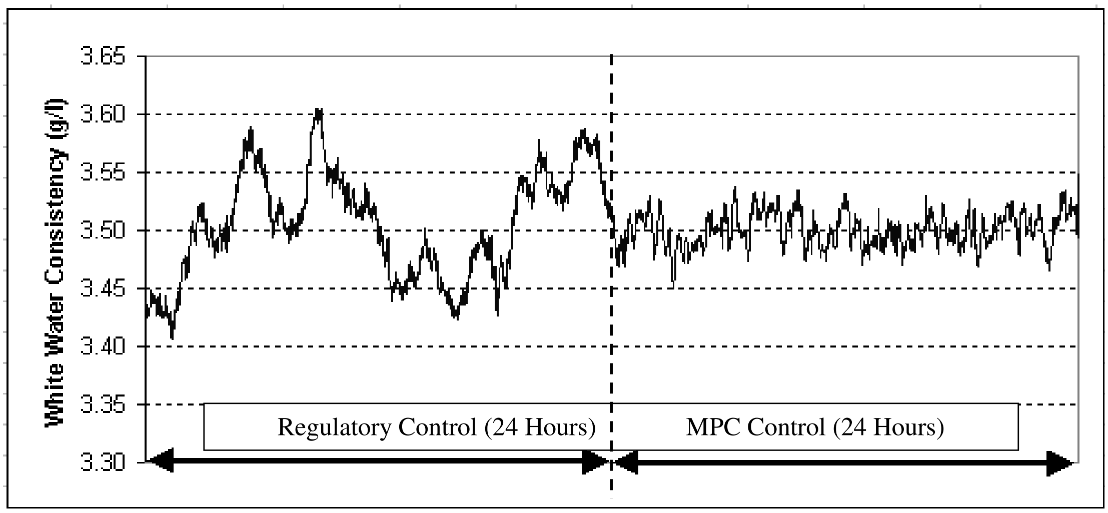
- Striking improvement in wet end stability

	Regulatory standard deviation (10 days run time)	MPC standard deviation (20 days run time)	% reduction in standard deviation
White Water Consistency (g/l)	0.0754	0.0249	67
Headbox Consistency (g/l)	0.0702	0.0418	60
(Wire) Retention (%)	0.487	0.378	22
Ash Retention (%)	0.918	0.797	13

- Also reduced variation, at the reel, in
  - weight
  - moisture
  - caliper
  - opacity

Newsprint Case Study: Controller Performance Evaluation 3

- White water consistency stabilisation



Wet End Stability Improvement using MPC: Fine Paper Case Study

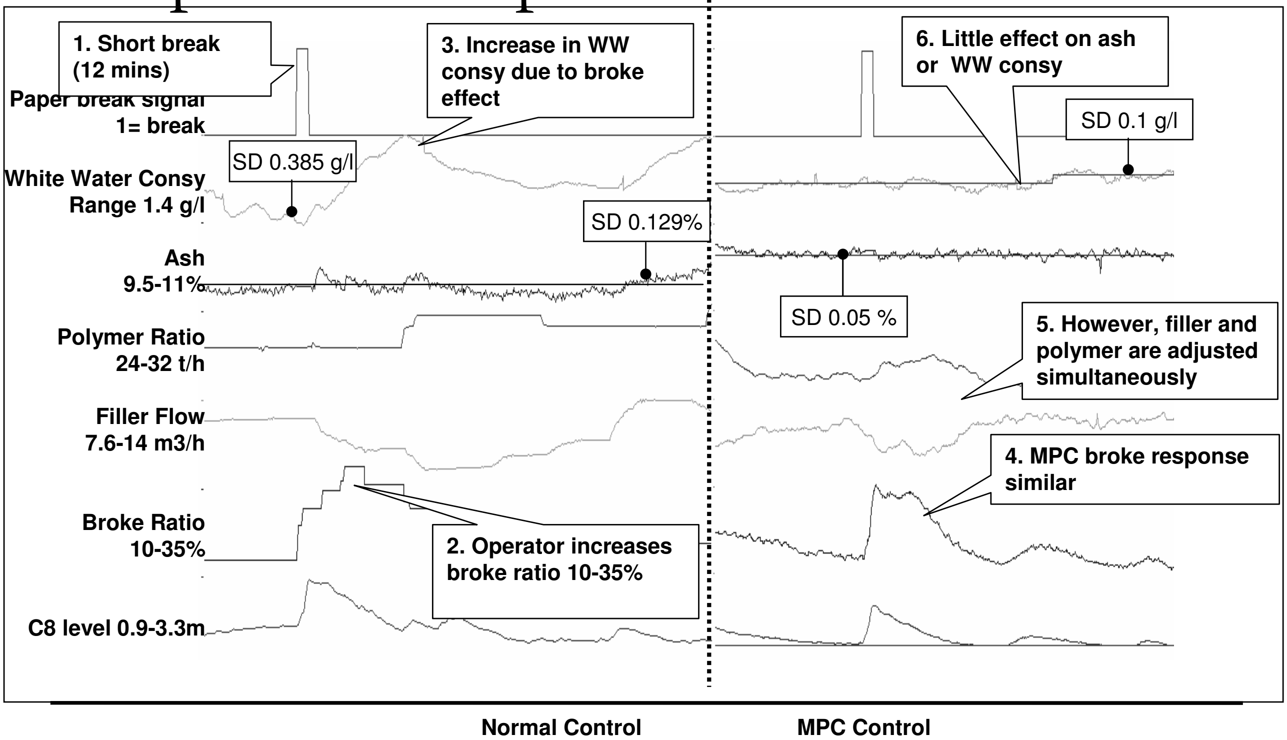
- An MPC wet end controller was implemented on the bigger of two fine paper machines at a French mill, built originally in 1974:
  - Runs at up to 1000 m/min, 3.5m trim, production ~ 100,000 t/yr
  - Four main grades: 60, 80, 120 and 160 gsm, bright copy & writing papers and coloured papers
  - Wet end additives: retention aids, filler, sizing agents, biocide, dye, OBA (Optical Brightening Agent) & cationic starch
- Ash and retention control loops were found to be very interactive
- Complex broke system with limited capacity tanks:
  - Three types of broke: wet end broke, dry end broke + broke from converting plant
- The machine is very multivariable: opportunity for performance improvement with MPC

Fine Paper Machine: MPC Controller Performance Overview

- Baseline data (before MPC) over 1 month, MPC data over 2 months
- Shuts and grade changes excluded in both cases
- Big reduction in variation

Variable Name	Unit	Standard Deviations		Reduction
		Baseline	MPC	
White water consist'y	g/l	0.53	0.09	**83%**
Headbox consistency	g/l	0.53	0.08	**85%**
Sheet ash	%	0.27	0.13	**52%**
Fibre retention	%	2.91	1.28	**56%**
Ash retention	%	2.71	1.14	**58%**
Mixing tank level	m	0.14	0.01	93%
White water tank level	m	0.04	0.04	0%
Polydisk level	m	0.05	0.01	80%

Fine Paper Machine: Paper Break Response Comparison



Fine Paper Machine: Performance Improvement

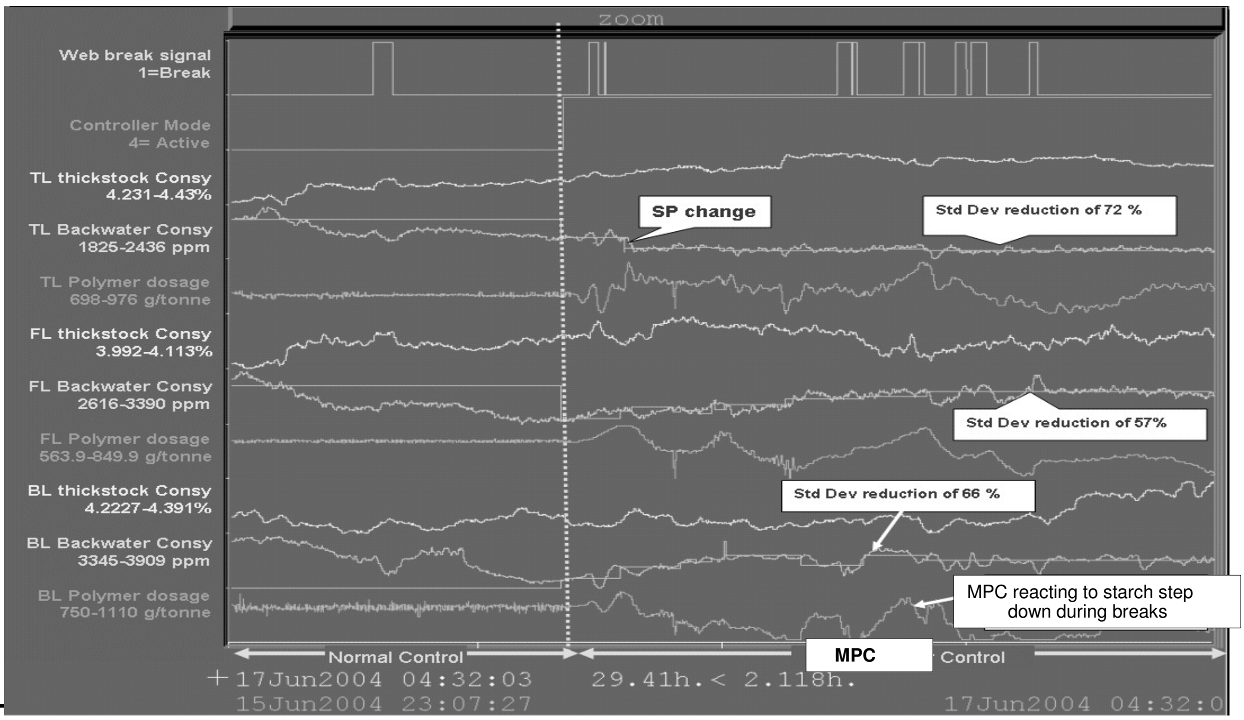
- The enormous reduction in wet end variation (ash and wwc) results in:
  - 35% reduction in production loss associated with sheet breaks
  - Shorter sheet break down-times
  - An 11% reduction in production loss due to off-quality production
  - Increase in saleable production consequently 2.6% + shorter breaks:

	Before MPC (6 months' data)	After MPC (2 months' data)	Reduction
Average length of sheet break	**15 mins**	**12 mins**	**20%**
% production loss due to sheet breaks	**4.9%**	**3.2%**	**1.7% (35%)**
% production loss for quality reasons	**8.1%**	**7.2%**	**0.9% (11%)**

Wet End Stability Improvement using APC: A Three Ply Board Machine

- The machine makes 90 – 240 gm three ply board from 100% recycled paper and board
- Wet end additives include starch (for strength) and retention polymer
- Top layer stock can be refined => mild effect on white water consistency
- The consistency of thickstock supplied to each layer can drift with time: can see the resulting effect on headbox consistency and WWC
- This is another very multivariable machine: opportunity for performance improvement using MPC:
  - MVs (control inputs): polymer flowrates for each ply
  - FFs (disturbances): starch addition rates, refining power, thick stock consistencies for each ply
  - CVs (outputs): WWC for each ply
- The MPC system has stabilised the machine dramatically:
- 7% increased production

Board Machine : MPC Performance Overview



5. Current MPC Process Industry Practice

- Today's commercial MPC packages are the result of tens of man-years of development effort; ABB's is the only new commercial package to have appeared in the last ten years
- Most MPC packages have their origins in originally quite small specialist companies founded in the late 1970s and early 1980s:
  - There were 6 or 7 such companies in Houston, Texas in the early 1980s
  - During the 1990s most of these companies were bought into large international control & automation companies
  - This has reduced or frozen the rate at which software development occurs
- The comprehensiveness of the MPC packages enable engineers to focus on the process when they are designing MPC systems:
  - What are the current operating issues, how can MPC improve performance?
  - MPC design parameters are used like a sophisticated controller tuning tool
  - Training is practitioner oriented: how to use the package, not what are the intricacies and subtleties of MPC algorithm design

Current MPC Process Industry Practice

- As yet, no commercial MPC design practice used in the process industry examines reachability & observability of models, or stability & robustness of MPCs:
  - Experienced practitioners use their process knowledge to specify extra sensors/actuators to give best results for MPC
  - Thereafter, MPC performance improvement is provided within the reachable, observable subspace
  - The question is how much is this performance improvement worth; process knowledge probably offers what a reachability/observability analysis would
- Perhaps there is a market opportunity for new smaller players in the MPC market, equipped with the latest university MPC algorithm designs? But note the importance of:
  - 24/7 support and maintenance arrangements, Europe (world?) wide
  - Alliances with other automation and control suppliers – today's companies tend to favour a one stop shop for their automation & control needs

Conclusion

- MPC came into being from the oil & petrochemical sector of the process industry, where it is now mature technology
- The academic and research community has made a significant contribution to MPC design in the last 15 years and the subject seems poised to break into fields beyond the process industry
- Ironically, in the 25 years of MPC applications in the oil & petrochemical sector, rather few MPC applications have been made in other process industry sectors
- Nevertheless, good opportunities for performance improvement using MPC appear to exist in:
  - pulp & paper:
    - 1% production increase on many paper machines is worth over € 750,000/year
    - Customers are always seeking improved quality
  - chemicals
  - food & beverage, especially dryers & evaporators and beer brewing
  - pharmaceuticals