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CHAPTER 3

Paper Machine Dryer Simulator for Control Through a Scanning Quality Gauge

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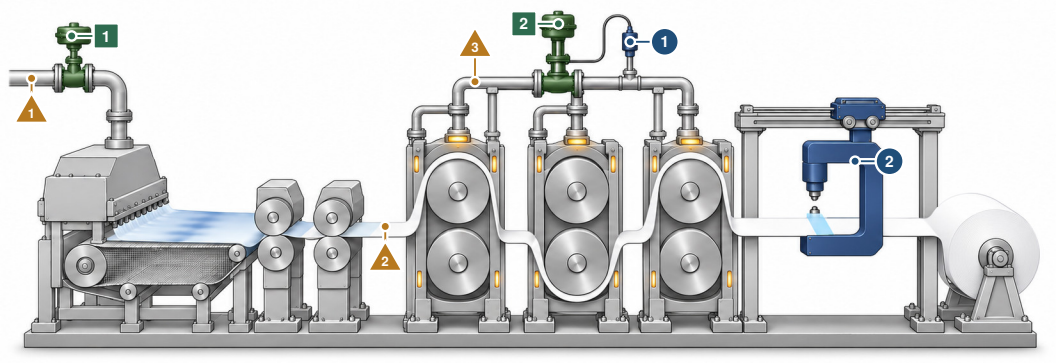
The app for this chapter
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CHAPTER 3

Paper Machine Dryer Simulator for Control Through a Scanning Quality Gauge



The controller moves 1 thick stock valve, sets the fiber reaching the sheet 2 steam valve, sets the dryer pressure

The controller reads 1 steam pressure, read all the time

2 scanning gauge, posts basis weight and moisture once per pass

What disturbs it 1 stock consistency 2 press dryness (a plugged felt) 3 mill steam header pressure

Notice that the only report on the sheet comes from the scanning frame at the dry end, long after both valves have acted. Illustration, not to scale.

IN PLAIN TERMS **Two Knobs and a Slow Report Card**

The main idea. A paper machine turns watery pulp into a moving sheet and dries it on hot rollers. Two knobs set how heavy and how wet the sheet is. One is the pulp valve and one is the steam.

The challenge. The only report on the sheet comes from a gauge that crosses it back and forth. It gives one average per crossing, so every answer is already old. Each knob also moves both results, because the gauge weighs the water along with the fiber.

Why it matters. Which knob holds which target, how the cross effects are canceled and how often the gauge reports decide how much sheet is made out of specification.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the history in Section 3.2, the fact on drying energy, the history of the first experiment (Section 3.4), the two try-its and the fact on the scan period (Section 3.6) and the key points
Study	65 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	25 min	the first page, the results (Section 3.6), Technology in Practice (Section 3.7), Limitations (Section 3.8) and the two open challenges

The control question A paper machine sells how heavy and how wet its sheet is, and measures both with a gauge that averages a whole traverse and holds the answer until the next pass. How much dead time does that instrument add, and how should two interacting quality loops be paired, decoupled and timed around it?

Learning objectives

- Compute the effective dead time of a scanning gauge from the transport delay and the scan period.
- Explain why the steam pressure moves the conditioned basis weight, and compute the relative gains and decoupler gains of the two-by-two plant.
- Show on the app that a shorter scan period settles a ringing loop with no gain changed, and say what it costs the cross direction.
- Judge which half of a static decoupler carries its benefit, and what it costs the other loop.
- Explain why a predictive controller with the scanner in its model loses to retuned loops when its model holds the machine speed.

Prerequisites Sections 1.4.5 (relative gain and pairing), 1.4.6 (simplified decoupling), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and data). Section 1.6.3 is needed only for the predictive controller.

The app https://apmonitor.com/apps/paper-machine/

See also Volume 5, Chapter 3 for composition control through a slow analyzer, Volume 5, Chapter 4 for a quality known hours late from sampled instruments, and Volume 5, Chapter 10 for a product moisture inferred between laboratory samples.

3.1 Introduction

The quality measurements a process plant actually controls on are seldom continuous. A composition arrives once per analyzer cycle, an assay once per shift, a coating weight once per traverse of a gauge, and in each case the instrument reports a property of product already made [1]. A paper machine is the extreme case. One head carrying a beta transmission gauge and an infrared moisture sensor traverses the full width of the sheet, and the two numbers it hands the control system are the only description of the product that exists. In the simulator of this chapter the head takes 20 s to cross an 8 m trim while 333 m of sheet passes it at 1000 m/min, so the reported basis weight is the average of a diagonal stripe rather than the value of anything at any instant.

What a scanning gauge costs a loop is arithmetic that a block diagram hides. Three lags live in the one instrument. The sheet takes L/v seconds to reach the frame, the boxcar average over one traverse is worth a further half period, and holding the answer until the next pass is worth half a period again. The effective dead time is therefore the transport delay plus one whole scan period, 21.9 s for moisture and 30.7 s for basis weight against transport delays of 1.92 s and 10.68 s. What the simulator sets right is the habit of treating a sampling interval as an implementation detail settled after the tuning. It is part of the plant, it is the larger part of it here, and a controller given the transport delay alone rings at a period of 100 s with a swing that grows. Tuning rules for dead-time-dominant plants already carry half a sample period added to the delay [2], and the application makes the whole term visible by drawing the posted staircase against the sheet it is supposed to describe.

The second structural fact is that the two handles are not two. Basis weight is sold conditioned, water included, so a beta gauge weighs the fiber and the water in it together. Evaporating water therefore removes saleable mass, the steam pressure becomes a basis weight actuator, and the plant is a two-by-two with four non-zero connections. The relative gain of the natural pairing is 1.52 and that of the other pairing is -0.52, which is Bristol's formal statement that one pairing is workable and severe while the other cannot be tuned [3]. Both facts generalize well past paper. Sheet and film processes of every kind, plastic film, coating, board and tissue, are measured the same way and pose the same machine-direction and cross-direction problem [4], and any plant whose controlled property is measured on a cycle inherits the dead-time accounting [1]. Volume 5, Chapter 3 meets the same accounting with an online analyzer, and Chapter 5 with a coat weight gauge whose delay is fixed in meters of web.

Simulators of paper machines are usually built to answer thermal questions. Multi-cylinder drying models resolve the heat and mass transfer through the felt, the sheet and the cylinder shell to predict a dryness profile down the machine [5, 6], and control studies on those models concentrate on the steam and condensate system [7]. However, a student handed a first-order plus dead-time transfer function and asked for proportional-integral settings never encounters the instrument that produced the dead time, and on a paper machine the instrument is most of it. This chapter works with a fine-paper machine whose quality controllers execute only when a traversing gauge posts a reading, so that the sample interval, the boxcar average and the zero-order hold appear as measured seconds of dead time and as an oscillation that no gain change removes. The drying model, the relative gain array, the decoupler and the predictive controller are all established methods. Section 3.2 traces how the scanning gauge shaped quality control on paper machines. Section 3.3 gives the fourteen-state machine with its instrument chain, every balance, constant and initial value. Section 3.4 derives the effective dead time of the gauge, measures the two-by-two gain matrix and designs a static decoupler from it. Section 3.5 describes the event-driven control layer, its loss-of-measurement logic, the production cascade and an optional predictive controller whose model contains the scanner. Section 3.6 orders the remedies on one measured plant, in scenarios that run from two handles moved by hand to a grade change with the steam header already sagging. Shortening the scan period buys dead time directly and outperforms any gain change. One half of the static decoupler carries almost all of its benefit, and the measurement says which half. With the production loop in service, decoupling trades a faster moisture loop for a slower weight loop. The same cases are measured under the predictive controller, against the shipped loops and against loops retuned by the controller's own tuning rule. Section 3.7 describes the real gauges, valves and controllers. Sections 3.8 and 3.9 state what the model cannot show and price moisture and press dewatering, and Section 3.10 sums up.

3.2 Quality Control on Paper Machines

Paper was made and sold long before either of its graded properties could be measured on the machine. Basis weight is defined by cutting a sample of known area from the reel, conditioning it and weighing it, and moisture by weighing the same sample before and after an oven. Both are laboratory tests on a finished reel, so the control loop of the 1940s closed through an operator who was told what the last reel had been and adjusted the thick stock valve or the steam pressure for the next one. The correction arrived hours after the sheet it described, and the machine ran with a generous margin above the customer's minimum weight because paper below specification cannot be shipped.

The instrument that changed the problem was the traversing beta gauge. A beta source on one side of the web and an ionization detector on the other give a signal proportional to the mass in the beam, and a frame that carries the pair across the sheet turns a point measurement into a description of the whole web. The reading arrives once per traverse rather than once per reel, which is three orders of magnitude faster than a laboratory test and still slower than every other measurement on the machine. Computer control followed, and the history segment below tells how its first application to a paper machine treated the machine-direction problem as regulation against a noisy sampled measurement rather than setpoint tracking.

> ⧖ HISTORY **1965: A Computer Takes the Basis Weight Loop**
>
> A feasibility study for a process computer at a kraft paper mill in Sweden ran from May to September 1963. It found basis weight varying with a standard deviation of 1.3 g/m^2 and set 0.7 g/m^2 as the target under computer control. The computer was installed late in December 1964, and the first on-line basis weight control ran on April 28, 1965, for ten hours. Its control law came from identification experiments on the running machine and was designed to make the variance of the output as small as possible. From the beginning of 1966 the loop ran continuously and held standard deviations of 0.5 g/m^2 in wet basis weight and 0.3 g/m^2 in dry [8].

The two decades that followed separated the problem in two. The machine-direction loops hold the average of each traverse with the thick stock valve and the dryer steam pressure, and the cross-direction loops hold the profile across the web with a row of slice or induction actuators driven from the same head. Adaptive and self-tuning regulators reached the machine-direction loops early, because the plant gain moves with the grade and the speed [9]. The cross-direction problem became a subject of its own, with a hundred or more actuators, an ill-conditioned interaction matrix and a spatial bandwidth limit that no controller can exceed [4]. The two problems share one instrument and pull it in opposite directions, because a faster traverse shortens the machine-direction dead time and reduces the number of measurement points across the sheet.

Assessment of what the resulting loops achieve came later and was uncomfortable. The minimum-variance benchmark, which compares a loop's output variance against the variance no feedback controller could remove given the delay, was introduced for this class of plant [10], and mill-wide audits built on it made control loop performance a routine engineering deliverable [11]. The recurring finding is structural rather than numerical. Loops are tuned against the plant and not against the instrument, pairings chosen at commissioning are never revisited, and interaction between the two quality loops is treated as noise. The scenarios of the app are built around those three failures.

The economic weight behind them is drying energy. The dryer section is the largest single steam consumer in an integrated mill, and reducing its load, by pressing more water out mechanically or by giving away less moisture, is consistently identified as one of the cheapest energy savings available in the industry [12]. Section 3.9 prices both on the simulated machine.

> ✦ DID YOU KNOW? **Drying in the Pulp and Paper Sector**
>
> Drying takes 22 % of the energy consumed by the pulp and paper sector of the United States, and running its thermal dryers cost an estimated $919 million in 2020. Steam-heated multicylinder dryers make up 85 to 90 % of the dryers in the sector, in a study the same assessment cites [13].

3.3 Process Model

The simulated machine runs 1000 m/min on an 8.0 m trim. Thick stock is metered by valve NCV-101 into an approach system, drained on the wire, pressed to 43 % dryness and carried through three banks of steam-heated cylinders with sheet path lengths of 28, 58 and 26 m. Scanning frame QT-401 stands 32 m past the last cylinder and 178 m past the slice. At the design line-up the sheet leaves at 80.000 g/m^2 and 5.500 % moisture, which is 38.40 t/h of saleable paper, 36.29 t/h of it fiber and 2.11 t/h of it water that the customer pays the paper price for. Figure 3.1 carries the machine, its instrument tags and each symbol the equations below use.

Table 3.1 sorts what the four loops reach. Mill units are kept throughout, so sheet properties are in g/m^2 and percent, flows in kg/min, speed in m/min, pressures in kPa gauge and temperatures in °C, with the clock in seconds because the scanner sets the time scale. Each conversion between a per-minute flow and a per-second balance is made once and at the point of use across the fourteen integrated states.

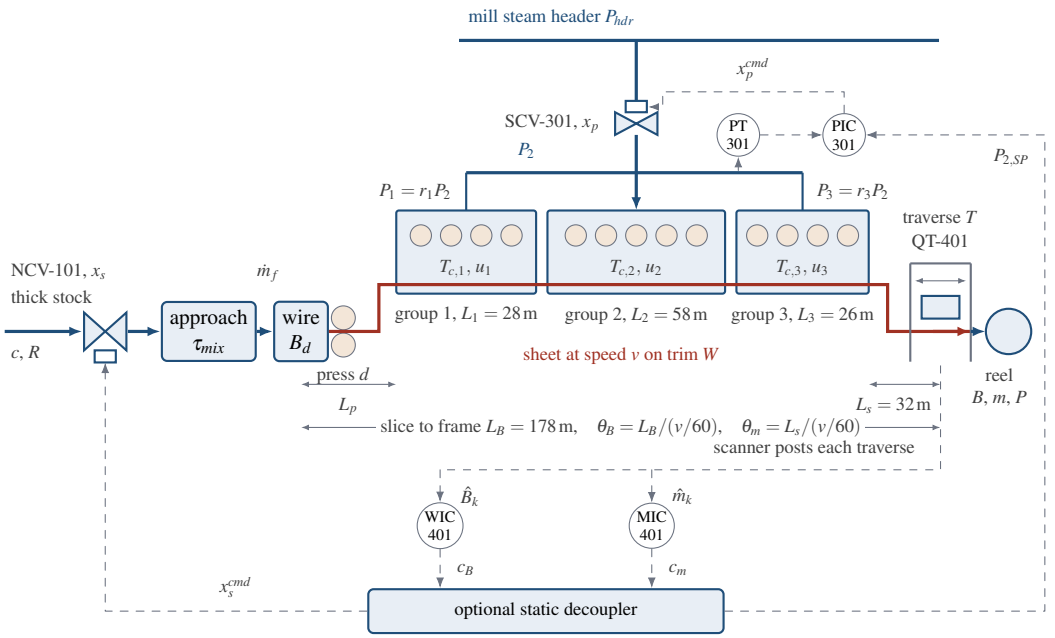


Figure 3.1 Fine-paper machine with the quality loops closed on one traversing gauge. Thick stock of consistency c and retention R passes valve NCV-101 and the approach system to lay down dry basis weight B_d on the wire, the press leaves the sheet at dryness d, and three groups of steam-heated cylinders at shell temperatures $T_{c,j}$ carry the sheet moisture ratio from u_P to u_3. Steam valve SCV-301 sets the main group pressure P_2 against mill header P_{hdr}, with the outer groups at fixed ratios r_1 and r_3. Scanning frame QT-401 posts the boxcar averages $\hat{B}_k$ and $\hat{m}_k$ once per traverse of period T, delayed by θ_B and θ_m. WIC-401 writes the stock valve and MIC-401 the group pressure setpoint that PIC-301 holds, and only PIC-301 reads a continuous transmitter.

3.3.1 Stock System and the Laid-Down Weight

The thick stock valve meters volume and the sheet is made of fiber, so the consistency of the stock is a disturbance and not a detail. The valve position, the approach system inventory and the forming response are three first-order lags in series, as shown in Equations (3.1) to (3.3).

$$\tau_v \frac{\mathrm{d}x_s}{\mathrm{d}t} = x_s^{cmd} - x_s \tag{3.1}$$

$$\tau_{mix} \frac{\mathrm{d}\dot{m}_f}{\mathrm{d}t} = Q_{th} \frac{x_s}{100} \frac{c}{100} - \dot{m}_f \tag{3.2}$$

$$\tau_{form} \frac{\mathrm{d}B_d}{\mathrm{d}t} = \frac{1000 R \dot{m}_f}{v W} - B_d \tag{3.3}$$

where x_s is the valve position in percent, Q_{th} is the thick stock flow at full lift in L/min, c is the consistency in percent, $\dot{m}_f$ is the oven-dry fiber reaching the headbox in kg/min, R is the overall retention, v is the machine speed in m/min, W is the trim in m and B_d is the dry basis weight in g/m^2. The driving term of (3.3) carries kg/min divided by m^2/min and multiplied by 1000 g/kg, so the two per-minute rates cancel and no factor of sixty belongs in it. The machine drive follows its own command with a lag of τ_{drive}, as shown in Equation (3.4).

$$\tau_{drive} \frac{\mathrm{d}v}{\mathrm{d}t} = v^{cmd} - v \tag{3.4}$$

Table 3.1 Variables of the Machine Direction Problem, With the Line-Up Every Scenario Opens On.

Symbol	Role	Nominal	Range
$\hat{B}$ (QT-401)	CV, sampled	80.00 g/m^2	45–130 g/m^2 SP
$\hat{m}$ (QT-401)	CV, sampled	5.50 %	3.5–9 % SP
P_2 (PT-301)	CV, continuous	306 kPa	60–480 kPa SP
P production	CV, $\hat{B}vW$	38.40 t/h	16–50 t/h SP
x_s (NCV-101)	MV	55.00 %	15–95 %
$P_{2,\mathrm{SP}}$	MV of MIC-401	306 kPa	60–480 kPa
x_p (SCV-301)	MV of PIC-301	60.00 %	0–100 %
v	MV of SIC-401	1000 m/min	400–1250 m/min
c consistency	DV, unmeasured	3.50 %	2.5–4.5 %
d press dryness	DV, unmeasured	43 %	36–48 %
P_{hdr}	DV, measured	550 kPa	350–700 kPa
R retention	DV, unmeasured	0.985	0.90–1.00
H hood humidity	DV, unmeasured	140 g/kg	60–260 g/kg
σ_B	DV, gauge noise	0.25 g/m^2	0–1.5 g/m^2
σ_m	DV, gauge noise	0.12 %	0–0.8 %
x_s state	state	55.00 %	0–100 %
$\dot{m}_f$	state	614.0 kg/min	≥ 0
B_d	state	75.600 g/m^2	≥ 1
v state	state	1000 m/min	20–1400 m/min
x_p state	state	60.00 %	0–100 %
P_2 state	state	306 kPa	0–900 kPa
$T_{c,1..3}$	states	112.9 / 138.0 / 125.5	°C, 10–260
$u_{1..3}$	states	1.029 / 0.139 / 0.058	kg/kg, 0.0005–6
u_P	state	1.326	kg/kg, 0.0005–6
ϕ threading	state	1	0–1

Equation (3.3) is the reason the fourth loop behaves as it does, because raising v at fixed $\dot{m}_f$ divides B_d by the same factor and delivers the same tonnage to the reel. Machine speed makes no production except through the basis weight loop.

3.3.2 Press and the Drying Stack

The press is algebraic. Its outgoing dryness is set by the operator through a disturbance slider with a small penalty for a heavier sheet, and the moisture ratio it delivers is approached with a lag, as shown in Equations (3.5) and (3.6).

$$d = \mathrm{clip}_{[0.20,0.70]}\left[\frac{D_p}{100}\left(1 - k_B\left(\frac{B_d}{B_{d,0}} - 1\right)\right)\right] \tag{3.5}$$

$$\tau_{press}\,\frac{\mathrm{d}u_P}{\mathrm{d}t} = \frac{1-d}{d} - u_P \tag{3.6}$$

where D_p is the press dryness setting in percent, k_B is the dryness lost per unit of relative basis weight, $B_{d,0}$ is the reference dry weight and u_P is the moisture ratio leaving the press in kilograms of water per kilogram of fiber. Every moisture state in the model is a dry-basis ratio, and the wet-basis moisture the industry quotes follows from Equation (3.7).

$$m = \frac{u}{1+u} \tag{3.7}$$

Confusing the two puts a water balance out by several percent of itself.

Each dryer group is a residence time and an evaporation flux, as shown in Equations (3.8) to (3.10).

$$t_j = \frac{L_j}{v/60} \tag{3.8}$$

$$e_j = h_d\,\mu_j\,\max(0,\ T_{c,j} - T_{ev})\left(1 - \mathrm{e}^{-\bar{u}_j/u_c}\right)\phi \tag{3.9}$$

$$\frac{\mathrm{d}u_j}{\mathrm{d}t} = \frac{u_{j-1} - u_j}{t_j} - \frac{e_j}{B_d} \tag{3.10}$$

where L_j is the sheet path length of group j in m, t_j is the residence time in s, e_j is the evaporation flux in grams of water per square meter of sheet path per second, h_d is the specific drying conductance, μ_j is a per-group multiplier, $T_{c,j}$ is the shell temperature, T_{ev} is the sheet evaporation temperature, u_c is the falling-rate scale, $\bar{u}_j = \frac{1}{2}(u_{j-1} + u_j)$ is the mean moisture ratio across the group, ϕ is the threading fraction and $u_0 = u_P$. Equation (3.10) is plug flow with a distributed sink, so the first term carries sheet in and out over the residence time and the second is the water boiled off. Evaluating the falling-rate factor at $\bar{u}_j$ rather than at the outlet matters, because a group that dries a great deal otherwise reports a conductance a third too low. The rate factor is 0.965 through group 1, 0.812 through the main bank and 0.246 through the after-dryer, which is why the last group owns the final moisture. The sheet does not sit at 100 °C, and its evaporation temperature is carried by the pocket air, as shown in Equation (3.11).

$$T_{ev} = T_{ev,0} + k_H\,(H - H_0) \tag{3.11}$$

where H is the hood exhaust humidity in g/kg and H_0 is its design value. A hood that is not carrying water away therefore removes drying capacity while nothing in the steam system looks wrong.

3.3.3 Cylinders and the Steam Side

The cylinder shells are the slow part of the plant. Each bank condenses steam on the inside, boils water off the outside and loses heat to the hood, as shown in Equations (3.12) and (3.13).

$$Q_j = e_j\,L_j\,W\,\Delta h_{ev} \tag{3.12}$$

$$C_j\frac{\mathrm{d}T_{c,j}}{\mathrm{d}t} = UA_j\,(T_{sat}(P_j) - T_{c,j}) - Q_j - UA_{amb}\,(T_{c,j} - T_{hood}) \tag{3.13}$$

where Q_j is the group duty in kW, Δh_{ev} is the heat per gram of water removed, C_j is the bank thermal mass in kJ/°C, UA_j is its condensing conductance and UA_{amb} is the loss to the hood. The flux of (3.9) is already per second, so (3.12) carries no time conversion. Each UA_j is set so that the group's design duty alone costs exactly 6 °C of steam-to-shell drop rather than chosen as a round number (the loss to the hood adds 0.3, 0.1 and 1.1 °C), which makes the shell time constants C_j/UA_j a consequence of the machine at 25, 19 and 84 s for the three groups, the after-dryer slowest because it is the most lightly loaded.

The three group pressures are recipe ratios of the one that is manipulated, the steam demand follows from the duties, and the valve delivers a pressure that droops with that demand, as shown in Equations (3.14) to (3.17).

$$P_1 = r_1 P_2, \qquad P_3 = r_3 P_2 \tag{3.14}$$

$$\dot{m}_{st} = \frac{60\sum_j Q_j}{h_{fg}} \tag{3.15}$$

$$\tau_{vp}\frac{\mathrm{d}x_p}{\mathrm{d}t} = x_p^{cmd} - x_p \tag{3.16}$$

$$\tau_{st}\frac{\mathrm{d}P_2}{\mathrm{d}t} = \mathrm{clip}_{[0,P_{hdr}]}\left[P_{hdr}\frac{x_p}{100} - k_d\,\dot{m}_{st}\right] - P_2 \tag{3.17}$$

where $\dot{m}_{st}$ is the steam condensed in kg/min, h_{fg} is the latent heat of the supply steam and k_d is the droop coefficient. The duties of (3.12) are in kJ/s and the operator reads steam in kg/min, which is where the factor of sixty in (3.15) comes from. The droop term in (3.17) is worth 24 kPa at the design 969 kg/min, and it is what turns a wetter sheet into a load disturbance that the pressure loop removes in seconds instead of something the moisture loop discovers through the gauge. Saturation temperature is a two-parameter fit to the steam tables, as shown in Equation (3.18).

$$T_{sat}(P) = 100.75 \left(\frac{P + 101.325}{100} \right)^{0.2549} \tag{3.18}$$

with P in kPa gauge and T_{sat} in °C. The fit is within 0.4 °C between 1.5 and 6 bar absolute, which is the whole range a dryer section uses.

The web itself is a state, so that a break and a rethread are events the rest of the model can see, as shown in Equation (3.19).

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \frac{\phi_{tgt} - \phi}{\tau}, \qquad \tau = \begin{cases} \tau_{break} & \phi_{tgt} < \phi \\ \tau_{thread} & \text{otherwise} \end{cases} \tag{3.19}$$

The asymmetry is deliberate, because a web parts in seconds and takes a quarter of a minute to get back across the machine.

3.3.4 What the Sheet Is Worth and What the Gauge Reports

Basis weight is sold conditioned, so what the beta gauge weighs and what the invoice says is the fiber plus the water still in it, as shown in Equation (3.20).

$$B = \frac{B_d}{1 - m}, \qquad P = \frac{B\, v\, W\, 60}{10^6}\, \phi \tag{3.20}$$

where B is the conditioned basis weight in g/m^2, m is the reel moisture from (3.7) evaluated on u_3, and P is the saleable production in t/h. The dry weight B_d is fixed on the wire and nothing in the dryer section changes it, so (3.20) is the entire mechanism by which the steam valve becomes a basis weight actuator.

The gauge reads that sheet twice over. The two properties are set at different places on the machine, so they arrive at the frame with different transport delays, both computed from the live speed, as shown in Equation (3.21).

$$\theta_B = \frac{L_B}{v/60}, \qquad \theta_m = \frac{L_s}{v/60} \tag{3.21}$$

with $L_B = 178\,\mathrm{m}$ from the slice and $L_s = 32\,\mathrm{m}$ from the last cylinder, giving 10.68 s and 1.92 s at design speed. Slowing the machine makes both longer, which is the reverse of what an operator slowing down to sort out a problem expects. The head then averages one traverse, posts the average and holds it, as shown in Equation (3.22).

$$\hat{B}_k = \frac{1}{T} \int_{t_k - T}^{t_k} B(\tau - \theta_B)\, d\tau + \varepsilon_k \sigma_B, \qquad \hat{B}(t) = \hat{B}_k \tag{3.22}$$

for $t_k \le t < t_{k+1}$, with $t_{k+1} - t_k = T$ the scan period, ε_k drawn from the unit normal distribution once per completed pass and σ_B the gauge repeatability. The moisture reading follows the same expression with θ_m and σ_m. Per-pass noise stands in for cross-direction profile variation aliasing into the machine-direction reading, which is the dominant source of scatter on a real gauge [14]. A pass that accumulated sheet for less than half a period posts nothing at all and the previous value stands, which makes a sheet break a loss of measurement rather than a reading of zero.

Table 3.2 Model Parameters. Adjustable Constants Are Displayed in the Model Panel and May Be Changed While the Machine Runs.

Symbol	Meaning	Value	Unit
Adjustable, displayed in the model panel			
W	trim width at the reel	8.0	m
Q_{th}	thick stock flow at full lift	31896.6	L/min
τ_v	stock valve travel	3.0	s
τ_{mix}	approach system mixing	22	s
τ_{form}	forming and headbox	6.0	s
τ_{drive}	machine drive ramp	8.0	s
τ_{press}	press section response	6.0	s
k_B	dryness lost per unit weight	0.05	—
h_d	specific drying conductance	0.39671	$\mathrm{g/m^2 s\,^\circ C}$
μ_3	after-dryer multiplier	0.85	—
u_c	falling-rate scale	0.35	kg/kg
$T_{ev,0}$	evaporation temp. at H_0	78.0	°C
k_H	evaporation temp. per H	0.05	$^\circ\mathrm{C}/(\mathrm{g/kg})$
Δh_{ev}	heat per gram of water	2.70	kJ/g
C_1	group 1 bank thermal mass	34000	kJ/°C
C_2	group 2 bank thermal mass	78000	kJ/°C
C_3	group 3 bank thermal mass	31000	kJ/°C
UA_{amb}	bank loss to the hood	6.0	kW/°C
T_{hood}	hood temperature	55	°C
r_1	group 1 pressure ratio	0.30	—
r_3	group 3 pressure ratio	0.63	—
τ_{st}	group pressure response	14	s
τ_{vp}	steam valve travel	4.0	s
k_d	pressure droop with demand	0.024752	$\mathrm{kPa}/(\mathrm{kg/min})$
h_{fg}	latent heat of supply steam	2135	kJ/kg
τ_{Pm}	pressure transmitter lag	1.5	s
τ_{thread}	time to thread the tail	15	s
—	basis weight tolerance	0.8	$\mathrm{g/m^2}$
—	moisture tolerance	0.30	%
—	runnability limit m_{wet}	8.0	%
—	brittle limit m_{dry}	3.2	%
—	shell picking limit	142	°C
—	paper, fiber and steam price	820 / 540 / 22	$/t
—	off-specification discount	0.55	—
Hidden, never displayed			
$B_{d,0}$	reference dry basis weight	75.6	$\mathrm{g/m^2}$
μ_1, μ_2	group 1 and 2 multipliers	1.00	—
H_0	design hood humidity	140	g/kg
UA_1	group 1 shell conductance	1347.10	kW/°C
UA_2	group 2 shell conductance	4032.91	kW/°C
UA_3	group 3 shell conductance	368.84	kW/°C
τ_{break}	time for the web to part	2.0	s

Sheet path lengths are $L_p = 34\,\mathrm{m}$ from the slice to the first cylinder, $L_{1,2,3} = 28$, 58 and 26 m through the three groups and $L_s = 32\,\mathrm{m}$ to the frame, for $L_B = 178\,\mathrm{m}$ in total.

3.3.5 Constants, Startup and Numerics

Every constant is in Table 3.2. Thirty-six sit in the model panel and can be moved while the machine runs. The remaining eight are never shown, because they are the calibration constants a student is meant to infer rather than read off the screen.

No scenario begins on a drifting machine. The initial condition solves Equations (3.2) to (3.17) for zero derivatives at the operator's three handles by damped successive substitution, which converges because the plant contains one dominant negative feedback. A hotter cylinder dries faster, which draws more heat, cools the shell and drops the group pressure through the droop term of (3.17). At the design line-up that solution returns thick stock valve 55.00 %, steam valve 60.00 %, group pressures 92, 306 and 193 kPa, shells at 112.9, 138.0 and 125.5 °C, and dryness running 43.0, 49.3, 87.8 and 94.5 % down the machine. The section removes 95.8 g/m^2 of water, which is 766 kg/min for 34.5 MW of duty split 8.1, 24.2 and 2.2 MW, and consumes 58.2 t/h of live steam for 38.40 t/h of paper. The application's verification suite checks that line-up against the model, and it checks separately that the residual of every state derivative is below 10^{-9} relative at the stored initial condition.

Time stepping is Runge-Kutta of fourth order at a fixed 0.25 s interval, short enough that several steps fall inside the 1.25 s pass of the sheet through the after-dryer at top speed. The regulatory scan is 0.5 s, the historian records two samples per simulated second, and the gauge scatter is seeded with 20260913. The scan period of the gauge is a setting, adjustable from 4 to 40 s. Section 1.6.1 explains the engine step, the seed and the speed multiplier, which here runs from 1× to 30× and changes only the pace of the wall clock.

3.3.6 Assumptions

Detail is concentrated at the instrument and cut back everywhere else. Each of the eight simplifications below stops being true somewhere, named with it.

The cross direction is absent. This machine has one line of sheet, so the application shows exactly what a traversing measurement costs in the machine direction and cannot show the profile control the same head exists to serve [4]. The absence also removes the real reason a mill hesitates to speed the traverse up, which survives as an argument and not as a measurement.

Per-pass noise stands in for profile variation. Aliasing of a real cross-direction profile into the machine-direction reading is systematic rather than Gaussian, so a normal draw per pass has the right magnitude with the wrong structure. The gauge is otherwise perfect, with no standardization cycle, no sheet flutter, no cross-sensitivity between the beta and infrared measurements and no drift.

Three dryer groups and no condensate system. A machine of this size carries forty to sixty cylinders in five or six groups, each with its own pressure, syphons and differential controller. Here the outer two groups follow the main bank by the fixed ratios of (3.14), and a flooded group cannot be produced.

Drying is one conductance and a falling-rate factor. There is no sheet temperature state, no pocket ventilation balance and no split between the contact and open-draw parts of a group, and h_d was fitted so the design line-up gives a plausible dryness profile rather than a measured one [5, 6].

The wire and press are algebraic. Equation (3.5) is a slider with a small basis weight correction, so the application shows that a plugged felt is the largest routine disturbance on the machine and not why it plugged. The press and dryer balances also divide by the dry weight on the wire at that instant rather than the weight formed 34 to 146 m upstream of each group, so the extra water a stock move brings reaches the frame through the last 32 m about 8 s before the fiber that carries it. This lumped approximation is retained for the scanner and interaction lessons, so stock-step water arrival is not a physical transport prediction.

Consistency, retention and hood humidity are sliders. The white water loop, the save-all, the broke system and the wet-end chemistry that set them are absent, which matters because their true dynamics recirculate over tens of minutes and a consistency upset on a real machine comes back around.

A sheet break is a threading fraction. Equation (3.19) falls in 2 s and recovers in 15 s, while the real event is violent and threading is manual and takes minutes. Faithful is the part the control system experiences, that the measurement stops, the controllers hold and the cylinders heat up with nothing to dry.

The arithmetic is too reliable. A frozen step, a frozen scan and one seed return the identical trajectory to any student on any computer, which no real console and no real network will do.

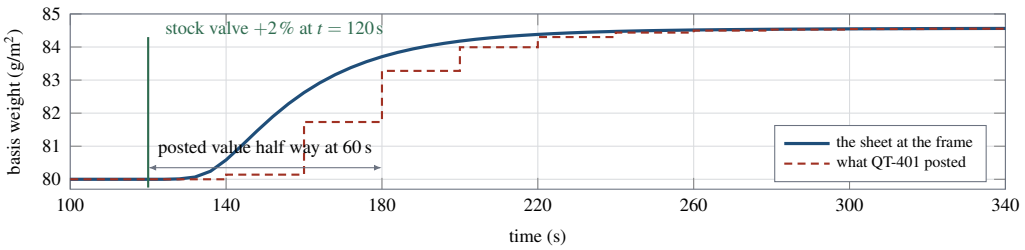


Figure 3.2 One open-loop stock step read through the scanning gauge, recorded in scenario 2. The very thick solid line is the sheet at the frame and the dashed staircase is the value QT-401 posted. The sheet at the frame reaches 63 % of its 4.58 g/m^2 move 43.5 s after the step and 95 % at 95 s, while the posted staircase is half way at 60 s.

3.4 Dynamic Analysis

3.4.1 The Effective Dead Time of a Scanning Gauge

Equation (3.22) contains three sources of phase lag and they add. The transport delay θ is a pure delay. The boxcar average over one traverse has its centroid half a period behind the instant of posting, so on any smooth trajectory the posted value is the sheet as it was $T/2$ before the pass ended. Between passes the number does not move, so the age of the value the controller acts on is distributed uniformly over $[0, T]$ and averages $T/2$ again. The effective dead time is therefore Equation (3.23).

$$\theta_{\text{eff}} = \theta + \frac{T}{2} + \frac{T}{2} = \theta + T \tag{3.23}$$

At the design line-up (3.23) gives $1.92 + 20 = 21.92$ s for moisture and $10.68 + 20 = 30.68$ s for basis weight. For moisture that is eleven times the transport delay by itself, and the instrument rather than the machine owns the number. The application's verification suite checks both halves of (3.23) on a ramped sheet. The posted value lags the truth by 9.74 s at the instant of posting, a quarter second short of $T/2$ because the boxcar sums the 0.5 s scans, and the mean age of the held value over a 300 s window is 10.13 s.

🕮 **Pause.** Try Exercise 3.1 before reading on.

The measured behavior of a single step is shown in Figure 3.2. The thick stock valve is stepped from 55.00 to 57.00 % at $t = 120$ s, which is worth 4.58 g/m^2 at the reel once settled. The dry weight at the frame begins to move 11.5 s later, because the fiber being weighed was formed 178 m upstream and the machine is doing 16.67 m/s. The conditioned weight starts about 5 s after the step, because the wetter sheet arrives first (Section 3.3.6), but only 0.06 g/m^2 of it comes before the fiber. The posted number does not move until the pass that ends at $t = 140$ s, 20 s after the step, and then it moves only to 80.140 g/m^2, the average of a traverse that was mostly old sheet.

Reading the two traces of Figure 3.2 against each other separates the plant from the instrument. The sheet is half way 36 s after the step and the posted number at 60 s, the sheet is 90 % of the way at 76 s and the posted number at 100 s, and both gaps of 24 s are within a few seconds of the 20 s that (3.23) attributes to the instrument. The posted trace is a sequence of averages rather than a sampled version of the true one. The 81.73 g/m^2 posted at $t = 160$ s is the sheet as it passed the frame 10 s earlier, while the paper under the head at that instant was already 82.66 g/m^2.

3.4.2 The Two-by-Two Gain Matrix

The second manipulated variable of the quality layer is the group pressure setpoint rather than the steam valve, because PIC-301 holds that setpoint against the header and the droop. Perturbing the model's own steady state by ± 0.25 % of stock valve at constant group pressure, and by ± 4 kPa of

group pressure at constant stock valve, gives the gain matrix of Equation (3.24).

$$\mathbf{K} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} +2.207 & -0.0514 \\ +0.889 & -0.0607 \end{bmatrix} \tag{3.24}$$

where the first row is basis weight in g/m^2 and the second is moisture in percentage points, the first column is per percent of stock valve and the second is per kPa of group pressure. Inverted, 19.5 kPa of group pressure buys a gram per square meter and 16.5 kPa buys a point of moisture. None of the four connections is small.

The signs are the interesting part. More stock is heavier because more fiber arrives per unit area, and wetter because the same dryer section has more water to remove, and by (3.20) the extra water is weighed as well, so the weight rises twice. More steam pressure is drier and also lighter, with not one gram of fiber different. Both effects are visible from the keyboard. A 2 % increase in stock valve at a fixed steam valve makes the sheet 4.58 g/m^2 heavier and 1.86 points wetter, of which only 2.75 g/m^2 is fiber, and a 6 % increase in steam valve makes it 1.79 points drier and 1.48 g/m^2 lighter. The manual figure of 4.58 g/m^2 exceeds twice K_{11}, which is 4.41 g/m^2, because a fixed valve is not a fixed pressure. The wetter sheet draws more steam and the droop of (3.17) lets the group pressure fall, which makes the sheet wetter and heavier again.

🕮 **Pause.** Try Exercise 3.2 before reading on.

The relative gain of the natural pairing follows from (3.24), as shown in Equation (3.25).

$$\Lambda_{11} = \left[1 - \frac{K_{12}K_{21}}{K_{11}K_{22}}\right]^{-1} = 1.517 \tag{3.25}$$

By the reading of Section 1.4.5, a relative gain between one and two says that pairing basis weight with the stock valve and moisture with the group pressure is correct and that the interaction is severe, because each loop slows the other down [3]. The other pairing has $\Lambda_{12} = 1 - 1.517 = -0.517$, so the gain of one loop changes sign between the other loop being in manual and in automatic, and the pair cannot be stabilized by any tuning of the two controllers. The application's verification suite recomputes Λ_{11} from the model rather than quoting it and requires the value to fall within 0.02 of 1.517.

3.4.3 Static Decoupling From a Signal That Already Exists

The two controllers reach each other only through the gauge, which is 21.9 s behind, although the correction each one needs is already available from the other controller's output at the instant it is computed. A simplified static decoupler passes each demand straight through and adds the other through the steady-state cross gain, as shown in Equation (3.26).

$$\begin{aligned} x_s^{cmd} &= \text{clip}_{[15,95]}\left[c_B + D_{12}\left(c_m - P^{ref}\right)\right] \\ P_{2,\text{SP}} &= \text{clip}_{[60,480]}\left[c_m + D_{21}\left(c_B - x_s^{ref}\right)\right] \end{aligned} \tag{3.26}$$

where c_B and c_m are the two controller outputs, $x_s^{ref} = 55\,\%$ and $P^{ref} = 306\,\text{kPa}$ are the design line-up the bias is taken about, the limits are in percent of stock valve and kPa, and the two gains are the ratios of Equation (3.27).

$$D_{12} = -\frac{K_{12}}{K_{11}} = 0.0233, \qquad D_{21} = -\frac{K_{21}}{K_{22}} = 14.64 \tag{3.27}$$

in percent of stock valve per kPa and in kPa per percent of stock valve respectively. These are the gains of Equation (1.8), and the simplified form is chosen for the reasons of Section 1.4.6: it needs only the two ratios and cannot introduce a pole of its own [15]. Chapter 2 uses one half of the same

structure on a plant whose gain matrix is triangular. An error in x_s^{ref} or P^{ref} is a constant bias that the two integrators remove, so both can be constants rather than values latched at commissioning. Equation (3.26) is static and therefore puts the right correction on at the wrong time, because the stock reaches the sheet through a 44 s path and the steam through a can bank whose slowest shell is 84 s. Section 3.6 measures what survives.

> ⧖ **HISTORY** **1965: The Coupling Found by the First Experiment**
>
> The engineers of that first computer-controlled machine did not know at the start that its two qualities were coupled. The first identification experiment showed it clearly. More thick stock flow raised both the moisture content and the dry basis weight, while a change of steam pressure moved the moisture but not the dry weight. They therefore controlled dry basis weight, estimated from the beta-ray and moisture readings, as a loop with one input, the thick stock flow. The moisture loop was given two inputs, with the stock flow used to remove the disturbance that the weight loop put into the moisture [8]. This chapter controls the conditioned weight instead, which couples the plant both ways.

3.5 Controller Design

3.5.1 The Discrete Algorithm

One shared proportional-integral-derivative implementation serves all four loops. It is the velocity form of Section 1.6.2, with the derivative on the measurement, and Equations (3.28) to (3.31) restate it in this chapter's symbols.

$$e_k = a\,(\mathrm{SP}_k - \mathrm{PV}_k) \tag{3.28}$$

$$P_k = K_c e_k, \qquad D_k = -K_c \tau_D\, a\, \dot{\mathrm{PV}}_k \tag{3.29}$$

$$S_k = S_{k-1} + (P_k - P_{k-1}) + (D_k - D_{k-1}) \tag{3.30}$$

$$\begin{aligned} u_k^u &= u_{bias} + S_k + I_{k-1} \\ u_k &= \mathrm{clip}_{[u_{\min}, u_{\max}]}\,(u_k^u) \\ I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{u_k - u_k^u}{T_t}\right] \Delta t_k \end{aligned} \tag{3.31}$$

where $a = \pm 1$ is the action, S_k accumulates the proportional and derivative terms, u_k^u is the unsaturated demand, I_k is the integral state, T_t is the tracking constant of the unwinding path and Δt_k is the interval since that loop last executed. They are Equations (1.11) to (1.14), with S_k the running sum of the fully formed terms. Windup is prevented by back-calculation, the second term of the integral update in (3.31), with $T_t = \tau_I$ on every loop, and the transfer between manual and automatic is bumpless as described in Section 1.6.2. The shared algorithm carries derivative action, with an optional first-order filter on the measurement, but no loop here exposes a derivative time and τ_D is zero on all four, because the only directly measured continuous variable on the machine is a steam pressure whose plant is a 14 s lag behind a 4 s valve and the other three act on a staircase.

The four loops are configured as listed in Table 3.3. Output limits are hard clips and there are no controller rate limits, because the actuator dynamics of (3.1), (3.4) and (3.16) already supply the travel time. The clips of (3.26) act after the sum and outside both controllers, which see only their own outputs, so a decoupled command held at a limit by the other loop's term would not slow either integrator. No shipped case reaches those limits, and the decoupled group pressure setpoint peaks at 455 kPa in the challenge run with the suggested settings.

3.5.2 Two Clocks and an Event

PIC-301 and SIC-401 execute every 0.5 s. PIC-301 reads a transmitter that never stops reading, while the tonnage SIC-401 reads changes with the live speed and, through $\hat{B}$, only when a pass posts. WIC-401 and MIC-401 execute on the arrival of a posted reading and not otherwise, so between

Table 3.3 The Four Implemented Loops and Their Default Settings. Action $a = +1$ Is Reverse Acting and $a = -1$ Is Direct Acting in the ISA Sense.

Loop	CV	MV	K_c	τ_I	a
WIC-401	$\hat{B}$	x_s	0.32	70	$+1$
MIC-401	$\hat{m}$	$P_{2,\mathrm{SP}}$	18	90	-1
PIC-301	P_2	x_p	0.45	20	$+1$
SIC-401	P	v	16	240	$+1$
Swapped pairing, kept as a separate controller pair					
WIC-401s	$\hat{B}$	$P_{2,\mathrm{SP}}$	6	200	-1
MIC-401s	$\hat{m}$	x_s	0.35	200	$+1$

Gains carry the units of the pairing: % of stock valve per g/m^2, kPa per point of moisture, % of steam valve per kPa and m/min per t/h. Integral times are in s. Output limits are 15 to 95 % on x_s, 60 to 480 kPa on $P_{2,\mathrm{SP}}$, 0 to 100 % on x_p and 400 to 1250 m/min on v.

passes their outputs are frozen and the machine runs open loop for 19.5 s out of every twenty. Writing them instead as continuous controllers fed a staircase is the standard mistake, and it produces a loop that integrates one stale error forty times over.

The integration interval each quality controller is handed is the elapsed time since the previous posting, clamped as shown in Equation (3.32).

$$\Delta t_k = \min\left(t - t_{k-1},\ 2T\right) \tag{3.32}$$

The clamp exists for one specific failure. During a break the gauge posts nothing, so $t - t_{k-1}$ grows without limit, and a controller handed a five-minute interval when the first reading after threading arrives adds $K_c \tau_I^{-1}$ times the error times five minutes to its integral in one step and throws the valve to its stop. Two periods also keeps the explicit back-calculation in (3.31) stable, because the worst ratio $\Delta t_k / T_t$ is then 2×40 s over the 60 s floor on τ_I, which is 1.33 and below the value of two at which an explicit unwinding step diverges. The 60 s lower limit on the integral time of both quality loops exists for that reason and not because a faster reset would be badly tuned.

3.5.3 Response to a Lost Measurement

Three behaviors are commissioned around the loss of the gauge and each prevents a specific failure. The quality controllers hold their last output, which is what every industrial quality control system does, even though the held stock valve position of 55.13 % and group pressure setpoint of 311 kPa were chosen for a sheet that no longer exists. The production setpoint is parked on the measurement while the web is down, because a 38 t/h target against no sheet is a 38 t/h error that no actuator can act on. The production loop is re-closed at 95 % of a threaded web rather than at 50 %, because against half a sheet the inferred tonnage is half of nothing. In a counterfactual run of scenario 10 with the gate moved to 50 % in a copy of the controller, the speed command goes to its 1250 m/min stop at $t = 460.5$ s, 24 s before the web is 90 % across, against a peak of 1032 m/min with the shipped gate.

3.5.4 The Production Cascade

SIC-401 moves the machine speed to hold a tonnage it can only change through the basis weight loop, which follows from Equation (3.3). It measures that tonnage as a mill production computer does, from the posted weight, the live speed and the trim, as shown in Equation (3.33).

$$\hat{P} = \frac{\hat{B}\, v\, W\, 60}{10^6}\, \phi \tag{3.33}$$

Neither the consistency nor the retention enters it, because no instrument on the machine reads them, and a speed move shows in $\hat{P}$ at once while the lighter sheet it makes reaches $\hat{B}$ one effective dead

time later. Ten percent more speed at a fixed stock flow delivers exactly the same fiber to the reel and a sheet 9.3 % lighter, and holding the grade at that speed needs 1.10 times the stock valve position. The loop is therefore gated on the weight loop being in service, it is disabled under the swapped pairing where the stock valve carries moisture, and its integral time of 240 s is an order of magnitude longer than the scan period of the loop nested inside it.

3.5.5 Model Predictive Control

A fifth quality structure, listed last, never the application's default and pinned only in scenario 14, gives the thick stock valve and the group pressure setpoint to one model predictive controller (MPC). It acts only in automatic and decides once when a run is initialized at $t = 0$ and then at each posting of the gauge, so its period is the scan period, 20 s as shipped. Each decision plans $N = 40$ passes ahead (800 s at that scan) in 11 move blocks of $[1,1,1,1,2,2,3,4,6,9,10]$ passes, 22 decision variables in all, and only the first move is sent, held until the next posting. A break posts nothing and so triggers no decision, which holds both commands as the loops hold theirs. The receding-horizon structure is the one industrial packages share [16, 17], as set out in Section 1.6.3.

Its model comes from the balances of Section 3.3, differentiated numerically about the design line-up with the declared values of Table 3.2, the nominal disturbances of Table 3.1, the web threaded and the speed fixed at 1000 m/min, and discretized with a zero-order hold at the 0.5 s scan. Its sheet and steam states are x_s, $\dot{m}_f$, B_d, u_P, x_p, P_2, $T_{c,1..3}$ and $u_{1..3}$. PIC-301 is inside it as the shipped discrete PI on its own tuning behind the 1.5 s transmitter, so the second input is $P_{2,\mathrm{SP}}$ and not the valve. The transport delays of (3.21) become chains of 21 and 4 scans (10.5 s and 2.0 s), the weight path being a copy of the stock line driven by the stock command 21 scans earlier, and the gauge of (3.20) is linearized with sensitivities $\partial B/\partial B_d = 1 + u_3 = 1.0582$, $\partial B/\partial u_3 = B_d = 75.600\,\mathrm{g/m^2}$ and $\partial m/\partial u_3 = 100/(1+u_3)^2 = 89.30$ points. The pass average and hold of (3.22) are composed exactly over one pass, as shown in Equation (3.34).

$$\begin{aligned} \mathbf{x}_{j+1} &= \mathbf{A}_h \mathbf{x}_j + \mathbf{B}_h \mathbf{v}_k + \mathbf{E}_h \mathbf{d}, \qquad j = kn, \ldots, kn+n-1 \\ \hat{\mathbf{y}}_{k+1} &= \frac{1}{n} \sum_{j=kn+1}^{kn+n} \mathbf{C}_g \mathbf{x}_j, \qquad n = T/h \end{aligned} \tag{3.34}$$

where $h = 0.5\,\mathrm{s}$, $\mathbf{x}$ collects the sheet and steam states, the PI integral, the transmitter and the two delay chains, $\mathbf{v}_k = [x_s^{cmd}, P_{2,\mathrm{SP}}]^\top$ is the decision held over pass k, $\mathbf{d}$ holds the estimated offsets of consistency, press dryness and header pressure, $\mathbf{C}_g$ is the linearized gauge and $\hat{\mathbf{y}} = [\hat{B}, \hat{m}]^\top$ is the next posting, all in deviations from the design line-up. With the stock decisions still in the weight chain carried as states, the plan's model has 28 states at the shipped scan, and the same composition serves any period from 4 to 40 s. Its steady gains, 2.2070, −0.0514, 0.8889 and −0.0607, round to those of (3.24), and steps on the running plant give 2.2067, −0.0514, 0.8877 and −0.0607. Started at the design point, it predicts the next 30 postings after a 1 % stock step within 1.5 % of the posted move and after a 10 kPa pressure step within 3.8 %, at scan periods of 4, 8, 20 and 40 s.

The quadratic program minimizes Equation (3.35) over the 22 block values.

$$\begin{aligned} J = &\sum_{k=1}^{N} \left[\left(\frac{\hat{B}_k - B^{\mathrm{SP}}}{0.8} \right)^2 + \left(\frac{\hat{m}_k - m^{\mathrm{SP}}}{0.30} \right)^2 \right] \\ &+ \sum_{j=1}^{11} \left[\lambda_s \Delta x_{s,j}^2 + \lambda_P \left(\frac{\Delta P_{2,\mathrm{SP},j}}{10} \right)^2 \right] \\ &+ \sum_{i=1}^{3} \left(\rho_i s_i^2 + \sigma_i s_i \right) \end{aligned} \tag{3.35}$$

Here $\hat{B}_k$ in g/m² and $\hat{m}_k$ in percent are predicted postings, Δ is the change between successive blocks with the first taken from the command in force, $\lambda_s = 1$ per squared percent of stock valve and $\lambda_P = 3$

per $(10\,\mathrm{kPa})^2$. Each slack $s_i \geq 0$ widens one soft limit over the whole horizon. The postings are held within the declared tolerances of $0.8\,\mathrm{g/m^2}$ and 0.30 points of their setpoints, widened by $0.8 s_1$ and $0.30 s_2$, and the steam valve that PIC-301 is predicted to command is held at or under $100\,\%$, widened by $10 s_3$ percent, at prices $\rho = (10, 10, 1000)$ and $\sigma = (1, 1, 100)$. The hard limits are the loops' own clamps, 15 to 95 % of stock valve and 60 to 480 kPa of pressure setpoint, and PIC-301, SIC-401, the hold on a lost measurement and every clamp stay in service beneath the plan. Neither structure receives a preview of a setpoint change.

Offset is removed by estimating disturbances [18]. A steady-state Kalman filter, with its gain from the discrete Riccati equation of the model sampled at the pass and augmented with the pass average, carries the consistency and press dryness offsets as random walks of 0.01 and 0.05 percentage points per pass, with the declared repeatabilities σ_B and σ_m as measurement noise. It advances every 0.5 s on the commands sent and corrects at each posting under every structure, so the MPC takes over warm. A second filter at 0.5 s reads PT-301 and estimates x_p, P_2 and a header offset, so that each plan starts from a steam side consistent with the transmitter. Any plan that fails the checks of optimality, finiteness and limits is discarded, and the weight and moisture controllers, which track every command the MPC sends, then act on that pass as two loops until a valid plan returns. The plant runs on the run's own parameters and disturbances, the gauge and the transmitter impose their averaging, hold, lag and noise, and the MPC reads only the two posted values, whether a pass has posted, the scan period, the PT-301 reading, the commands in force, the setpoints, its own settings, the tuning of PIC-301 and the declared constants. It never reads the speed or the tonnage.

The two move suppressions and the two random-walk sizes were chosen once, on scenario 14, from a grid of 369 settings, as the one making the least off-specification paper among the 62 that pass no more gauge noise into the sheet over the last ten minutes than the shipped decoupler. The rule was first applied before the correction that gave SIC-401 the measurement of (3.33) in place of the true fiber flow, and then once more on the corrected application. The earlier choice ($\lambda_s = 100$, $\lambda_P = 30$, 0.05 and 0.8 percentage points) makes 6.09 t of off-specification paper on scenario 14 against 2.68 t for the settings shipped. A decision takes 0.56 to 0.61 ms on average in Node.js.

3.6 Results

The fifteen scenarios of the app are ordered the way a laboratory would work through them, from the machine by hand (scenario 1) through the gauge, the scan period, the interaction, the pairing and the decoupler (scenarios 2 to 8) to a grade change, a sheet break, three routine upsets, the predictive controller and a graded challenge (scenarios 9 to 15). Each carries its own mode, structure, tuning, disturbances, timed events and completion rule, as Section 1.6.4 describes for every app, and every number in Tables 3.4 to 3.7 was taken from the running app. The screen during the grade move of scenario 6 is reproduced in Figure 3.4.

3.6.1 The Machine With a Clean Gauge and a Noisy One

Scenario 3 closes both quality loops on an undisturbed machine with the gauge repeatability set to zero. Nothing happens. Over 18 min and 53 posted traverses the stock valve does not move by a thousandth of a percent and the sheet holds $80.000\,\mathrm{g/m^2}$ and $5.500\,\%$, which is the only time in the application that it is true. With the default basis weight repeatability of $0.25\,\mathrm{g/m^2}$ set before Run, the stock valve command accumulates $4.79\,\%$ of travel over the same window and the sheet, which was flat, wanders between 79.77 and $80.17\,\mathrm{g/m^2}$. Doubling the repeatability to $0.5\,\mathrm{g/m^2}$ doubles that travel to $9.58\,\%$ and spreads the sheet from 79.54 to $80.33\,\mathrm{g/m^2}$. Over five other seeds the travel at $0.25\,\mathrm{g/m^2}$ runs from 3.48 to $5.02\,\%$ and always doubles with the noise. The variation in the paper is of the same order as the noise in the gauge, because one diagonal stripe across an eight-meter sheet is not the sheet and the loop transmits the difference into the product.

Table 3.4 Scan Period at a Fixed Moisture Tuning of 44 kPa per Point and 60 s. Peak-to-Peak Is the Moisture Swing Read Over 700 to 1400 s, With the Scan Period Set Before Run. Sheet Averaged Is the Paper One Traverse Integrates Over at 1000 m/min.

Scan period T (s)	30	20	10	8
θ_{eff}, moisture (s)	31.9	21.9	11.9	9.9
Peak-to-peak, scenario 3[a] (points)	4.49	2.62	0.18	0.07
Peak-to-peak, scenario 4[b] (points)	12.6[c]	8.72	0.33	0.12
Sheet averaged (m)	500	333	167	133

[a] Weight loop at 0.32 and 70 s, moisture setpoint 5.5 to 5.0 % at 200 s, the application's own verification run. [b] Weight loop at 0.50 and 60 s, setpoint move at 120 s. [c] Unstable, the steam valve running between its stops.

3.6.2 Scan Period Against Loop Stability

Scenario 4 loads the settings an internal model control rule returns when the dead time entered is the 1.92 s of transport rather than the 21.9 s the instrument costs, which is a moisture gain of 44 kPa per point against the tuned 18 kPa. A half-point moisture setpoint move at $t = 120$ s then produces an oscillation that grows, from 1.35 points peak to peak in the first cycle to 8.26 points in the eleventh, so that over the next twenty minutes the moisture spans 1.18 to 9.90 % about a 5.00 % setpoint, with a period of 100 s. That period is 4.5 times the 21.9 s of Equation (3.23), where a dead-time-dominant loop at the edge of stability oscillates, and the growth places this one beyond the edge. The basis weight goes around with it between 76.70 and 83.97 g/m^2 although nobody moved that setpoint. Each pass the controller sees an error that is largely its own last correction not having arrived, and corrects again on the strength of it. The weight loop of scenario 4 is tuned on the transport delay as well (0.50 % per g/m^2 and 60 s), and through the interaction it triples the ring. With that loop at its tuned 0.32 and 70 s the same moisture tuning swings 2.84 points over 700 to 1400 s, against 8.72 points.

Scenario 5 leaves that tuning alone and speeds the head up from twenty seconds a pass to eight at $t = 700$ s. The growth stops and the oscillation dies away, falling from 3.24 points peak to peak over 400 to 700 s to 1.24 points over the three minutes that begin three minutes after the change and roughly halving every three minutes after that, and the moisture stays within 0.05 points of 5.00 % from 937.5 s after it, with no gain touched. Run the other way, with 8 s passes slowed to thirty within a minute of the setpoint move, the moisture is 2.24 points from setpoint by 700 s. Table 3.4 holds the moisture tuning at 44 kPa per point and 60 s and sweeps the scan period alone.

> **TRY IT IN THE APP** **5 · Scan Period Against Loop Stability**
>
> Load the scenario, press Run in Auto and watch the Moisture strip. The loop rings with the tuning of scenario 4 and the swing grows. At 700 s the head is speeded up from twenty seconds a pass to eight, no gain is touched, and the oscillation dies away until the moisture stays within 0.05 points of 5.00 %.

Reading Table 3.4 across is unambiguous. Halving the traverse from 20 to 10 s turns a growing swing of 2.62 points into a decaying 0.18 points, a factor of fifteen, and in scenario 4 cuts it from 8.72 to 0.33 points, on a plant that did not change and a controller that was not retuned. At thirty seconds a pass the scenario 4 tuning does not hold the sheet at all. This is the highest-value change available on a quality control system and it is a genuine trade, because the same head also measures the cross-direction profile and the sheet it averages over shrinks with it, from 500 m per pass at 30 s to 133 m at eight. Machine-direction control wants the head to run and cross-direction control wants it to dawdle [4].

Table 3.5 An Eight Gram Grade Move With Four Decoupler Configurations. Times Are Measured From the Setpoint Move and Off-Specification Tonnage Is Read at $t = 900$ s, by Which Point It Has Stopped Accruing in Every Column.

	Neither	D_{12} only	D_{21} only	Both
D_{12} (%/kPa)	0	0.023	0	0.023
D_{21} (kPa/%)	0	0	14.5	14.5
Peak moisture error (points)	+1.80	+1.92	+0.24	+0.23
Time of that peak (s)	62	62.5	102.5	103
Moisture inside 0.3 points (s)	214.5	177.5	0	0
Weight first in band (s)	87.5	75	108.5	111
Weight settled in band (s)	87.5	202.5	477.5	496
Off-specification paper (t)	2.38	2.20	3.14	4.54

✦ DID YOU KNOW? A Faster Head Beats a Retuned Gain

From the simulator: with the moisture tuning held at 44 kPa per point, the setpoint move of scenario 3 leaves a swing of 4.49 points at a 30 s pass and 0.07 points at 8 s. Each reading then averages 133 m of sheet instead of 500 m (Table 3.4).

3.6.3 Interaction and What Half a Decoupler Is Worth

Scenario 6 raises the basis weight setpoint from 80 to 88 g/m^2 with two independent loops in service and the moisture setpoint untouched, and scenario 8 repeats it with the decoupler of Equation (3.26) switched on. Table 3.5 reports all four combinations of the two decoupler gains, every figure read on the sheet at the frame by $t = 900$ s against a setpoint move at $t = 120$ s. The production loop stays in service, so the heavier sheet also slows the machine toward the speed that holds 38.4 t/h, 921 m/min by 900 s.

Two independent loops make an 8 g/m^2 grade move into a 1.80 points moisture excursion that peaks 62 s after the setpoint moved, about three passes of the head, and that is not back inside three tenths of a point for good until 214.5 s. The full decoupler cuts the excursion to 0.23 points, and the moisture never leaves that band. The two gains are not equally worth having. Turning D_{21} off returns the excursion to 1.92 points while turning D_{12} off leaves it at 0.24 points, so the stock-to-steam half carries essentially all of the benefit to the moisture and this measurement says which way to run a one-way decoupler. The D_{12} only column makes 2.20 t of off-specification paper against 2.38 t with no decoupling, with the same moisture excursion within 0.12 points.

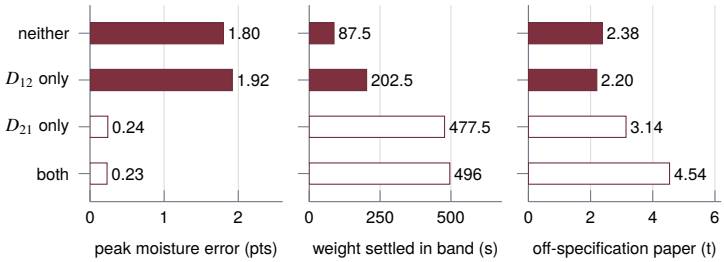


Figure 3.3 The eight gram grade move of scenarios 6 and 8 under the four decoupler configurations of Table 3.5. Dark bars run without the stock-to-steam gain D_{21} and white bars with it. Notice that D_{21} alone cuts the moisture peak from 1.80 to 0.24 points, while the same white bars show the weight settling later and more off-specification paper with the production loop in service.

> **TRY IT IN THE APP** **8 · A Decoupler**
>
> Load the scenario, press Run in Auto and watch the Moisture strip after the weight step at 120 s: the peak error is 0.23 points. Switch to Advanced, press Reset, set Stock-to-steam decoupling to 0 and run again. The peak returns to 1.92 points, more than with no decoupler at all (Table 3.5).

The weight loop pays for it. Decoupling makes the weight slower to reach its band, at 111 s against 87.5 s, because the stock valve now carries a steam-driven bias as well as its own controller's output, and the weight then overshoots to 88.94 g/m^2 and stays just above its band from 313.5 to 616 s. Over that interval the production loop is still slowing the machine, from 954 m/min at 300 s to 931 m/min at 600 s, and by (3.3) a slower machine lays a heavier sheet on the wire at the same stock flow. The weight is settled in its band at 496 s against 87.5 s, and the off-specification tonnage rises from 2.38 to 4.54 t. With the production loop in service, decoupling on this plant is the familiar trade between the two loops, a faster moisture loop bought with a slower weight loop. Doubling D_{21} to 29.25 overshoots the other way, to 1.77 points dry, and has made 8.64 t of off-specification paper by 900 s and is still making it. Figure 3.3 draws the four configurations side by side.

The residual 0.23 points is not a tuning error. Equation (3.26) is static, so it puts the right amount of steam on at the wrong time, and the mismatch between a 44 s stock path and an 84 s dryer path is what remains. The correction is nonetheless made from a signal the control system already holds instead of one that will not exist for another 21.9 s.

3.6.4 A Pairing That Cannot Be Tuned

Both connections in (3.24) are large, so both pairings are physically available. Basis weight responds to steam pressure at 19.5 kPa per gram per square meter, moisture responds to the stock valve at 1.12 % of valve per point, and step testing either loop with the other in manual returns a clean first-order plus dead-time fit and a sensible tuning. Scenario 7 puts both in service and dilutes the stock chest from 3.50 to 3.35 % consistency at $t = 150$ s. Twenty-two minutes after the dilution the natural pairing has the sheet back at 80.0 g/m^2 and 5.49 %, and the swapped pairing is at 72.8 g/m^2 and 13.12 % and still walking, with the stock valve down at 47.5 % and the group pressure setpoint down at 117 kPa. Integrated over the same 1500 s run, with a point of moisture weighted as four grams, the absolute error of the swapped pairing is 15.5 times that of the natural one, and it has made 13.6 t of off-specification paper against 2.1 t. That is what $\Lambda_{12} = -0.52$ means in operation. Each swapped loop has its own Auto and Manual switch, and with the weight loop alone in Manual the group pressure setpoint holds at 306 kPa while the moisture loop on the stock valve is stable on its own. The moisture falls to 3.87 % and climbs back through 5.00 % at 1200 s, slowly because that loop is tuned at 0.35 % per point and 200 s.

Table 3.6 Three Routine Upsets Open Loop and Closed Loop. Open Loop Is the Steady State With Both Valves Held. Recovery Is the Time From the Upset Until the Moisture at the Frame Is Back Inside 0.3 points for Good, Except in the Dilution Column Where It Is the Basis Weight Returning to Its 0.8 g/m^2 Band.

	Header dip 550 to 380 kPa	Felt plug 43 to 41 %	Chest dilution 3.50 to 3.30 %
Open-loop moisture (points)	8.06	3.43	−2.7
Open-loop weight (g/m^2)	—	—	−6.6
Closed-loop peak moisture (%)	6.60	8.23	3.59
Closed-loop peak weight (g/m^2)	—	—	73.2
Recovery (s)	117	327	328
Actuator that moved	x_p	$P_{2,\mathrm{SP}}$	x_s
from	61 %	310 kPa	55 %
to	85.6 %	354 kPa	58.9 %

Pause. Try Exercise 3.3 before reading on.

3.6.5 Disturbances the Loops Can and Cannot See

Table 3.6 collects the three routine upsets, each with its open-loop effect on the sheet and its effect with the full architecture of Table 3.3 in service. These scenarios run with the default gauge noise, and over three other seeds the closed-loop peaks move by at most 0.18 points and 0.14 g/m^2 and the recovery times by up to 57 s.

The header dip of scenario 12 is the one the machine sees. Left alone it is worth eight points of moisture, because 206 kPa in the main group instead of 306 gives a sheet leaving at 13.56 % that would not survive the calender. Instead PT-301 sees the sag within a second, the steam valve runs from 61 to 93.7 % before settling at 85.6 %, and the sheet peaks 1.1 points high, is back inside 0.3 points for good in 117 s and within 0.15 points of setpoint in 285.5 s. Eight points of upset became one, and the one that got through did so only while the valve was traveling. That is the argument for a regulatory layer underneath a quality layer, because the same disturbance reaching the sheet unmeasured would be discovered a scan period later.

The felt plug of scenario 13 is the one nothing measures. Two points of press dryness is 3.43 points of reel moisture open loop, larger than any setpoint move anybody makes deliberately, and closed loop the sheet still peaks at 8.23 % thirty-three seconds after the felt goes, above the 8 % runnability limit. The chest dilution of scenario 11 is faster than the instrument, because the dry weight on the wire has made 62 % of its fall by the time the first pass that shows it posts, 30 s after it starts, so the sheet undershoots past its open-loop value to 73.2 g/m^2 91 s after the upset and the moisture, which nobody touched, falls to 3.59 %, four tenths of a point above the brittle limit.

3.6.6 Loss of Measurement and the First Reel Back

Scenario 10 parts the web at $t = 150$ s and threads it again five minutes later with both quality controllers in automatic throughout. During the break the gauge posts nothing, both controllers hold, and the cylinders keep condensing steam with nothing to evaporate into. The group 2 shell climbs from 138.2 to 144.5 °C, which is its saturation temperature, and groups 1 and 3 rise six degrees each, while five minutes of break puts 3.1 t of fiber in the broke pit. The first paper through after threading is the wet slug that was sitting in the dryer section, at 9.70 % moisture 36.5 s after the tail is sent across (9.70 to 10.00 % over four seeds), and 56.5 s later the same sheet is over-dried at 4.49 % against a 5.5 % target, because it is meeting cylinders six degrees hotter than they were. The control system finds out one scan period later and has acted a second one after that. No tuning shortens the sequence, because the whole of it happens inside two samples of the only instrument that can see it.

3.6.7 Grade Change and the Challenge

Scenario 9 moves three setpoints at once, from 80 to 64 g/m^2, from 5.5 to 6.0 % moisture and from 38.4 to 34.0 t/h. The moisture overshoots upward first, to 6.63 %, which is the wrong direction for a lighter sheet. Twenty percent less fiber is twenty percent less mass to weigh, so the conditioned weight of (3.20) collapses, WIC-401 cuts the stock valve from 55 to 45 %, and MIC-401 takes the group pressure from 306 down to about 170 kPa to stop the sheet going bone dry. The weight first reaches its band 257 s after the change and the moisture is in its band to stay 239 s after it, although the gauge noise moves the moisture time between 239 and 1037 s over six seeds. The production rate has not arrived at half an hour, reading 33.6 t/h against 34.0 t/h with the machine still winding up through 1103 m/min, because a cascade whose inner loop reports three times a minute has to be an order of magnitude slower again. Half an hour of grade change leaves 4.32 t of the 16.67 t made as neither grade, and five other seeds range from 3.05 to 5.08 t.

The graded challenge asks for 88 g/m^2 at 5.4 % on a machine whose press is half a point wet, whose hood is already humid, whose header is 50 kPa low and whose head is taking thirty seconds a pass, with a consistency dilution and a hood failure arriving later in the run. The answer has four parts and only one is tuning. The pairing has to be the natural one. The decoupler has to be on, because an eight gram weight move is a one and a half point moisture disturbance and there is no reason to make the moisture controller discover it through a gauge 32 s behind. The scan period has to come down, because at thirty seconds a pass (3.23) gives 31.9 s of effective dead time in the moisture loop and 40.7 s in the weight loop, against 11.9 and 20.7 s at ten seconds. Only then does the tuning follow. The constraint has to be checked before any of it, because once the dilution and the hood failure are in, the new grade needs the stock valve at 62.3 % and the group pressure at 450 kPa, which is a steam valve at 96 % of a 500 kPa header. Configured that way, which is the suggested line-up (decoupled, the tuning of Table 3.3, a 10 s scan), the last third of the run holds the sheet inside 0.35 g/m^2 and 0.21 points and the posted values the challenge scores inside 0.56 and 0.30 points, 44 and 33 % inside the limits of $\pm 1.0\,\mathrm{g/m^2}$ and ± 0.45 points that apply from 1188 s to the end of the 1800 s run. Left as it starts (two loops, slack tuning, a 30 s scan) the machine never reaches the grade at all, finishing seven grams light and 1.2 points wet with 17.2 t of off-specification paper against 8.5 t, and its worst posted deviations in the last third are 8.44 g/m^2 and 1.25 points. The challenge is judged on the case as given, so a changed model parameter or disturbance voids the attempt. Settings chosen before Run define the starting line-up and remain allowed, and the shipped tuning still fails from such a line-up, with a 2.99 g/m^2 maximum late weight error.

3.6.8 Model Predictive Control Against the Decoupled Loops

Scenario 14 is the grade change of scenario 9, 80 to 64 g/m^2, 5.5 to 6.0 % and 38.4 to 34.0 t/h at $t = 120$ s, with both quality handles given to the MPC of Section 3.5.5, and the challenge is now scenario 15. Table 3.7 runs it and eight other cases under four structures on each case's own seed, noise, events and duration, with the same instruments, no preview for any structure, the shipped structures at their shipped tuning (the challenge at its suggested line-up) and the MPC held at scenario 14's settings in every case. The third column is the like-for-like comparator, the decoupler retuned once on the grade change by the rule that chose the MPC's settings over a grid of 400 tunings ($K_c = 0.45$ and $\tau_I = 70$ s on weight, 13 and 60 s on moisture) and then held on every case.

On scenario 14 the MPC makes 2.68 t of off-specification paper against 4.32 t for the shipped decoupler and 6.53 t for two loops, while the retuned decoupler makes 1.51 t. On five further noise seeds it makes less than both shipped structures and more than the retuned decoupler every time, as listed in Table 3.7. The MPC moves at once and hard. At the posting that carries the change it takes the stock valve from 55.17 to 46.25 % and the pressure setpoint from 305.0 to 226.0 kPa, where the decoupler takes the stock only to 49.73 % with nearly the same pressure, and its weight enters the band 93.5 s after the change against 257.5 s.

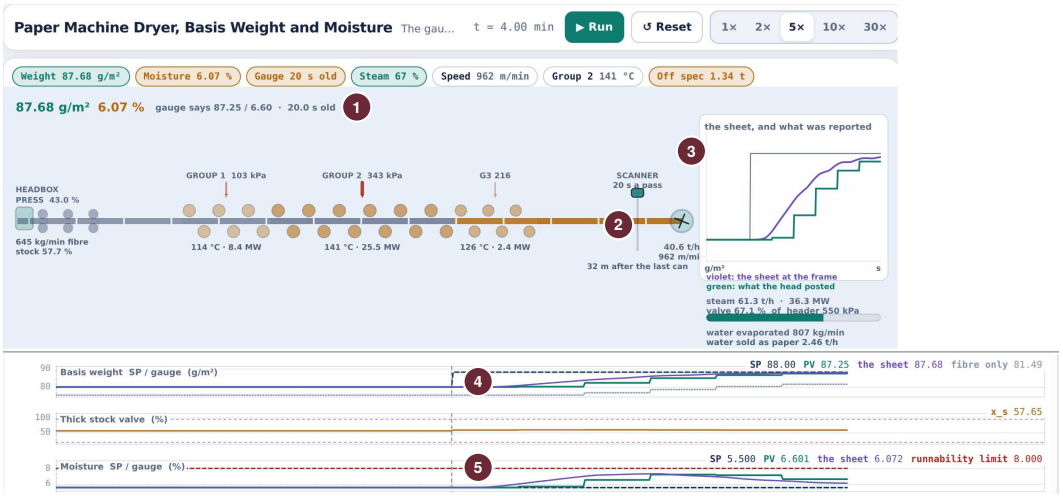


Figure 3.4 The machine at $t = 240$ s in scenario 6, two minutes after the basis weight setpoint moved from 80 to 88 g/m^2 with two independent quality loops in service and the moisture setpoint left at 5.5 %. The picture is a composite of two parts of the screen: the header and plant view above, and the first three trend strips below the gray rule. (1) The readout of the sheet beside what the gauge says. (2) The scanning head, drawn on its frame at the position reached in the current traverse. (3) The sheet at the frame against the staircase the head posted. (4) The basis weight strip, which carries the posted staircase the controller acts on, the sheet at the frame and the dry weight the steam valve cannot touch. (5) The moisture strip, with the excursion into a loop that was asked to do nothing, whose 1.80 points peak 62 s after the step Table 3.5 reports. The gauge still posts 6.601 % against a 5.500 % setpoint while the sheet at the frame is down to 6.072 %, and the posted 87.25 g/m^2 against an 87.68 g/m^2 sheet is the same lag on the weight strip.

Most of the gap to the retuned decoupler is the machine speed. SIC-401 reads the tonnage of (3.33), so the lighter grade first slows the machine to 955 m/min at 160 s and then drives it to 1054 m/min by 280 s, while the MPC's model holds 1000 m/min. By (3.3) a faster machine lays a lighter sheet. The MPC's sheet, at 63.30 g/m^2 and 6.21 % at 220 s when the decoupled loops' was still 71.56 g/m^2, falls to 59.99 g/m^2 with the moisture at 7.11 % by 280 s, as shown in Figure 3.5, and its moisture is in band to stay only 665.5 s after the change. With the gain of SIC-401 at zero, so that the speed stays at 1000 m/min, the MPC makes 1.95 t against 3.27 t for the retuned decoupler. The retuned loops gain from the production loop, and the MPC loses to it. The shipped decoupler is nearly indifferent to the fixed speed, at 4.37 t against 4.32, while the MPC falls from 2.68 to 1.95 t.

The tuning rule's noise condition holds on the tuning seed alone. There the MPC's 2σ of weight over the last ten minutes is 0.260 g/m^2 against 0.271 g/m^2 for the shipped decoupler, but on four of the five further seeds it is the larger. On the quiet machine of scenario 3 with the default gauge noise the MPC spreads the sheet over a 2σ of 0.305 g/m^2 against 0.214 and moves the stock valve 15.4 % against 7.9, where the earlier settings gave 0.211 g/m^2 and 6.25 %. The settings that suit the grade change pass more of the gauge noise into the paper.

Elsewhere the MPC makes the least off-specification paper of the four structures on the chest dilution (3.92 t against 5.59, 7.55 and 6.14) and on the header dip (0.51 against 1.93, 1.36 and 1.51), and on the challenge with its suggested line-up it makes 3.73 against 8.50 for the shipped decoupler and 7.11 for the retuned one, with 0.16 points of worst posted moisture against 0.30. On the clean moisture step it makes the least and is in band soonest at each of the scan periods 8, 10, 20 and 30 s. It loses three cases. The eight gram weight move costs it 3.33 t against 2.38 for two loops and 1.84

Table 3.7 Two Loops (TL), the Shipped Decoupler (Dec), the Decoupler Retuned Once by the MPC's Rule (Ret) and the MPC on Nine Cases. Each Case Runs on Its Own Seed, Noise and Events for 1800 s Unless Stated.

Case and measure	TL	Dec	Ret	MPC
Grade change, sc. 14, off spec (t)	6.53	4.32	1.51	2.68
seeds 1–5, least (t)	3.68	3.05	1.10	2.28
seeds 1–5, most (t)	5.08	5.08	1.33	2.39
both in band to stay (s)	1617.5	753.5	654.5	665.5
moisture in band to stay (s)	1617.5	239.5	113.5	665.5
2σ weight, last 10 min (g/m^2)	0.300	0.271	0.246	0.260
2σ moisture, last 10 min (points)	0.315	0.181	0.151	0.177
SIC-401 gain 0, off spec (t)	8.73	4.37	3.27	1.95
Weight move, sc. 6, to 900 s (t)	2.38	4.54	1.84	3.33
SIC-401 gain 0 (t)	5.65	3.36	2.26	1.13
Gauge noise, sc. 3, 2σ weight (g/m^2)	0.238	0.214	0.272	0.305
2σ moisture (points)	0.201	0.113	0.094	0.162
stock valve travel (%)	7.0	7.9	10.0	15.4
Moisture step, sc. 3, to 1400 s (t)	0.22	0.28	0.40	0.20
in band to stay (s)	23.5	29.0	40.0	21.5
Chest dilution, sc. 11 (t)	5.59	7.55	6.14	3.92
Header dip, sc. 12 (t)	1.93	1.36	1.51	0.51
Felt plug, sc. 13 (t)	4.81	7.40	5.76	5.04
Sheet break, sc. 10 (t)	1.15	1.35	1.75	1.62
Challenge, suggested (t)	—	8.50	7.11	3.73
worst posted moisture (points)	—	0.30	0.29	0.16

Off spec is the application's off-specification tonnage and band times count from the event on the true sheet at the frame. The noise case sets 0.25 g/m^2 and 0.12 points per pass before Run, with 2σ over 60 to 1800 s. The moisture step is 5.5 to 5.0 % at 200 s on a clean gauge at the 20 s scan. The suggested challenge line-up is decoupled, so two loops have no entry. The MPC decided at every posting, 90 times in an 1800 s run at the 20 s scan (74 in the break, 180 in the challenge at its 10 s scan), in 0.56 to 0.61 ms on average in Node.js, and rejected no plan.

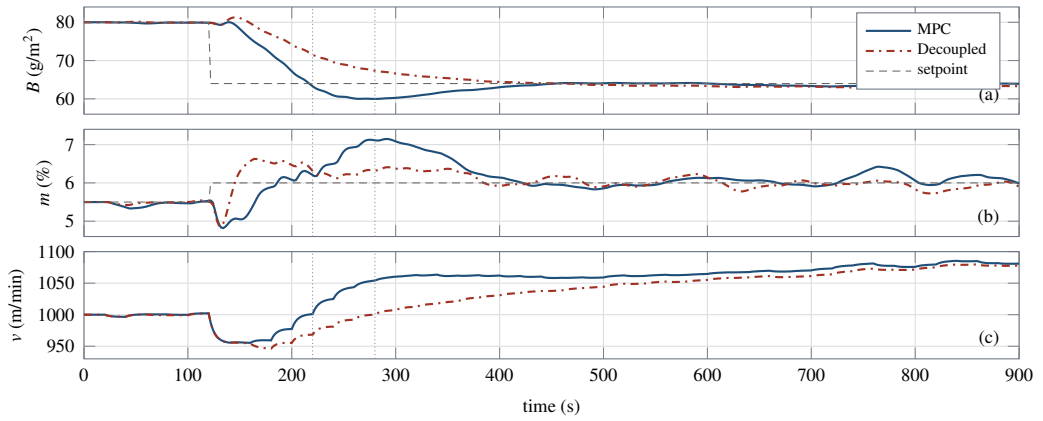


Figure 3.5 Scenario 14 under the MPC and under the decoupled loops of scenario 9, read on the true sheet at the frame. (a) Basis weight. (b) Moisture. (c) Machine speed set by SIC-401. The MPC is solid, the decoupled loops are dash-dotted and the setpoint is thin and dashed. The dotted lines mark 220 and 280 s.

for the retuned decoupler, and with the gain of SIC-401 at zero the same move costs it 1.13 t against 2.26, 3.36 and 5.65, so this loss is also the speed. The felt plug costs 5.04 t against 4.81 for two loops, and 4.29 against 4.94 with the speed held. The sheet break costs 1.62 t against 1.15 and 1.35, and

still 1.45 against 1.26 for the decoupler with the speed held. Its model has no break, and between the rethread at 450 s and 900 s it moves the stock valve over 51.3 to 56.9 % while the decoupled loops stay within 54.9 to 55.3 %. Switched to MPC on the challenge as loaded, the machine still fails, at 0.53 points of moisture against the 0.45 allowed, but with 5.40 t of off-specification paper against 17.22 for the shipped loops.

Ablations locate what the model contributes. Reading each posting as the sheet now, with the scanner and the transports left out, costs the most on the grade change, the weight move, the dilution and the felt plug (3.37, 4.36, 5.71 and 6.36 t against 2.68, 3.33, 3.92 and 5.04). Replacing the steam observer by the design header costs the most on the header dip (6.49 against 0.51 t) and the challenge (10.58 against 3.73). Two single-loop plans in one program, each handle seeing only its own quality, make 2.43 t on the grade change, less than the full plan and less on four of the five further seeds, and 3.08 on the weight move, so the interaction in the model does not pay on the two setpoint moves, although it does on the dilution, the felt plug, the header dip and the challenge (4.84, 5.32, 0.59 and 4.38 t without it). The steam valve ceiling never binds in a shipped scenario, and every scenario and the suggested challenge run identically with and without it apart from the solver’s iteration count. It binds only when the header of scenario 12 is lowered to 320 kPa, where it is worth 3.88 t against 5.64 without it and 8.56 for the shipped decoupler.

3.7 Technology in Practice

What Measures It

Basis weight is read by attenuation of beta radiation. The first survey of nucleonic gauges by the International Atomic Energy Agency, in 1962 and 1963, counted around 20 000 gauges in 21 countries, and in Finland 72 % of them were used in the paper industry [19]. On the first computer-controlled paper machine the beta-ray gauge sat at a fixed position at the dry end and moisture was read by a capacitance gauge that could traverse the web but was normally held still. The machine tender and the test laboratories also measured basis weight, and the weight and size of each reel, a very accurate average, calibrated the other gauges [8]. Full-sheet web scanning systems now read moisture, thickness, ash and many other properties of the web [20]. The chapter’s frame QT-401 carries a beta gauge and an infrared moisture head, averages one traverse and holds it, with per-pass repeatabilities of 0.25 g/m^2 and 0.12 %.

> **TECHNOLOGY Sensor: The Beta Transmission Gauge**
>
> A transmission gauge places the material between a radioactive source and a detector, and the material attenuates the beta particles before they reach the detector. Krypton-85, strontium-90, promethium-147 and thallium-204 are the sources listed for gauging paper [19]. Beta rays are absorbed about equally by fiber and by water, so the reading is proportional to the mass of both per unit area, the wet basis weight [8]. A drifting gauge leaves no mark on a trend, because the loop holds the drifted reading on its setpoint while the reel moves off grade. The first computer-controlled machine therefore used the weight and size of each finished reel to compensate the drift of its beta-ray gauge [8]. The chapter’s gauge is perfect apart from a repeatability of 0.25 g/m^2 per pass.

What Moves It

On the first computer-controlled machine the computer moved basis weight through the setpoints of analog regulators on the thick stock flow valve and the thick stock dilution valve [8]. The chapter keeps the first of these as NCV-101, a valve with a 3 s travel feeding an approach system that adds a 22 s mixing lag. The steam side is a valve on the main dryer group, and the machine drive is the third handle, moved only by the production loop.

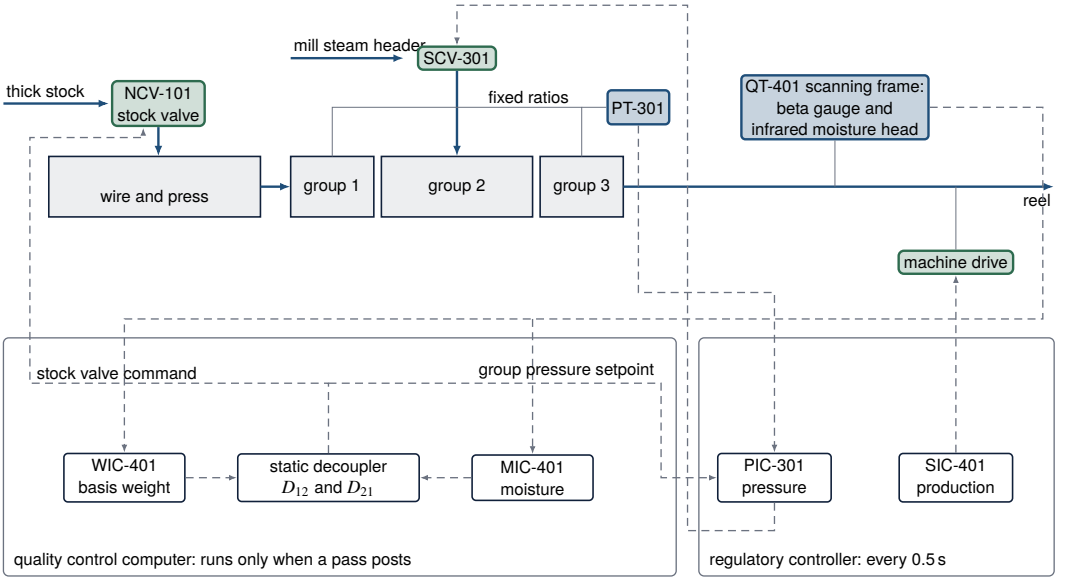


Figure 3.6 The quality loops on plant hardware. The scanning frame carries the beta gauge and the infrared moisture head across the sheet and posts one average of each per pass. Only then does the quality computer run WIC-401 and MIC-401, whose outputs pass through the static decoupler to the stock valve and to the setpoint of PIC-301, which holds the main group pressure through SCV-301 every half second. SIC-401 moves the machine drive. Notice that the steam valve is the only final element under a loop with a continuous measurement.

TECHNOLOGY **Final Element: Steam to the Dryer Groups**

A multi-cylinder dryer section carries 40 to 90 steam-heated cylinders, and groups of them run at different steam pressures. The first cylinders the sheet meets run at the lowest pressure and temperature and later groups run hotter, which keeps the paper from sticking to the shells. The drying rate depends on the temperature and volume of the steam entering the cylinders and on how well condensate is removed from inside them, as well as on the felts, the hood air and the pocket ventilation [20]. A group that floods therefore dries less at the same pressure, and the moisture loop sees only a wetter sheet. In the chapter one valve, SCV-301, sets the main group pressure with a 4 s travel, the outer groups follow at ratios of 0.30 and 0.63, and no condensate system is modeled.

Where the Controller Runs

Industrial control loops are often nested or cascaded, so that one loop's setpoint comes from another loop, and supervisory and lower-level loops run with cycle times from milliseconds to minutes [21]. A distributed control system adds a supervisory level that oversees the controllers of the local processes [21]. The chapter's structure sits on two such levels with different clocks. PIC-301 and SIC-401 execute every 0.5 s as ordinary PID blocks. WIC-401 and MIC-401 execute only when the head posts a pass, every 20 s as shipped, and the decoupler between them is two gains and two sums. The optional predictive controller decides once per posting as well, in 0.56 to 0.61 ms on average. Figure 3.6 draws the loops on their devices.

IN PRACTICE **Steam per Kilogram of Water**

Energy use in papermaking is set most by the operation of the steam and condensate system and of the air handling around the dryers. A well-maintained drying system averages about 1.3 kg of steam per kilogram of water evaporated, and many run with higher steam use [20]. The same check can be made on the simulated machine, which at its design line-up consumes 58.2 t/h of live steam while it removes 766 kg/min of water.

What Is Modernizing It

A 2025 assessment of industrial drying notes that conventional dryers often dry unevenly, leaving overdried regions that raise energy use and degrade paper quality, while microwave drying targets wet spots. It reports machine learning applied to drying that reduced steam use by 1.5 %, and it lists the life of existing dryers, 30 to 60 years, as a barrier that makes their replacement slow [13]. Sensors that read properties beyond weight and moisture on the moving web are a second direction, taken up in the open challenges below. For the chapter's structure, a dryer section that keeps its steam-heated cylinders for decades means that the pairing and the decoupler of Section 3.4 will run on the same plant for a long time, and are worth getting right.

3.8 Limitations

The model cannot be used to size a dryer section. Three lumped groups, a fitted conductance, no condensate system, no sheet temperature state and no pocket ventilation balance put it well short of what a thermal design calculation requires [5, 6], and no number in it should be read as a prediction of a real machine's dryness profile. The cross direction is absent altogether, which is the largest omission, because the traversing head serves profile control as much as machine-direction control and the trade in Table 3.4 therefore has only one of its two sides measured here [4]. The gauge is perfect apart from its per-pass noise, so standardization cycles, sheet flutter, cross-sensitivity between the two measurements and slow drift are all outside the model, and a drifting gauge is a more common cause of an off-specification reel than any upset in Table 3.6.

OPEN CHALLENGE **Controlling the Property the Customer Buys**

Stiffness is one of the most important properties of paper, yet it is measured offline on samples cut from the finished reel, manually and slowly, too late to adjust the machine. Mills therefore use more pulp than necessary so that the product meets its stiffness standard, and as much as 5 % of the paper made each year is judged substandard and remanufactured. A laser ultrasonic sensor that reads stiffness on the moving web was at the demonstration stage in a 2012 review, which noted that a mill could then run to stiffness targets rather than basis weight targets [22]. Here basis weight stands in for what the customer buys. Progress would be an online property measurement trusted as a setpoint.

Dry weight control is deliberately not offered. Mills also control $B(1-m)$ from the same two readings, and that pairing interacts much less than the conditioned pairing of Equation (3.20), so working out why it helps is worth more than being handed it. Apart from the predictive controller, the four loops implemented are the only ones available, and consistency ratio control, dry line control, a steam box, a condensate differential loop and cross-direction actuators are absent even though each changes the machine-direction problem. The disturbances arrive as steps and timed events instead of the slow wandering a real plant does, and consistency, retention and hood humidity are open sliders whose real dynamics recirculate through the white water and broke systems over tens of minutes. Section 3.3.6 names the point at which each simplification stops holding.

The predictive controller's model omits whatever moves with the operating point. It is linearized once at the design grade, where the moisture gain to the group pressure is −0.0607 points per kPa, while the plant's is −0.0905 near the new grade of scenario 14 (stock 46 %, 190 kPa) and −0.0452 at the challenge's line-up. It fixes the speed at 1000 m/min and the transports at their design values, although at the 1103 m/min that ends scenario 14 they are 9.68 and 1.74 s, and it has no break. Its

Kalman filter assigns every such error to the consistency and the press dryness, so with neither changed it ends scenario 14 reading 3.21 % and 39.90 %. Its settings come from one case and one noise sequence, its bands are the declared tolerances whatever the run's are, and each soft limit has a single slack for the whole horizon.

> ⚠ **OPEN CHALLENGE** **Control That Keeps Performing Through Grade Changes**
>
> An industry research plan of 1999 counted among its priorities techniques that sustain the performance of control systems without deterioration over time. Its pathway for control system effectiveness listed multivariable and nonlinear control and control systems that automate start-up and transitions, with product loss during transitions minimized as the result sought [23]. In this chapter half an hour of grade change still leaves 4.32 t as neither grade, and the predictive controller, linearized once at the design grade, loses to retuned loops. Progress would be a multivariable controller whose model follows the grade and the speed.

3.9 Discussion

Moisture is sold at the price of paper. At the design line-up the machine ships 38.40 t/h of which 2.11 t/h is water, so one reel in eighteen is water that the customer pays for at $820 per tonne. At a fixed fiber rate every tenth of a point of moisture setpoint is worth about 41 kg/h more of it, which is roughly 33 $/h, and the economic case for a tighter moisture loop is that the setpoint can then move closer to the specification limit without crossing it. The variability the loop cannot remove sets that distance, and Table 3.4 prices it, because the same controller holding 4.49 points of swing at thirty seconds a pass and 0.18 points at ten seconds needs entirely different margins.

The other half of the economics runs the other way. Water removed in the press is much cheaper than water removed in the dryers, and the exchange rate depends on what is being held. Leaving the steam valve where it is, two points of press dryness add 2.0 MW of dryer duty while the sheet drifts to 8.9 % moisture, which is 1.0 MW per point of dryness. Holding the reel moisture on 5.5 % instead costs 3.1 MW for the same two points, which is 1.5 MW per point and 40 kW for every tonne an hour of production, because the extra water now has to be boiled off rather than shipped. The fixed-valve calculation understates the cost by half, and it is the calculation a felt-conditioning budget is usually argued from. Dryer energy is the largest single steam demand in a paper mill and one of the cheapest places to save it [12].

Nothing restricts the plant of this chapter to the four loops built on it. The fourteen balances of Section 3.3 form a complete nonlinear state-space model with hard actuator limits, and the controller of Section 3.5.5 uses their linearization to coordinate the two qualities as one two-input problem. Its steam valve ceiling never binds in the challenge, where the plan predicts at most 96.1 % and the valve reaches 96.3 %, nor in any other shipped scenario (Section 3.6.8). A sampled, averaged and held measurement is also where state estimation earns its keep, because a moving horizon estimator running on Equations (3.2) to (3.10) reconstructs the current sheet between passes and recovers part of the phase that (3.23) removes, which is the reasoning that puts a soft sensor in front of a slow laboratory measurement [1]. Volume 5, Chapter 10 builds such a soft sensor for powder moisture and corrects its bias from a sampled, delayed laboratory result. The unmeasured consistency of scenario 11 and the unmeasured press dryness of scenario 13 are both estimable from the two quality readings and the steam demand, and the predictive controller's filter estimates both, although it confuses them with its own linearization error (Section 3.8). Rebuilding the balances in the Gekko Optimization Suite under Python takes the eight hidden constants as the quantities to be estimated [24].

3.10 Conclusion

This chapter studied a fine-paper machine as a laboratory for control through an instrument that is late, intermittent and spatially incomplete at once. The simulator integrates fourteen states, with the scanning gauge represented as a boxcar average over one traverse, a zero-order hold between passes and a transport delay computed from the live speed. The effective dead time is the transport delay plus

one whole scan period, 21.9 s for moisture and 30.7 s for basis weight, and a loop tuned against the transport delay alone rings at 100 s with a growing swing, 4.5 times the dead time it faces. Shortening the traverse from 20 to 10 s at an unchanged gain reduces that swing from 8.72 to 0.33 points and halves the sheet each reading averages over, from 333 to 167 m.

Basis weight sold conditioned makes the plant a two-by-two with a relative gain of 1.52 on the natural pairing and −0.52 on the other, and the swapped pairing left in service for twenty-two minutes after a consistency dilution reaches 72.8 g/m^2 and 13.12 % while still walking. A static decoupler cuts the moisture excursion of an eight gram grade move from 1.80 to 0.23 points, while the weight, held just above its band as the production loop slows the machine, takes the off-specification tonnage from 2.38 to 4.54 t.

An optional predictive controller with the gauge, the transports and PIC-301 in its model makes 2.68 t of off-specification paper on a grade change against 4.32 t for the shipped decoupler, and it loses to the decoupler retuned by the same rule (1.51 t) chiefly because its model holds the speed that the production loop moves.

A fuller model would add a cross-direction profile with slice actuators, a condensate system with a differential loop per group, dry weight as a selectable controlled variable, and a consistency transmitter so that feedforward on the disturbance can be compared against feedback on the quality. As it stands, the plant’s limiting element is the instrument, and the reader learns it by operating the machine.

KEY POINTS

- The gauge is late by the time the sheet takes to reach it plus one pass of the head, and for moisture the gauge owns most of that delay.
- Shortening the pass from 20 to 10 s at an unchanged gain cuts the scenario 4 swing from 8.72 to 0.33 points.
- Conditioned basis weight couples the plant both ways: the relative gain is 1.52 on the natural pairing and −0.52 on the swapped one, which cannot be tuned.
- A static decoupler cuts the moisture excursion of an eight gram grade move from 1.80 to 0.23 points, almost all of it from the stock-to-steam half, while the weight loop pays.

Where else this applies. Chapter 2 runs one half of the same decoupler on a triangular plant, and Volume 5, Chapter 3 meets the same dead-time accounting with an online analyzer.

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3.11 Exercises

3.1 ○ Concept check · 2 min

At the design line-up the moisture loop faces an effective dead time of 21.9 s, although the sheet takes only 1.92 s to travel from the last cylinder to the frame. What makes up the other 20 s?

(a) The can bank, whose slowest shell has an 84 s time constant

(b) The 0.5 s regulatory scan, added once for each of the forty scans of a pass

(c) The approach system and the forming lags between the stock valve and the wire

(d) Half a scan period for the boxcar average and half a period for the hold

3.2 ○ Concept check · 1 min

In scenario 1, with the machine in Manual, raising the steam valve by 6 % makes the sheet 1.48 g/m^2 lighter, although not one gram of fiber changes. Why?

(a) The beta gauge weighs the water in the sheet, and more steam evaporates more of it
(b) Hotter cylinders shrink the sheet, so less fiber lies on each square meter
(c) The production loop speeds the machine up as the group pressure rises
(d) The press leaves the sheet wetter when the dryer cylinders run hotter

3.3 Concept check · 2 min

Each loop of the swapped pairing, basis weight on the group pressure and moisture on the stock valve, gives a clean first-order plus dead-time fit and a sensible tuning when it is step tested with the other loop in Manual. Why does the pair fail when both are put in service in scenario 7?

(a) The gain of 19.5 kPa per g/m^2 needs more pressure than the group can take
(b) Closing either loop reverses the sign of the gain the other acts on, as $\Lambda_{12} = -0.52$ says
(c) The gauge posts the two qualities at different times, so the loops drift out of step
(d) The swapped loops have no back-calculation, so both integrators wind up together

3.4 Theory and calculation · 6 min

The scanning frame stands $L_B = 178\,\text{m}$ from the slice and $L_s = 32\,\text{m}$ from the last cylinder. Use Equations (3.21) and (3.23).

(a) At 1000 m/min and a 20 s scan, find the two transport delays and the two effective dead times. *Checkpoint:* 10.68 s and 1.92 s; 30.68 s for weight and 21.92 s for moisture.

(b) Repeat the effective dead times for scan periods of 30 and 10 s, and find the length of sheet one traverse averages over at each. *Checkpoint:* 40.68 s and 31.92 s with 500 m; 20.68 s and 11.92 s with 167 m.

(c) The operator slows the machine to 800 m/min at the 20 s scan. Find the transport delays and effective dead times now, and say whether slowing down helps the quality loops. *Checkpoint:* 13.35 s and 2.40 s; 33.35 s and 22.40 s.

3.5 Theory and calculation · 7 min

Use the gain matrix of Equation (3.24), $K_{11} = 2.207$, $K_{12} = -0.0514$, $K_{21} = 0.889$ and $K_{22} = -0.0607$, with the units given there.

(a) Compute the relative gains Λ_{11} and Λ_{12}. *Checkpoint:* 1.52 and -0.52.

(b) Compute the Niederlinski index of Equation (1.7) for the natural pairing and for the swapped pairing. *Checkpoint:* 0.66 and -1.93.

(c) Compute the decoupler gains of Equation (3.27). With the shipped $D_{21} = 14.5$, find the steady moisture change per percent of weight controller output, and repeat for $D_{21} = 29.25$. *Checkpoint:* $D_{12} = 0.0233$, $D_{21} = 14.6$; $+0.009$ and -0.887 points per percent.

3.6 Theory and calculation · 5 min

At the design line-up the machine runs at 1000 m/min on an 8.0 m trim, making 80.00 g/m^2 at 5.50 % moisture. Use Equations (3.7) and (3.20).

(a) Find the dry weight, the saleable production and the water and fiber in it, in t/h. *Checkpoint:* 75.60 g/m^2; 38.40 t/h, of which 2.11 t/h is water and 36.29 t/h fiber.

(b) In scenario 1 a 2 % stock step adds 2.75 g/m^2 of fiber and makes the sheet 1.86 points wetter. Find the new conditioned weight. *Checkpoint:* About 84.57 g/m^2, against the 84.58 g/m^2 measured.

(c) At a fixed fiber rate, find the extra water sold for each tenth of a point of moisture setpoint, and its value at the paper price of \$820 per tonne. *Checkpoint:* About 41 kg/h, worth about \$33 an hour.

3.7 App challenge · 8 min

Load scenario 2, The gauge: step the stock and time the answer. Run it to 300 s at the default seed and a speed of 10. The stock valve steps from 55 to 57 % at 120 s. Read the posted basis weight (`weight_meas_gsm`) and the sheet at the frame (`weight_true_gsm`) from the trend or the exported file.

(a) At what time does the posted basis weight first change after the step, and to what value? *Checkpoint:* At 140 s, to 80.14 g/m^2.

(b) The settled move is 4.58 g/m^2. Find the times after the step at which the sheet and the posted value first pass half of it, 82.29 g/m^2. *Checkpoint:* About 36.5 s and 60 s.

(c) What does the posting made at 160 s report, and what is the sheet at the frame at that instant? In the exported file a posting first appears in the row half a second after the pass ends. *Checkpoint:* 81.73 g/m^2 against 82.66 g/m^2.

Accept weights within 0.02 g/m^2 (0.05 g/m^2 for the sheet in (c)) and times within 1 s. Account for the gap in (b) with Equation (3.23).

3.8 App challenge · 8 min

Load scenario 4, Tuned as if the gauge were continuous, and use the default seed and a speed of 30. The moisture loop carries 44 kPa per point and 60 s, and the moisture setpoint moves from 5.5 to 5.0 % at 120 s. Read the sheet moisture (`moist_true_pct`) from the exported file.

(a) Run to 1400 s. Find the lowest and highest moisture between 700 and 1400 s, and the period of the oscillation. *Checkpoint:* 1.18 and 9.90 %, 8.72 points peak to peak, a period of about 100 s.

(b) Reload the scenario, set Scanner period to 10 s before Run, and run to 1400 s again. Find the same two values. *Checkpoint:* 4.83 and 5.16 %, 0.33 points peak to peak.

(c) Divide the period of (a) by the effective dead time of the moisture loop, and explain the result of (b) without a change of gain. *Checkpoint:* 4.5; the dead time falls from 21.9 to 11.9 s.

Accept moistures within 0.02 points and the period within 3 s.

3.9 App challenge · 8 min

Use the default seed and a speed of 30, and run each case to 900 s. The basis weight setpoint moves from 80 to 88 g/m^2 at 120 s with the moisture setpoint left at 5.5 %. Read the highest sheet moisture after the step (`moist_true_pct`) and the Off spec tile (or `metric_offspec_t`) at 900 s.

(a) Load scenario 6, The interaction, undeclared, which runs two independent loops. *Checkpoint:* 7.30 % and 2.38 t.

(b) Load scenario 8, A decoupler, which runs the full decoupler. *Checkpoint:* 5.73 % and 4.54 t.

(c) Reload scenario 8, switch to Advanced, set Steam-to-stock decoupling (D_{12}) to 0 before Run, and run again. *Checkpoint:* 5.74 % and 3.14 t.

Accept moistures within 0.02 points and tonnages within 0.02 t. Which half of the decoupler carries the benefit to the moisture, and why does the off-specification tonnage rise?

3.10 Application area · 4 min

A plugged press felt drops the press dryness by two points. With the steam valve held, it adds 2.0 MW of dryer duty while the reel moisture drifts to 8.9 %. With the reel moisture held on 5.5 %, it adds 3.1 MW. Use Equation (3.15) with $h_{fg} = 2135\,\mathrm{kJ/kg}$ and the steam price of Table 3.2.

(a) Find the extra steam in each case, in kg/min and t/h. *Checkpoint:* 56.2 kg/min (3.37 t/h) and 87.1 kg/min (5.23 t/h).

(b) Find the hourly steam cost of holding the moisture, and say why holding it costs half as much again as leaving the valve alone. *Checkpoint:* About \$115 an hour.

3.11 Application area · 4 min

A sheet break stops the gauge from posting for five minutes, and the quality controllers hold their last outputs. The moisture loop runs at $K_c = 18\,\text{kPa}$ per point and $\tau_I = 90\,\text{s}$, with the integration interval of Equation (3.32).

(a) The first reading after threading shows a moisture error of one point. Find the integral step with an unclamped interval of 300 s and with the clamp at the 20 s scan. *Checkpoint:* 60 kPa and 8 kPa.

(b) The integral time of both quality loops cannot go below 60 s. Find the largest ratio $\Delta t_k / T_t$ the clamp allows at the longest scan, 40 s, and say why it matters. *Checkpoint:* 1.33, below 2.

(c) Name the two other protections the production loop needs around a break, and what each prevents. *Checkpoint:* A parked setpoint and a reclose at 95 % of a threaded web.

3.12 Review the agent · 5 min

An AI assistant reviews scenario 14 and writes: “The MPC makes 2.68 t of off-specification paper on the grade change, against 1.51 t for the decoupled loops retuned by the same rule. Its model of the scanner and the interaction is therefore not worth having. Raise its move suppressions until it behaves like the decoupler, or replace it with the retuned loops.” Find the flaw in the reasoning and say how you would check it on the app.