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CHAPTER 6

The Drying Front Sets the Line Speed of a Battery Electrode Coater

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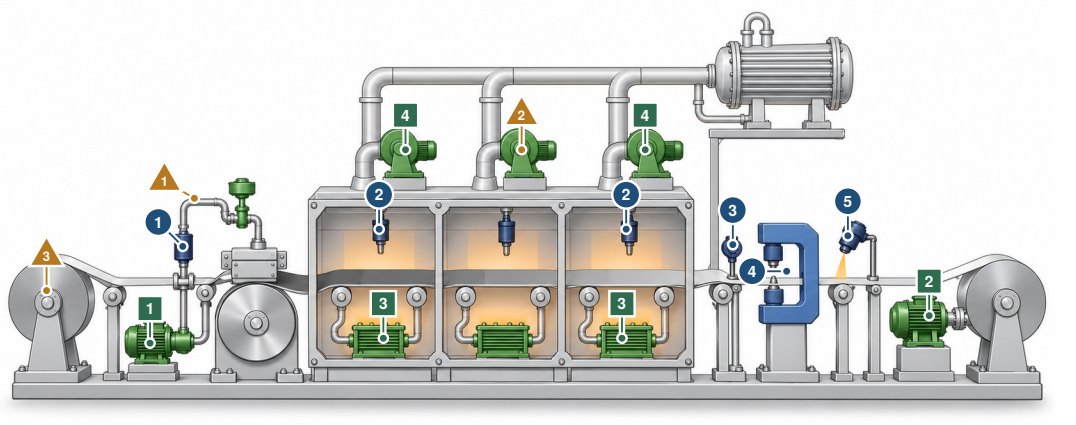
The app for this chapter
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CHAPTER 6

The Drying Front Sets the Line Speed of a Battery Electrode Coater



The controller moves 1 slurry pump 2 line drive (speed) 3 zone air heaters 4 exhaust fans and dampers

The controller reads 1 slurry density 2 solvent vapor in each zone 3 line speed 4 coating weight 5 web temperature at the exit

What disturbs it 1 a thinner slurry 2 a weakening exhaust fan 3 a splice in the foil

An electrode coater whose dryer, drawn with three of its six zones, keeps each zone's solvent vapor under a quarter of its explosive limit: notice the vapor monitor in every zone, because the zone that limits the speed moves with the drying front. Illustration, not to scale.

IN PLAIN TERMS Drying a Battery Coating Without a Fire Risk

The main idea. A coating line spreads a wet paste on thin metal foil and dries it in a long oven of six heated rooms. The paste gives off a vapor that can burn, so fresh air blown through each room keeps that vapor far below the level that could catch fire.

The challenge. A faster line raises the vapor in only one room, the one where the coating is just drying out. Drying too hard also weakens how well the coating holds the foil, and only a test an hour later finds it.

Why it matters. The vapor limit, not the coating, sets how fast the line can run.

THREE WAYS TO READ THIS CHAPTER

Explore	13 min	the first page, the two history segments (Section 6.2), the fact on the air heater (Section 6.4), the two try-it segments and the fact on the predictive controller (Section 6.7) and the key points
Study	70 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the results (Section 6.7), Technology in Practice (Section 6.8), Limitations (Section 6.9) and the open challenge

The control question The solvent vapor in a six-zone electrode dryer must stay under a quarter of its lower explosive limit, and that cap, not the coating, bounds the line speed. Which zone binds, which handle brings it back, and what do an override, a push and a better profile buy when binder damage is found only an hour later?

Learning objectives

- Compute the coat weight, the wet film and the solvent load from the die's ratio law, and the gauge's transport delay L/v.
- Explain why a faster line raises the vapor only in the zone that the drying front enters, and derive the exhaust bound on any profile.
- Choose the override's handle (exhaust, zone heat or speed) for a zone from where it sits against the drying front.
- Measure what each layer (override, push, feedforward, predictor, profile) adds to the challenge, and state what the margins cost.
- Judge a predictive controller that holds unmeasured quality predictions at their limits.

Prerequisites Sections 1.4.2 (active constraints and back-off), 1.4.3 (selectors), 1.4.4 (external reset) and 1.6.2 (velocity form). Section 1.6.3 is needed only for the predictive controller.

The app https://apmonitor.com/apps/electrode-coating/

See also Volume 5, Chapter 5 for a predictor on a moving line, Volume 5, Chapter 10 for a throughput push on inferred limits and Volume 5, Chapter 11 for parcels through a long delay. Volume 3, Chapter 6 for feedforward with a slow ratio trim and Volume 3, Chapter 4 for selectors that protect a ratio.

6.1 Introduction

A cathode coater turns a slurry into an electrode in about two minutes. In the line simulated here a pre-metered slot die lays an NMP slurry of 70 % solids on aluminum foil 1.2 m wide, a wet film 115.7 µm thick that carries 77.1 g/m^2 of solvent and dries to 180 g/m^2 of coating. At 35 m/min the six 9 m zones of the dryer must take about 0.054 kg/s of NMP out of the web, and a beta gauge 60 m from the die weighs the result 102.9 s after it was coated. Raising the speed to 40 m/min leaves the vapor in zones 2 and 3 almost where it was, near 21 % LEL, and carries zone 4 from 18.57 to 29.7 % LEL, past a cap of 25. A gentler profile, with zones 2 to 4 cooler by 10 to 25 °C, nearly triples at the same speed the strength with which the coating holds the foil, from 8.0 to 23.3 N/m, and nothing measured on the line tells the two runs apart.

Two misconceptions meet in this plant. The first is that a dryer limits a line by its heat, so that more speed loads every zone a little more. A zone that is wet from end to end evaporates at the rate its air allows whatever the speed, and a faster web only carries the wet coating into the next zone, so the safety constraint moves with the drying front and the zone that binds depends on the speed and the profile. The second is that a constraint is held by cutting the throughput. Cutting the speed lowers the vapor only in the zone the front is entering, and in a wet zone a slower web is wetter for longer, so the right handle differs from zone to zone. The quality side has the same shape. Binder carried to the surface by fast drying lowers the adhesion of the electrode [1, 2], and its cause lies in a stretch of the profile that no instrument on the line watches.

The class is wide. Any plant whose throughput is bounded by a safety or quality limit measured at many points, with the active limit moving between those points as the operating point changes, has this form, among them solvent ovens for coatings and printing, spray dryers, kilns and multi-bed reactors. The spray dryer of Volume 5, Chapter 10 pushes its throughput under overrides on margins that are inferred, much as the push of this chapter predicts limits that no instrument on the line measures. Selector logic has switched between such constraints in industry for decades with designs that rest on experience [3], a model of the constraint corrected by measured biases is the basis of constraint adaptation in real-time optimization [4], and dead-time compensators, surveyed in [5], address a measurement that arrives a transport delay after its cause.

These pieces are rarely seen together on one plant whose truth can be read beside its instruments. This chapter specifies a six-zone NMP cathode dryer, built as a browser simulator, so completely that it can be rebuilt, and reports measured runs on it. Its coat weight loop, explosive-limit override, push toward the binding constraint and offline profile search can each be enabled separately, and the runs ask where the constraint binds and what each layer buys. Ratio control, the Smith predictor, override selection, bias-corrected constraint models and direct search are established methods [3–6], and the drying and migration laws are simplified from published work [2, 7]. The optional model predictive controller of Section 6.5.6 is a standard receding-horizon design [8], and its comparison with the push is reported as measured, losses included. A focused search found no published treatment of constraint pushing against a vapor limit that moves with a drying front, or of the release logic a multi-zone override needs, so the measured findings below, including two defects of such logic found and fixed during review, are results of this model and not general claims about override design. The solvent ledgers close to within 10^{-13} of the solvent fed, the drying law is checked against an independent integration, and the equations and constants listed here are enough for a second implementation.

Section 6.2 traces the industry, its safety rule for solvent ovens and the evidence on binder migration. Section 6.3 sets out the line as modeled: the die, the web as parcels, the zones and their vapor, the migration index, the instruments and every parameter with its basis. Section 6.4 explains why the vapor cap binds at the drying front and derives an exhaust bound on any profile. Section 6.5 describes the control layers as implemented, from the zone loops through the override and the push to the optional MPC. Section 6.6 keeps code verification apart from agreement with sources. Section 6.7 measures the nine cases, the comparison of the MPC with the push and the challenge, Section 6.8 sets the devices of a real line beside the model, and Sections 6.9 and 6.10 state the limitations and the conclusions.

6.2 Electrode Lines, Solvent Ovens and Binder Migration

The inventor of the lithium-ion cell has described how it was first developed and made commercially practical, with successful safety tests as the turning point [9]. Its use has since moved from portable electronics into vehicles, and the production technologies of automotive cells, from electrode making to cell assembly, have been reviewed for their current status and challenges [10]. Within that chain the dryer and the recovery of its solvent stand out. An economic analysis of NMP-based and water-based electrode drying found that electrode manufacturing makes up about 8 to 9 % of the pack cost either way, and that water could cut the cost of drying and solvent recovery by up to a factor of two and save 3 to 6 million dollars of capital equipment for a plant making 100,000 packs of 10 kWh [11]. A continuum model of cathode drying showed that about 90 % of the solvent leaves in less than half the drying time and that splitting the oven into zones can cut the drying energy by at least half and the peak solvent flux by at least 40 % [12].

The safety rule came from older industries, the ovens that dry solvent coatings, and the history segment that follows tells its story.

> ⧖ HISTORY **Solvent Ovens and Their Margin, 1969 to 2007**
>
> Industrial ovens evaporate flammable solvents, and because the vapor can burn, the exhaust air carries it out before it builds up. Fire-protection guidelines set how much air that takes as a ventilation ratio over the solvent load [13]. United States regulation requires the air exhausted through a spray booth to dilute solvent vapor to at least 25 percent of its lower explosive limit, and it sends the drying and curing apparatus of spray finishing to the oven standard NFPA 86A-1969 [14]. A federal tip sheet of 2007 showed what continuous monitoring changes. With lower flammable limit monitors an oven may run a smaller safety ratio, and the monitor can set the ventilation through an adjustable-speed drive on the exhaust fan or through its dampers. In the tip sheet's example of a continuous strip coating process the ratio fell from 4:1 to 2:1, halving the exhaust and the energy [13].

Table 6.1 Roles of the Variables and Their Design Values in Case 3 (Standard Profile, 35 m/min)

Variable	Role	Design	Range
g	CV, beta gauge	180 g/m^2	SP 150–220
$\max_z$ %LEL$_z$	CV of the push and override	21.1	cap 25
T_z	CV, zone air (TIC 1–6)	125/105/110/125/125/125	70–170 °C
h	MV, wet-film ratio	115.7 µm	40–220
v	MV, line speed	35 m/min	10–80
$Q_{h,z}$	MV, zone heater	—	0–300 kW
F_z	MV, zone exhaust	1.53 kg/s	30–100 % of fan
x	DV, slurry solids	70 %	64–76
—	DV, pump slip, fan capacity	0, 100 %	0–8, 40–100
—	DV, events	—	drift, fan, heater, splice
s, T, M	states, per parcel (120)	—	—
$m_{v,z}$, T_z	states, per zone	—	—
v, Q, F_z	states, actuators	—	—
s_{exit}, M	outputs, residual and migration	0.068, 6.13 g/m^2	truth only

The current NFPA 86 could not be consulted for this chapter and is not quoted here. A ratio of 4:1 is the quarter of the limit used as the cap in this simulator, and the halved ratio corresponds to the half of the limit allowed with continuous monitors, a margin the simulator does not use.

Binder migration is the quality side of the same oven, and the second history segment follows the laboratory evidence on it. The tip sheet's monitor sets the exhaust, and no source found in a focused search treats the line speed as a variable pushed against the explosive-limit constraint of a multi-zone dryer.

> ⧖ HISTORY **Binder Migration and the Peel Test, 2016 to 2018**
>
> Graphite anodes dried at higher temperatures in a laboratory impingement dryer held their copper foil less strongly in a 90° peel test, which pointed to a change in the binder at the interface between the foil and the coating [1]. Film solidification and binder migration were then studied together during anode drying [15], and a three-stage profile, a mild drying stage between two fast ones, kept the adhesion while cutting the drying time by about 40 % against a reference process [16]. A mathematical model of binder transport agreed qualitatively with such experiments: low drying rates left the binder even across the film and high rates piled it near the evaporating surface. For the film it studied the rate had to stay near 1 µm/s or below, and drying fast at the start and slowly near the end gave the most even binder [2].

6.3 The Coating Line as Modeled

The line is a generic teaching design assembled from public values, as shown in Figure 6.1. Foil from an unwind passes a slot die 3 m before the dryer, six zones of 9 m each with their own air heater, nozzles on both sides of the web, an exhaust damper and a vapor monitor, then 3 m of open web to the beta gauge and the rewind, so the gauge is $L = 60$ m of web from the die. The exhaust of every zone is fresh-air dilution that leaves for a common condenser. A densitometer reads the slurry before the pump, a pyrometer reads the web at the dryer exit, and a laboratory cuts a strip at the gauge every half hour and reports its peel strength half an hour later. The variables are classified in Table 6.1.

6.3.1 The Die and the Coat Weight

The slot die is pre-metered, so everything the pump delivers lands on the foil, and the slurry density follows a volume-additive mixing rule, as shown in Equation (6.1).

$$\frac{1}{\rho} = \frac{x}{\rho_s} + \frac{1-x}{\rho_l}, \qquad h_{wet} = \frac{Q}{wv}$$
$$m_A = \frac{Q\rho x}{wv}, \qquad s_0 = m_A \frac{1-x}{x} \tag{6.1}$$

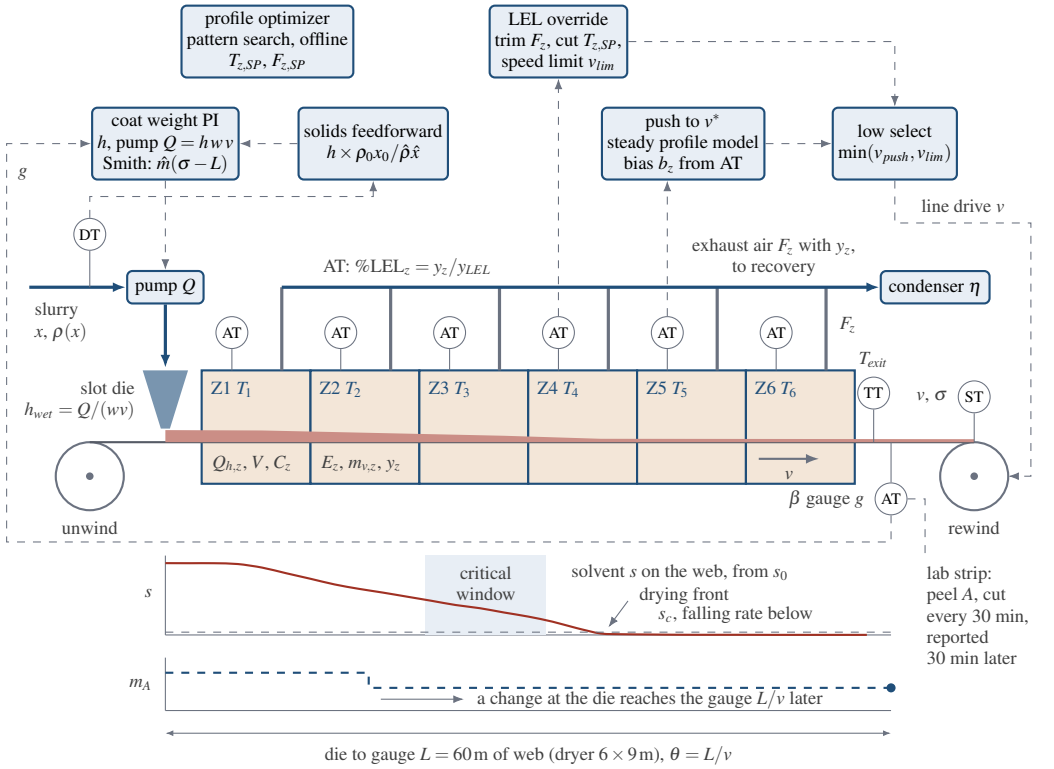


Figure 6.1 The cathode coater as modeled, mirroring the Line view of the simulator. The pump delivers Q of slurry of solids x and density $\rho(x)$, read by the densitometer DT, to the slot die, which lays a wet film h_{wet} on the foil moving at v. Each zone z holds air at T_z heated by $Q_{h,z}$, with volume V and heat capacity C_z, gathers the solvent E_z the web evaporates into its vapor $m_{v,z}$ (mole ratio y_z), and exhausts F_z to the condenser of recovery η, while its monitor AT reads $\%\text{LEL}_z$. TT reads the exit web, the beta gauge reads g and ST the speed and the web length σ, and the laboratory strip gives the peel strength A. Below, the solvent s on the web against position from case 4 (Standard profile) at 3600 s, with the critical window and the critical content s_c, and the coat weight m_A along the web, whose change at the die reaches the gauge L/v later. Above, the control layers as implemented, each fed by instruments only. Positions along the line are to scale. Process model only, not an equipment or safety drawing.

where ρ_s and ρ_l are the densities of the solids and of NMP, w the coated width and s_0 the solvent laid per unit area. At 70 % solids the slurry is 2223 kg/m^3, and the pump that lays 180 g/m^2 at 35 m/min delivers 4.86 L/min. In Auto the pump is geared to the line, $Q = hwv$ at every step with h the controller's wet-film ratio, and in Manual its flow is held at the operator's value whatever the speed. The delivered flow lags its command with $\tau_Q = 0.3$ s and loses the slip fraction set by the viscosity slider, and the line drive moves toward its command at no more than 0.5 m/min per second.

6.3.2 The Web as Parcels

The web is a Lagrangian line of parcels $\Delta\ell = 0.5$ m long, born at the die and retired at the gauge, so a parcel keeps the coat weight it was given and the gauge sees it exactly L/v later at any speed history. Each parcel carries its solvent s, its temperature T and its migration index M, and dries with the flux

of Equation (6.2).

$$\begin{aligned} \frac{\mathrm{d}s}{\mathrm{d}t} &= -\dot{m} \\ \dot{m} &= \beta\,\frac{M_w}{R\,T_f}\left[p_{sat}(T)\,f(s) - y_z P\right] \\ f(s) &= \begin{cases} 1 & s \ge s_c \\ (s/s_c)^n & s < s_c \end{cases}, \qquad \beta = \frac{h_t}{\rho_{air}\,c_p\,Le^{2/3}} \end{aligned} \tag{6.2}$$

where $T_f = (T + T_z)/2$ is the film temperature, $\rho_{air} = PM_{air}/(RT_f)$, P is atmospheric, h_t is the nozzle coefficient on the coated side and the mass coefficient β follows from it by the Chilton and Colburn analogy [7]. Above the critical content s_c the surface is wet and the rate is set by the air, the constant-rate period. Below it the solvent's activity on the web falls as $(s/s_c)^n$ with $n = 2$, so the web can only dry toward the content in equilibrium with its zone's vapor. The parcel's energy balance, Equation (6.3), carries the foil, the dry coating and the solvent left.

$$\begin{aligned} C_w(s)\,\frac{\mathrm{d}T}{\mathrm{d}t} &= (h_t + h_b)(T_z - T) - \Delta H_v\,\dot{m} \\ C_w &= c_{foil} + m_A c_s + s\,c_l \end{aligned} \tag{6.3}$$

In the constant-rate period the web sits near the temperature at which the nozzles' heat balances the evaporation, a wet-bulb temperature. Outside the dryer a parcel sees room air at 25 °C with $h = 8\,\mathrm{W/(m^2\,K)}$ and no vapor, and what it loses there is booked to the hall. The vapor pressure of NMP is a Clausius–Clapeyron line through two points of the NIST Chemistry WebBook, the normal boiling point 475.2 K and 354.7 K at 0.013 bar [17], as shown in Equation (6.4).

$$p_{sat}(T) = P_0 \exp\!\left[-B\left(\frac{1}{T} - \frac{1}{T_b}\right)\right], \qquad B = 6093\,\mathrm{K} \tag{6.4}$$

which gives 6.98 kPa at 120 °C and 14.8 kPa at 140 °C, a doubling every 17.6 K near 120 °C.

6.3.3 Zones, Vapor and the Explosive-Limit Fraction

Each zone is a well-mixed volume of air at T_z, supplied with fresh air equal to its exhaust, so its vapor and air temperature obey Equation (6.5).

$$\begin{aligned} \frac{\mathrm{d}m_{v,z}}{\mathrm{d}t} &= E_z - \frac{F_z}{m_{air,z}}\,m_{v,z} \\ y_z &= \frac{m_{v,z}/M_w}{m_{air,z}/M_{air}} \\ C_z\,\frac{\mathrm{d}T_z}{\mathrm{d}t} &= Q_{h,z} - (F_z c_p + UA)(T_z - T_{amb}) - Q_{web,z} \\ \%\mathrm{LEL}_z &= 100\,y_z/y_{LEL} \end{aligned} \tag{6.5}$$

where $m_{air,z} = PVM_{air}/(RT_z)$, $E_z = \sum w\Delta\ell(s_A - s_B)/\Delta t$ over the parcels in the zone during the step, $Q_{web,z}$ the heat they take, and $y_{LEL} = 0.013$, the lower explosive limit of NMP, 1.3 to 9.5 vol% in air on the International Chemical Safety Card [18]. In steady state the vapor is the evaporation over the exhaust, $y_z = (E_z/M_w)/(F_z/M_{air})$. The exhaust flow follows its damper command with a 5 s lag, limited by the fan's capacity F_{max} times the fan's health, and the heater delivers its command between zero and its rating, which a heater fault lowers to 40 %. Three ledgers are integrated alongside, as shown in Equation (6.6).

$$\begin{aligned} \text{fed} &= \text{evaporated} + \text{hall} + \text{past gauge} + \Delta\text{web} \\ \text{evaporated} &= \text{exhausted} + \Delta\text{vapor} \\ \text{exhausted} &= \text{recovered} + \text{emitted} \end{aligned} \tag{6.6}$$

with the condenser recovering a fixed $\eta = 0.95$ of what is exhausted.

6.3.4 The Migration Index and the Peel Test

The migration index counts how far the drying rate exceeds a safe rate while the film passes through a critical window around the end of its shrinkage, and the laboratory converts it into a peel strength, as shown in Equation (6.7).

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \left(\dot{m} - r_{safe}\right)^{+} \text{ for } 0.5 \le 1 - \frac{s}{s_0} \le 0.8$$
$$A = \frac{A_0}{1 + M/M_{max}} \tag{6.7}$$

with $r_{safe} = 1.0\,\mathrm{g/(m^2\,s)}$, $A_0 = 30\,\mathrm{N/m}$ and the threshold $M_{max} = 2\,\mathrm{g/m^2}$ where the peel strength halves. The safe rate is the source's estimate, 1 µm/s of NMP recession for a 114 µm film [2], which is 1.03 g/(m^2 s), and the window's start, about half the solvent gone, lies where that model's binder at the surface rises fastest when a high rate lasts too long. The window's end at 80 %, the critical content, the peel law and its threshold are teaching values. The index is a proxy that stands for binder carried to the surface, and it answers to where the window lands. A hotter first zone moves the window earlier, so with zones 3 and 4 held, zone 1 alone at 115 °C on the Standard profile tests worse than at 125 °C (7.2 against 8.0 N/m), while zones 3 and 4 alone at 95 and 100 °C test 28.6 N/m. The sources make a fast first stage harmless [2, 16], not helpful, so the first-zone result belongs to the proxy.

6.3.5 Instruments

The controller sees only a packet of measurements, and one of the application's tests searches its source for any truth field and fails on a match. The zone thermocouples have a 5 s lag and 0.3 K of colored noise, the vapor monitors an 8 s lag and 0.2 % LEL, the exhaust transmitters a 2 s lag and 1 %, the densitometer a 10 s lag and 1 kg/m^3, and the pyrometer a 2 s lag. The beta gauge weighs everything passing it, the dry coating, any solvent left and the second foil of a splice, as shown in Equation (6.8).

$$\tau_g \frac{\mathrm{d}g}{\mathrm{d}t} = m_A(\sigma - L) + s_{exit} + m_{spl} + \sigma_g n(t) - g \tag{6.8}$$

where $\tau_g = 2\,\mathrm{s}$, σ is the web length the encoder has counted, $\sigma_g = 0.6\,\mathrm{g/m^2}$ and n a unit colored noise with a 1 s correlation time. The laboratory is the framework's sampled analyzer (Section 1.6), which cuts a strip at the gauge every 1800 s, reports Equation (6.7) with 0.8 N/m of noise 1800 s later and holds the report until the next. The residual solvent and the migration index are truth only.

6.3.6 Parameters and Their Evidence

Table 6.2 lists every constant with its basis. None is plant data. Each is a public property, a value fitted to two public points, or a teaching value chosen to make a consistent design point, and the safety and quality limits are teaching values whose real counterparts come from the oven standard and from the electrode specification.

6.3.7 Integration, Line-Out and the Declared Stream

The application integrates with its own scheme inside the framework's engine (Section 1.6.1). In each 0.5 s step every parcel takes one fourth-order Runge–Kutta step in the zone it is in, with that zone's air and vapor frozen, and every zone is then advanced exactly over the step, because Equation (6.5) is linear in its own state once the evaporation is known. Parcels past the gauge leave and new ones are born at the die. The controller executes every 2 s and the historian logs every 2 s. A case begins in the steady state of its own settings. A steady march of one parcel through the line, with the zone vapor found by fixed-point iteration, fills the line with parcels in the state the march gives at their positions, and in Auto the pump is set so the gauge, residual included, reads the target. Over 120 s open loop from that start the zone vapor moves by at most 0.05 points of LEL and the air by 0.007 K. A steady

Table 6.2 Parameters, With Value and Basis. Source: Cited Public Value. Fitted: Through Cited Points. Teaching: Chosen. Adj.: Adjustable in the Application

Symbol	Meaning	Value	Basis
w	coated width	1.2 m	teaching
L	die to gauge (3 + 6×9 + 3)	60 m	teaching, adj. exit
$\Delta\ell$	parcel length	0.5 m	numerical
ρ_s, ρ_l	solids, NMP density	4430, 1028 kg/m^3	teaching, source
x_0	recipe solids	70 %	teaching, adj.
$m_{A,SP}$	coat weight per side	180 g/m^2	teaching, adj.
$h_t = h_b$	nozzle coefficient, each side	30 W/(m^2 K)	teaching, adj.
$Le^{2/3}$	Lewis number term	1.9	teaching
c_{foil}	15 µm aluminum	36.5 J/(m^2 K)	derived
c_s, c_l	solids, NMP heat capacity	800, 1700 J/(kg K)	teaching
T_b, B	boiling point, slope	475.2 K, 6093 K	fitted [17]
ΔH_v	heat of vaporization	500 kJ/kg	source [17]
y_{LEL}	lower explosive limit	1.3 vol%	source [18]
s_c, n	critical content, exponent	3 g/m^2, 2	teaching, adj.
r_{safe}	safe rate in the window	1.0 g/(m^2 s)	source [2], adj.
—	window, dried fraction	0.5–0.8	start source, end teaching
M_{max}, A_0	migration threshold, peel scale	2 g/m^2, 30 N/m	teaching, adj.
s_{max}	residual limit at the gauge	0.5 g/m^2	teaching, adj.
—	LEL cap	25 %	class [13, 14]
V, C_z, UA	zone air, capacity, loss	11.5 m^3, 80 kJ/K, 200 W/K	teaching
Q_{max}	heater rating per zone	300 kW	teaching, adj.
F_{max}	fan capacity per zone	1.8 kg/s	teaching, adj.
τ_F, τ_Q	exhaust, pump lags	5, 0.3 s	teaching
η	condenser recovery	0.95	teaching
T_{amb}	room	25 °C	teaching

model at the Standard profile and 35 m/min gives 18.25, 20.72, 21.09 and 18.61 % LEL in zones 1 to 4, a residual of 0.068 g/m^2 and an energy of 1.475 MJ/m^2 at the heaters.

The coater is one link of a battery line of applications, from the `lithium-refinery` and `cathode-kiln` applications to `ev-fast-charge`. The kiln of Volume 5, Chapter 11 fires the cathode material that this line coats, and it too carries its product as Lagrangian parcels through a long transport delay. The coater declares its product in a stream table, 180 g/m^2 per side with 96 % active material at 170 mAh/g, 2.938 mAh/cm^2 per side, all teaching values. The table is a declaration that a later application may copy and cite, not a coupling, and no other application reads it.

6.3.8 Assumptions

One side is coated per pass, and the second side would repeat it on a second pass that is not simulated. The die stays inside its coating window, so bead breakup, edge build-up and the cross-web profile are absent. Each zone is well mixed, and the web sees its zone's air temperature and vapor with fixed nozzle velocities. The falling rate is an activity law with no diffusion limit inside the film, so binder sorption of NMP, skin formation and cracking of thick films are not represented, and the residual is least reliable at the smallest values. The LEL is a room-temperature value, although explosive limits fall slightly in hot air, and y_z is the ratio of NMP to air, which differs from the mole fraction by 0.3 % at the cap. One fan serves the six dampers and loses capacity evenly. The migration index and the peel law are teaching proxies, and a real electrode's adhesion also depends on its binder, carbon and calendering.

6.4 Why the Drying Front Carries the Cap

6.4.1 Wet Zones Do Not Answer to Speed

A zone the wet film fills from end to end evaporates at the constant rate its air sets, $wL_z\dot{m}$, whatever the speed, so its vapor at a fixed exhaust is fixed. On the steady model of the Standard profile at 85 % exhaust, zones 2 and 3 sit at 20.4 and 21.2 % LEL at 30 m/min and at 20.9 and 20.9 % LEL at

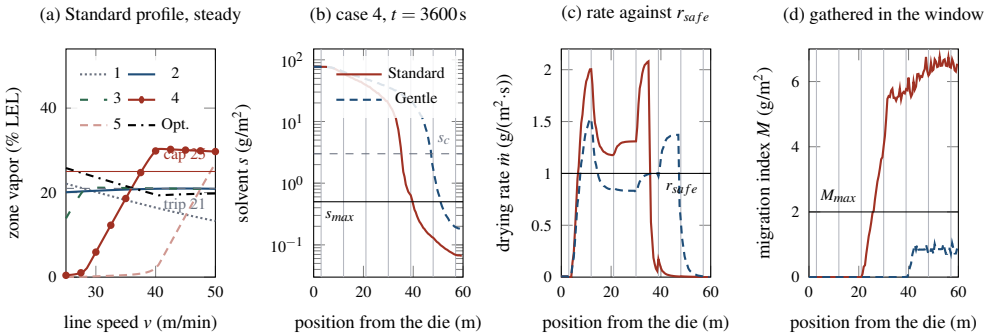


Figure 6.2 Where the vapor cap and the migration are decided, from the simulator's own functions. (a) Zone vapor against line speed on the steady model, Standard profile at 85 % exhaust, with zone 1 dotted, zone 2 solid, zone 3 loosely dashed, zone 4 solid with dots, zone 5 densely dashed and the worst zone of the Optimized profile dash-dotted. The cap is the thin solid line at 25 and the trip the thin dashed line at 21. The wet zones 2 and 3 stay near 21 % LEL while the zone the drying front enters climbs past the cap. (b to d) Case 4 at 3600 s and 35 m/min, every parcel on the line, on the Standard (solid) and Gentle (dashed) profiles: the solvent against position with the critical content and the residual limit, the drying rate against the safe rate, and the migration index against its threshold. Thin vertical lines are the zone boundaries. The Standard profile's zone 4 at 125 °C dries the window at up to 1.82 g/(m^2 s) and the web reaches the gauge with an index of 6.2 g/m^2, while the Gentle profile holds its window to 1.29 g/(m^2 s) at the peak and reaches the gauge with 0.87 g/m^2. The strips the laboratory cut at 1800 s tested 8.0 and 23.3 N/m.

50 m/min, as shown in Figure 6.2a. The zone that the drying front enters is only partly wet, and a faster web carries more wet coating into it, so its vapor climbs. Zone 4 rises from 5.9 to 29.9 % LEL between 30 and 40 m/min and first passes 25 at 38 m/min, after which it is wet throughout and levels off near 30. Zone 1 falls with speed, from 22.1 at 25 m/min to 13.3 % LEL at 50 m/min, because a faster web enters it colder and stays colder longer. Above 45 m/min the front reaches zone 5. The constraint therefore binds on whichever zone holds the front, and the profile decides which one that is. In the language of Section 1.4.2, the active constraint is a different variable at different operating points.

🕮 **Pause.** Try Exercise 6.1 before reading on.

6.4.2 An Exhaust Bound on Every Profile

All the solvent the die lays must leave through the exhaust, so the fans bound the speed of any profile, as shown in Equation (6.9).

$$w\, v\, s_0 = \sum_z E_z \le \frac{M_w}{M_{air}}\, 0.25\, y_{LEL} \sum_z F_{max,z} \qquad (6.9)$$
$$\Rightarrow\ v \le 77.86\,\mathrm{m/min}$$

Six fans of 1.8 kg/s at a quarter of the LEL carry at most 0.120 kg/s of NMP. Real profiles stay well under the bound because the first zone heats the web and the last finishes it at low rates. None of 3000 random profiles at 80 m/min, with air from 80 to 160 °C and exhaust from 50 to 100 %, kept both the cap and the residual limit. With the residual kept the lowest worst zone was 34.4 % LEL, and with every zone under the cap the lowest residual was 16.72 g/m^2. Eight pattern searches with only the cap and the residual as limits reached 70.9 m/min at best, so no profile reaches the top of the speed range, 80 m/min, and the application says so.

> **DID YOU KNOW? The Air, Not the Solvent, Takes the Heat**
>
> A process model of solvent recovery for a battery plant using 4.1 million kilograms of NMP a year put the dryer's own heat load near 130 kW and the air heater's near 3800 kW. The air heater works that hard because the dryer air must keep the vapor far below its flammability limits [11].

6.4.3 The Profile Decides the Window

The critical window is a stretch of the dried fraction, not of the line, and its position along the dryer moves with the speed and the profile. At 35 m/min on the Standard profile it lies between 21.5 and 31.5 m from the die, in zones 3 and 4, and zone 4 at 125 °C drives the rate there to 1.82 g/(m^2 s) against a safe rate of 1.0, as shown in Figure 6.2c. The Gentle profile's 95 and 100 °C in zones 3 and 4 place its window between 28.5 and 41.5 m and hold the rate there to 1.29 g/(m^2 s). The residual answers to the last zone in the same way. Below s_c the rate is the web's vapor pressure times its activity, so on the Optimized profile at 50 m/min the residual is 1.377, 0.615, 0.324 and 0.244 g/m^2 with zone 6 at 105, 125, 147.5 and 160 °C, while zone 6's vapor moves only from 13.7 to 15.7 % LEL. Three objectives thus live in three places along the line, the cap at the front, the migration in the window and the residual at the exit.

6.5 The Control Layers as Implemented

All loops execute every 2 s on the instrument packet, in the order zone air, exhaust, override, push and coat weight, and the plant receives the commands at the next physics step.

6.5.1 Zone Air and Exhaust

Each zone's air is held by the framework's velocity-form PID of Section 1.6.2, Equations (1.13) to (1.15), with a control period $\Delta t_c = 2\,\mathrm{s}$. Its derivative term is off in every loop of this application, which leaves a PI law whose running sum is never clamped and whose integral alone carries back-calculation, with a tracking time equal to τ_I. The zone loops output the heater's share of its rating, 0 to 1, with $K_c = 2\,\%$ per kelvin and $\tau_I = 45\,\mathrm{s}$, and their setpoint is the profile's less any heat cut the override has made. Each exhaust damper takes its setpoint as a fraction of the fan's nameplate. With the override on, an integral trim $\delta_z \leftarrow \delta_z + 0.5\,(\%\mathrm{LEL}_z/100 - 0.20)\Delta t_c$, clipped between zero and the damper's room to full flow, adds exhaust while a zone's monitor reads over the push target of 20 % LEL and gives it back below.

6.5.2 Coat Weight: Ratio, Predictor and Feedforward

The coat-weight loop is the same PI on the gauge, so a light gauge raises the wet-film ratio, with $K_c = 0.3\,\mu\mathrm{m}$ per g/m^2, $\tau_I = 90\,\mathrm{s}$ and the ratio limited to 40 to 220 µm. Its output is the ratio h, and the pump flow is hwv, so a speed change carries the pump with it. With the predictor on, the loop's measurement is the model coat weight now, corrected by the gauge against what the model laid down for the web under the gauge, as shown in Equation (6.10).

$$\mathrm{PV} = \hat{m}(t) + g(t) - \hat{m}(\sigma - L), \qquad \tau_m \frac{\mathrm{d}\hat{m}}{\mathrm{d}t} = h\hat{\rho}\hat{x} - \hat{m} \tag{6.10}$$

The model's lag is $\tau_m = 2.3\,\mathrm{s}$, and its value is stored against the encoder's web length every 0.25 m and read back exactly 60 m later, so the predictor's delay is L/v at every speed, which a predictor keyed to a fixed time would not be. The float glass line of Volume 5, Chapter 5 runs a predictor of the same family on a ribbon whose thickness is measured downstream of where it is formed. The lag stands for the pump and the gauge's average. Without it a gain above 0.64 µm per g/m^2 made the sampled loop through the algebraic model term unstable. With the solids feedforward on, $\hat{\rho}\hat{x}$ comes from the densitometer through the inverse of Equation (6.1), and the ratio is scaled by $\rho_0 x_0/\hat{\rho}\hat{x}$, the recipe's solids load over the estimate's. The feedforward acts on a measured disturbance at the input, and the gauge loop remains as a slow trim, the arrangement that the water plant of Volume 3,

Chapter 6 uses for its coagulant dose. A change of either option, and Manual to Auto, re-bases the integral on the output the loop has (Section 1.6.2), and the measured jump in the next period is 0.000 µm. The gauge reading is held while a splice that the encoder tracked passes it.

6.5.3 The Explosive-Limit Override

The override uses three handles in order. The exhaust trim is the first. A zone whose monitor reads at or over the trip, 21 % LEL, while its exhaust is already at capacity gets a second handle chosen by the push's profile model on measured inputs. If a line 2 m/min slower lowers that zone's predicted vapor by more than 0.3 points, which is the case for a zone the front is entering, the zone joins the speed-limited set. Otherwise, as for a wet zone or the first zone, its own air setpoint is cut at 8 °C/min, up to 40 K, and the heat returns at 1 °C/min once the zone reads 1.5 points under the trip. The speed limit starts at the requested speed when the set first fills, falls at up to 15 m/min per minute (from 40 % of that rate at the trip to all of it 1.5 points over) while any zone of the set reads at or over the trip, holds within 2 points under it, and rises at the push rate, 2 m/min per minute, below that, until the request falls under the limit and the override lets go. A low selector applies $\min(v_{push}, v_{lim})$, and the push's own speed tracks the applied one while the limit acts, which is the external reset of Section 1.4.4, so the hand-back is bumpless. The selector itself is the cap of Section 1.4.3, with the twist that the protected variable is whichever zone holds the front. Over 25 releases in case 8 the largest step in the speed request was 0.000 m/min.

Two release rules were added during the review of the application, each after a measured defect, and both are part of the controller of this chapter. In the first, the exhaust trim held a speed-limited zone at its 20 % LEL target, inside the hold band from 19 to 21, so a zone that had joined the set at a low speed kept the limit down for good. Case 3 with the setpoint raised at 50 s rested at 28.1 m/min, and in sweeps of the moment of the change, 10 of 81 runs and 22 of 82 runs rested under 31 m/min. A zone now leaves the set after 60 s under the trip with 3 % of room in its exhaust, after which its trim holds it, and the same sweeps rest under 31 m/min in 0 of 81 and 0 of 82 runs, with the case 3 run at 35.5 m/min. In the second, after a deep cut in case 7 the zone upstream of the front took the speed handle as well and the line settled near 21.5 m/min instead of 27.6, in 3 of 8 seeds at the shipped step and 6 of 8 at half of it, so halving the step changed the lesson. A zone upstream of one already speed-limited now takes the heat handle, and all 16 runs average 27.2 to 27.9 m/min. An alternative rule that chose the handle at the requested speed was tried and dropped because it let the line run at 44.7 m/min on cut heat at a setpoint of 45 m/min. The challenge's runs were unchanged by both rules, while the predictor-off run of case 2 moved from a gauge range of 119.9 to 276.8 to one of 122.5 to 271.0 g/m^2.

6.5.4 The Push

Every 10 s the push runs the plant's own steady model with the declared parameters of Table 6.2, Equations (6.1) to (6.7) in steady state, on the measured zone air, the exhaust each zone can get, the gauge and the solids estimate, and finds the fastest speed that meets every limit, as shown in Equation (6.11).

$$v^{*} = \max\{v : b_z\,\%\mathrm{LEL}_z(v) \le 20,\; s_{exit}(v) \le 0.8\,s_{max},\; M(v) \le 0.9\,M_{max}\} \tag{6.11}$$

The bias b_z is each monitor's reading over the model's prediction at the present speed, filtered with a 120 s time constant and clipped between 0.5 and 2, the constraint-adaptation idea of real-time optimization [4]. The search scans down from 80 m/min in steps of 2 and bisects to 0.1 m/min. A limit broken at every speed, a zone whose vapor the speed moves by less than 1.5 points over the range, and a zone the override holds by its heat are reported and left out, because no speed can meet them. The push's speed moves toward v^{*} at 2 m/min per minute in either direction. The push's model has the declared parameters and not the run's, so a learner's edit of the plant is model error that only the bias corrects, and only for the vapor. The margins of Equation (6.11), a target of 20 under a trip

of 21 and a cap of 25, and 80 % and 90 % of the quality limits, are the back-off of Section 1.4.2, paid for in line speed. The extruder of Chapter 5 runs a throughput supervisor of the same kind against its torque, pressure and dryer limits.

6.5.5 The Profile Optimizer

The Optimized profile is the result of a coordinate pattern search in the manner of direct search [6] on the same steady model, over six zone temperatures from 80 to 160 °C and six exhaust fractions from 0.5 to 1, with steps from 10 down to 2.5 °C and 0.1 down to 0.05, as shown in Equation (6.12).

$$\max_{T_{1..6},F_{1..6}} J = v_{max}(T,F) - w_E\,E(T,F,v_{max}) \tag{6.12}$$

where v_{max} is the fastest speed with every zone at 20 % LEL, the residual at 0.40 g/m^2 and the migration at 1.8 g/m^2, found by a scan and a bisection, and E the heater energy per square meter. From the Standard profile with $w_E = 0$ it ran 4516 model evaluations and found 137.5, 105, 102.5, 100, 105 and 147.5 °C with exhausts of 100, 100, 95, 85, 95 and 100 %, which allows 51.88 m/min at 1.10 MJ/m^2, a hot first zone, a mild window and a hot last zone. The search is local and runs offline, and the learner applies its result as a profile. The tests run it again and require the same answer. In the infeasibility sweep one of eight starts stopped at 34.3 m/min.

6.5.6 Model Predictive Control

A model predictive controller (MPC) is offered as an option for the speed and the zones. The push, with the zones on their profile, is what the application loads and what every case except case 9 uses, and case 9 pins the MPC. Every $T_s = 10$ s, or every fifth control period, one quadratic program sets the line speed request and the six zone air setpoints together over $N = 60$ steps, or 10 min. The horizon is cut into seven move blocks whose lengths are 1, 1, 2, 2, 4, 6 and 44 steps. The plan is applied in receding horizon as Section 1.6.3 describes [8, 19], and the first plan is made at $t = 0$, so the historian records the MPC acting from the first row. Everything below the plan runs as shipped. The zone loops receive $T_{p,z} + \delta_{T,z} - c_z$, the profile's air plus the plan's trim less any heat cut c_z the override has made, the exhaust dampers keep their trim and the coat-weight loop stays geared to the speed. The plan's speed takes the push's place in the override's low selector, $\min(v_{mpc}, v_{lim})$, before the clamp of 10 to 80 m/min, so the override, its heat cut, the exhaust trim and the clamp act above the plan exactly as they act above the push.

The controller moves speed v and six zone requests $T_{SP,z}$, with eight outputs: the residual s_{exit} and the migration index M at the gauge and the six monitors' $\%\mathrm{LEL}_z$. Its gains are the push's steady model, Equations (6.1) to (6.7) in steady state, computed from the declared values listed in Table 6.2 and not from the run's, so that a learner's edit of the plant is model mismatch for the MPC as it is for the push. At each decision the model is relinearized at the operating point the controller reads, the applied speed and setpoints, the exhaust each zone can get as the push reckons it, the gauge's coat weight and the recipe's solids, or the densitometer's with the feedforward on, by forward differences of 0.5 m/min and 1 K, eight steady marches in all. A zone whose heater is at its rating is linearized at its thermocouple when that reads under the setpoint, and the plan may not raise that zone's setpoint. The dynamics of each pair are a first-order lag with a dead time, Equation (6.13), in which x_z is the distance from the die to the middle of zone z, the speed v is in m/s and the transport parts scale with it.

$$\begin{aligned}
v \to s_{exit}, M:&\ \theta = 0.185\,L/v, \quad \tau = 0.4\,L/v \\
v \to \%\mathrm{LEL}_z:&\ \theta = \max(8,\, 0.38\,x_z/v) \\
&\ \tau = \max(10,\, 0.45\,x_z/v) \\
T_{SP,z} \to \%\mathrm{LEL}_z:&\ \theta = 10, \quad \tau = 16 \\
T_{SP,j} \to \%\mathrm{LEL}_{z>j}:&\ \theta = 8 + (z-j)L_z/v, \quad \tau = 15 \\
T_{SP,j} \to s_{exit}, M:&\ \theta = (L - x_j)/v - 4, \quad \tau = 9
\end{aligned} \tag{6.13}$$

Times are in seconds and $L_z = 9\,\text{m}$. The shapes come from steps of 1 m/min and 2 K, both ways, on the application in Auto at 50 m/min on the Optimized profile, override off and gauge noise zero, against an unstepped twin on the same seed. An independent refit of the same kind returns 10 s and 16 s for zone 3 on its own vapor and 62 and 14.5 s for zone 1 on zone 6, with residuals of 1.6 to 1.7 % of the change, and 42 and 9.5 s for zone 3 on the residual against the shape's 37.4 and 9 s. Its gains agree with the linearization within 2 % for every vapor pair and every zone's effect on the residual, 2.21 against 2.17 points of LEL per m/min from the speed to zone 6, and within 6 % for the speed's effect on the residual. The speed's effect on the residual, a ramp over the web's transit, fits with 30 % RMS error and the migration index with 25 to 72 %, so the index borrows the residual's shapes. Each pair's step response, sampled at T_s, becomes impulse weights on a delay line of the inputs applied in each period, at most 12 periods long, which gives up to 77 states. At steady state the model equals the linearization.

The decisions are the moves of the seven handles from the inputs applied now, constant within each block. Each plan minimizes Equation (6.14), in which $\hat{y}_{i,k}$ is a predicted output, j counts the blocks, $T_{p,z}$ is the learner's profile and Δu_0 is measured from the input applied now.

$$
\begin{aligned}
\mathscr{J} = &- \sum_{k=1}^{N} \frac{v_k}{\text{m/min}} + \rho_T \sum_{k=1}^{N} \sum_{z=1}^{6} \left(T_{SP,z,k} - T_{p,z}\right)^2 \\
&+ \lambda \sum_{j=0}^{6} \left[\left(\frac{\Delta v_j}{0.5\,\text{m/min}} \right)^2 + \sum_{z=1}^{6} \left(\frac{\Delta T_{SP,z,j}}{1\,\text{K}} \right)^2 \right] \\
&+ \sum_{i=1}^{8} \left(\nu_i \varepsilon_i + \kappa_i \varepsilon_i^2 \right) \\
\text{s.t. } & \hat{y}_{i,k} \le \bar{y}_{i,k} + \varepsilon_i, \quad \varepsilon_i \ge 0 \\
& 20\,\text{m/min} \le v_j \le 80\,\text{m/min}, \quad |\Delta v_j| \le r_{push} T_s \\
& |T_{SP,z,j} - T_{p,z}| \le \Delta T_{max}, \quad |\Delta T_{SP,z,j}| \le 2.5\,\text{K}
\end{aligned}
\tag{6.14}
$$

Speed earns one unit per m/min per step, and $\lambda = 10$ prices moves. The pull $\rho_T = 0.002$ per K^2 per step keeps a zone near its profile when nothing else decides it. The limits $\bar{y}_{i,k}$ are soft and judged on every second step, with one slack per output, eight in all. They are the push's own target for each zone's vapor, 20 % LEL, the residual limit $s_{max} = 0.5\,\text{g/m}^2$ and the migration threshold $M_{max} = 2\,\text{g/m}^2$ in the default setting, At the limits. The alternative setting, Push margins, moves the last two to the push's $0.8\,s_{max}$ and $0.9\,M_{max}$ of Equation (6.11). The slack prices are $\nu = 2 \times 10^3$ and $\kappa = 2 \times 10^4$ per point of LEL, 2×10^5 and 2×10^6 per g/m^2 of residual and 2×10^4 and 2×10^5 per g/m^2 of migration, each far above what a m/min earns over the horizon. A limit that the free response already crosses is re-entered along a straight line over 60 s. The handle limits are hard. The speed stays in the push's range and moves no faster than the push rate, at most $r_{push} T_s = 0.33\,\text{m/min}$ from one block to the next, with r_{push} read as the push reads it, so neither structure can change the speed faster than the other. Each zone may move $\Delta T_{max} = 10\,\text{K}$ from the profile, and at most 2.5 K from one block to the next, within the setpoint range of 70 to 170 °C. Heater energy is not priced. The move price was chosen once, before any comparison, on case 9 with seeds 1 to 3 over 60 min. Of λ from 0.1 to 30, all six values moved the speed request no more than the push did (98.5 m/min), and the rule, the largest λ within 1 % of the best throughput of 3693 m^2/h, chose $\lambda = 10$ at 3688 m^2/h. Nothing was retuned afterwards for any case.

Each zone's vapor carries the push's bias b_z of Equation (6.11), the monitor's reading over the declared model's value at the measured speed, air and flows, filtered over 120 s and clipped between 0.5 and 2. This output-disturbance estimate makes the vapor limits offset-free on what the monitors read [20]. The residual and the migration index have no on-line measurement, so the plan predicts them from the declared model and holds the prediction at its limit, as the push holds its own prediction under a margin. No preview of the solids drift, the fan loss or any other event reaches either structure.

The program has 57 variables (49 input values and 8 slacks) and 444 rows, past the 30 states and 6 inputs for which the shared solver class is documented, and a dual active-set solver [21] handles it. A plan is discarded if the solver returns it as anything but optimal, if a value in it is infinite or undefined, or if it breaks a bound. The push, or the setpoint ramp when the push is off, then takes the line from the applied speed, which it has tracked as external reset, while each zone’s trim returns to the profile at the override’s heat-back rate, 1 °C/min. A switch from the MPC to the push leaves the first period unmoved and then moves the speed request 0.017 m/min and the setpoints 0.033 K per period. Over 8786 plans, on every case as loaded, on four more seeds of case 9, on the challenge with its suggested settings and at one extreme setting, none was rejected. At the shipped settings the Hessian’s condition number was 4.28×10^{6}, a plan took at most 124 iterations and the stationarity residual of the optimality conditions was at most 3×10^{-7} of the largest linear term. The MPC reads what the push reads, the instruments, the applied inputs, the limits and the declared values. Replay tests in which two plants differ in their nozzle coefficient, heater rating, critical content, safe rate, gauge distance, solids and pump slip, with the instruments of the first copied into the second, find identical plans, and eight mutated copies of the controller that each read one truth field or run parameter all fail the application’s tests. Over the 540 plans of case 9 in Chrome a plan takes 11.9 ms on average and 16.5 ms at the most, 0.12 % of one core at real time and 36 % at the top speed of 300 times real time, where the page draws 59.6 frames per second against the push’s 59.9.

6.5.7 Three Models

Section 6.3 is the simulation model. The application identifies no control model except the delay-line shapes of the MPC, and the coat-weight tuning ships with the cases. The controller’s internal models are the predictor’s coat weight, $h\hat{\rho}\hat{x}$ through a lag, and the steady profile model of the push, the override’s handle choice and the optimizer, which shares the plant’s equations. The push and the override’s handle choice evaluate it with the declared parameters and meet model error only through the monitors’ bias. The MPC’s internal model is the same steady model evaluated with the declared parameters and joined to the identified shapes, so a learner’s edit of a parameter reaches neither the push nor the MPC.

6.6 Code Verification and Agreement With Sources

Code verification asks whether the program solves the equations above. The three ledgers of Equation (6.6) close over a disturbed run with speed steps, the solids drift, the fan loss and a heater fault, to residuals of 5.3×10^{-12}, 3.1×10^{-13} and 5.6×10^{-14} kg against 115.432 kg of solvent fed. Independent quadratures over the challenge’s suggested run of 5000 m give 495.387 kg pumped against the ledger’s 495.358 and 491.497 kg exhausted against 491.488. A separate explicit integration of the steady march with 2 mm steps, written without the application’s code, gives 18.24, 20.73, 21.09 and 18.61 % LEL in zones 1 to 4 of the Standard profile at 35 m/min against the application’s 18.27, 20.71, 21.09 and 18.64, and at 40 m/min the two agree to 0.05 points. Equation (6.1) holds exactly for the coating laid at the die and for the coating weighed at the gauge, and the gauge’s delay equals L/v within one logged row (104.0 against 102.9 s at 35 m/min). Halving the step to 0.25 s keeps every challenge verdict and moves the suggested throughput from 3076 to 3073 m²/h and the mean residual by 0.75 %, and halving the parcel to 0.25 m leaves the zone vapor unchanged to 0.01 points and moves the Standard profile’s migration index from 6.13 to 6.23 g/m². Loaded fresh, reached through the case menu from a different case, or restarted with Reset, each case logs the same run bit for bit.

Agreement with sources is a separate and weaker claim. The model’s constant drying rates, 1.17 and 1.36 g/(m² s) in the wet zones at 105 and 110 °C, lie near the 1.19 g/(m² s) of the experiments the binder model reproduces, and the 115.7 µm wet film is close to its 114 µm [2]. The vapor pressure’s slope, 50.7 kJ/mol, lies among the WebBook’s enthalpies of vaporization of 47.7 to 53.4 kJ/mol between 345 and 425 K, and at 25 °C, outside the two fitted points, the line gives 50 Pa against the safety card’s 39 Pa [17, 18]. No readable source gives a critical content or a falling-rate law for an

Table 6.3 The Nine Cases and the Challenge

#	Settings and events	Teaching point
1	Manual pump and speed, 35 m/min	coat weight is a ratio
2	Auto, $K_c = 0.6$, target 180 to 185 g/m^2 at 60 s, override on	delay limits gain, the predictor
3	Auto at 35 m/min, override off, raise to 40	the front's zone binds
4	Standard against Gentle, pause at 60 min	migration, found late
5	Optimized at 50 m/min, zone 6 cooled	residual at the exit
6	Solids drift of 2 points from 2 min	feedforward from density
7	Fan to 70 % from 5 min, override off	choosing the handle
8	Push and override on, Standard profile	constraint pushing
9	Optimized at 50 m/min, push and override on, MPC on speed and zones, drift at 10 min	speed and zones in one plan
Ch.	Challenge, 5000 m: drift at 20, fan at 40, splice at 60 min	the whole problem

Table 6.4 Measured Results of the Cases

#	Run	Result
1	30 m/min, pump held	gauge 209.7 g/m^2, first moves 122.5 s after
2	predictor off	gauge 122.5–271.0 g/m^2, swings 30 min
	predictor on	within 1.5 % from 3.0 min
	off, K_c = 0.5 / 0.4 / 0.3	settles at 26.7 / 6.0 / 3.0 min
3	override off, 40 m/min	zone 4 30.3 % LEL, over 25 at 93 s
	override on	peak 22.9 % LEL, mean 35.6 m/min
4	Standard / Gentle	first peel 8.0 / 23.3 N/m
	Optimized at 35 m/min	13.7 N/m
5	zone 6 147.5 to 125 °C	residual 0.327 to 0.630 g/m^2
6	feedforward off / on	worst weight 1.59 / 0.49 %
7	override off	zone 3 25.8 % LEL, 1491 s over
	override on	worst 24.8 % LEL, mean 27.6 m/min
8	Standard / Gentle / Optimized	36.4 / 37.2 / 51.2 m/min
	Push against MPC, means of five seeds over 90 min	
5	push on, zone 6 to 125 °C at 10 min	3419 / 3815 m^2/h, residual over 103 / 1271 s
6	push on	2405 / 2308 m^2/h, strips over 15 / 13 of 15
8	as loaded	2603 / 2484 m^2/h, strips over 15 / 7 of 15
9	MPC at the limits	3364 / 3658 m^2/h, strips over 0 / 8 of 15
	MPC, push margins	3364 / 3639 m^2/h, strips over 0 / 0 of 15

NMP cathode, so s_c and n remain teaching values, and no peel strength in this chapter is a prediction for a real electrode.

6.7 Nine Cases and a Challenge, Measured

The cases are listed in Table 6.3. All values in this section were taken without a browser, stepping the engine through the same calls the page makes (Section 1.6.1), on the case's default seed unless five seeds are named, with only the change a sentence names, and the scripts that produce them are kept with the application's records. The headline results are gathered in Table 6.4. Each case has a completion rule of the kind Section 1.6.4 describes, and the exported file places each instrument's column beside a prefixed column that holds the true value.

6.7.1 A Ratio and a Late Gauge

Case 1 runs the pump and the speed by hand. Slowing the line from 35 to 30 m/min with the pump held makes the die lay more than 185 g/m^2 within 2.0 s, but the gauge rises 2 % only 122.5 s later, because the web needs 120 s to carry it 60 m. It settles at 209.7 g/m^2, the 180 times 35/30 of the ratio with the residual added. Matching the pump from 4.86 to 4.16 L/min brings the gauge back within 1.5 % 126.0 s later. The worst zone stays near 21 % LEL throughout.

Case 2 gives the loop twice the shipped gain, $K_c = 0.6$, and steps the target to 185 g/m^2 at 60 s. With the predictor off the loop makes about 50 corrections before the gauge sees the first, and the

gauge swings between 122.5 and 271.0 g/m^2 for the whole half hour. Its heavy half-swings load the dryer, the override slows the line to 20 m/min in 73 % of the steps, the delay stretches from 103 to 180 s, and zone 4 spends 46 s over the cap. With the predictor on, the same gain holds the gauge between 179.0 and 186.2 g/m^2 and within 1.5 % of the target from 3.0 min, while the override takes the line no lower than 32.8 m/min. Without the predictor the gain must come down. At 0.5 the loop swings for 26.7 min, and with the shipped integral time of 90 s a gain of 0.4 settles at 6.0 min and the shipped 0.3 at 3.0 min, as fast as the predictor, because the transit time is the floor for both. The predictor buys gain, not time.

Pause. Try Exercise 6.3 before reading on.

6.7.2 The Constraint at the Front

Case 3 raises the setpoint from 35 to 40 m/min at 30 s with the override off. Zone 1 falls from 18.25 to 16.5 % LEL, zones 2 and 3 stay near 21, and zone 4 climbs from 18.57 to 29.7 % LEL, crossing 25 at 93 s and peaking at 30.3 % LEL. With the override on from the start, the exhaust trim opens first, and when zone 4 reaches the trip with its exhaust at capacity, at 77 s, the speed limit takes over. Zone 4 peaks at 22.9 % LEL and never reaches the cap, and the line hunts between 33.6 and 37.6 m/min from 10 to 30 min, a mean of 35.6. The hunt has a cause. Zone 4 gains about 2 points of LEL per m/min with the front in it, and a speed change reaches it only as the web carries it there, about a minute later. Over 81 moments of the change from 20 to 100 s the mean speed was 35.4 to 35.9 m/min and no zone crossed the cap.

> **TRY IT IN THE APP 3 · Raise the Speed: A Zone Crosses Its Cap**
>
> Load the scenario and press Run on the Zones view with the LEL override Off. At 30 s set Line speed setpoint to 40 m/min and watch the zone bars against the 25 % LEL line. Zones 2 and 3 stay near 21 while zone 4, which the drying front enters, climbs from 18.57 to 29.7 % LEL and crosses the cap at 93 s.

Case 7 weakens the fan to 70 % over ten minutes at the same speed. With the override off, zones 2 and 3, wet from end to end, rise with the falling exhaust, from 1.53 to 1.26 kg/s, and zone 3 crosses the cap at 14.4 min and stays over for 1491 s. A slower line would not help these zones. With the override on, no zone crosses the cap (worst 24.8 % LEL, zone 4), the dampers being wide open already, so the override cuts the air of zones 1 to 3 by 9.4, 5.5 and 7.5 K on average between 20 and 40 min and limits the speed for zone 4, which cycles eight times between 24.0 and 30.6 m/min, a mean of 27.6, about a fifth less output. A gentler cut of 10 m/min per minute lets zone 4 reach 25.5 % LEL for 17 s, and one of eight seeds sees 25.3 % LEL for 11 s even at the shipped rate, during the first cut while the fan is still weakening.

> **TRY IT IN THE APP 7 · Fan Degradation: The Caps Creep Up**
>
> Run the scenario with the LEL override Off: at the same 35 m/min zone 3 crosses the cap at 14.4 min and stays over for 1491 s. Set LEL override to On, press Reset and run again. No zone crosses the cap: the override cuts the air of zones 1 to 3 and limits the speed for zone 4, and the line averages 27.6 m/min.

Pause. Try Exercise 6.2 before reading on.

6.7.3 Migration, Residual and Solids

Case 4 runs the Standard and Gentle profiles at 35 m/min to the first peel test at 60 min. The strip cut at 30 min holds 8.0 N/m on the Standard profile, a migration index of 6.20 g/m^2, and 23.3 N/m on the Gentle one, an index of 0.66 g/m^2, against a pass at 15 N/m. The gauge reads 179.3 g/m^2 on both, the residual is 0.067 and 0.180 g/m^2, and the worst zone over the hour is 21.5 and 20.2 % LEL, so nothing on the line tells them apart, as shown in Figure 6.2. The Optimized profile tests 13.7 N/m at this speed, because it was found for 52 m/min, where its window falls in its mild zones.

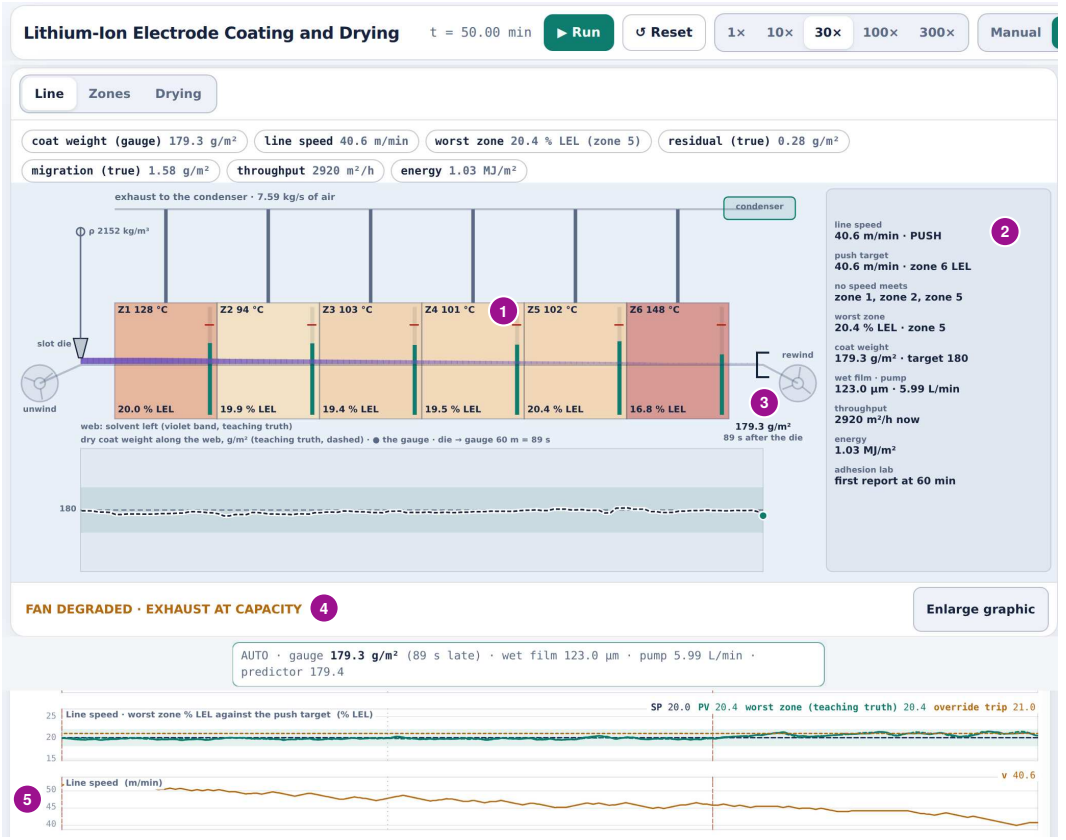


Figure 6.3 Line view of the suggested challenge run at $t = 50$ min, a composite of the application's window: the header, the Line view, the status line of the coat-weight card and, below, the trend strips of the worst zone and the line speed. The drift has thinned the slurry to 68 % solids, which the densitometer reads as 68.02 (a value this view does not print), and the fan has just reached 70 % of its nameplate, so every damper is at capacity and the status strip (4) reads FAN DEGRADED. The override has cut the air of zones 1, 2 and 5 by 10.4, 11.5 and 3.5 K, which the zone labels show only as air temperatures, and the push, leaving those zones out, holds 40.6 m/min against zone 6 (2), with the monitors (1) reading 20.0, 19.9, 19.4, 19.5, 20.4 and 16.8 % LEL under the 25 % LEL cap. The gauge (3) reads 179.3 g/m^2, 89 s after the die, with a wet film of 123.0 µm and the predictor's measurement at 179.4 on the card's status line, and the dashed coat weight along the web stays on its 1.5 % band. Over the 30-minute window of the trends (5) the line speed falls from 51.4 m/min at 20 min to 40.6, touching 39.8 (values from the run's log, of which the trend prints only the last), as the fan weakens, and the worst zone stays at the push's 20 % LEL target under the override's 21. The first laboratory report is due at 60 min.

Case 5 runs the Optimized profile at 50 m/min and cools zone 6. At 147.5 °C the web leaves with 0.327 g/m^2 at 142.5 °C. With zone 6 at 125 °C from 600 s, the residual passes its 0.5 g/m^2 limit 21 s later and reaches 0.630 g/m^2, and the exit web reads 119.6 °C, the one instrument that moves with the residual.

Case 6 thins the slurry from 70 to 68 % solids over 15 min. The die meters volume, so the wet film stays at 115.6 µm while the dry weight falls. With the feedforward off the worst error is 1.59 % at 16.9 min, and the loop then raises the film to 122.9 µm. With the densitometer's estimate (68.03 against 68.0 %) scaling the ratio, the worst error is 0.49 %. The thinner slurry carries 9.8 % more

Table 6.5 Case 9 Over 90 min, Means of Five Seeds. Strips Over: Laboratory Strips Whose True Index Exceeds M_{max}, of 15. Trip: Seconds With a Zone Over 21 % LEL. Ovr.: Override Engagements. Travel: Speed Request Travel

Structure	m²/h	Strips over	s_{exit} worst	Trip (s)	Ovr.	MJ/m²	Travel (m/min)
Push (shipped default)	3364	0	0.387	0	0.0	1.218	150
MPC, push margins	3639	0	0.436	54	3.6	1.145	58
MPC, at the limits (default)	3658	8	0.497	52	3.8	1.139	57
MPC, zones held, push margins	3363	0	0.409	0	0.0	1.219	49
Push at the limits (not shipped)	3465	1	0.423	14	1.0	1.185	131
MPC, delay left out	3660	6	0.469	213	13.4	1.141	54
Fixed 48 m/min, best in hindsight	3430	4	0.392	133	7.2	1.196	26

solvent per square meter, so the override slows the line to 30.8 m/min without the feedforward and 30.3 m/min with it.

6.7.4 The Push

Case 8 turns on the push with the Standard profile. Between 30 and 60 min it holds a mean of 36.4 m/min, between 33.4 and 37.7, bound by zone 4, and it reports that no speed meets the migration limit on this profile (an index of 7.05 g/m²). The wander is the push's 20 % LEL target and the override's 21 % LEL trip handing the speed back and forth, because at a gain of about 2 points per m/min the two are only half a meter per minute apart, and the override engages ten times in the half hour. A push target of 19 % LEL narrows the wander to 35.2 to 37.1 m/min at a mean of 36.3 with four engagements, and 18 costs six meters per minute (a mean of 30.0 m/min). The Gentle profile allows 37.2 m/min, bound by the migration index, and the Optimized profile 51.2 m/min, between 49.6 and 52.1, bound by the migration index at 90 % of its threshold with a residual of 0.363 g/m².

6.7.5 One Plan for the Speed and the Zones

Case 9, named Speed and zones in one plan, starts at 50 m/min on the Optimized profile with the push, the override, the predictor and the solids feedforward on, and with the MPC of Section 6.5.6 setting the speed and the zones. At 10 min the slurry's solids begin to fall by 2 points over 15 min. Each row of Table 6.5 changes only the structure or one of its settings, over 90 min on the case's own seed and seeds 1 to 4, with the same instruments, noise and events and no preview, and is scored on the engine's truth.

Like for like, with the push's own margins of $0.8\,s_{max}$ and $0.9\,M_{max}$, the MPC coats 3639 m²/h (3633 to 3643 over the seeds) against the push's 3364 m²/h (3362 to 3367), 8.2 % more at every seed, with none of 15 strips over the threshold, 6 % less heater energy per square meter (1.145 against 1.218 MJ/m²) and 61 % less travel of the speed request (58 against 150 m/min). The whole gain is the zones. Held on their profile at the same margins, the plan makes 3363 m²/h, the push's throughput, so the dynamic model and the delay lines add nothing to the area. What the plan does with the zones is visible in its mean trims after 30 min on the case's seed, about +10 K on zones 1 and 3 and −1 to −5 K on zones 2, 4, 5 and 6, a hotter start and a milder window that the offline search of Section 6.5 could not choose for a slurry that thins while the line runs.

The default setting, At the limits, makes 3658 m²/h, so riding the limits adds 19 m²/h, 0.5 %, for 8 of 15 strips over the threshold. Held zones at the limits make 3474 m²/h with 1 of 15 strips over, and a diagnosis copy of the push at the limits, which is not part of the application, makes 3465 m²/h, so riding the limits is worth about 3 % to either structure when only the speed moves. The transport delay in the model is worth fewer trips rather than more area. Without it the plan makes 3660 m²/h but engages the override 13.4 times instead of 3.8 and spends 213 s over the trip instead of 52 s. The best of 126 shipped settings in hindsight, 48 m/min fixed with the push off, makes 3430 m²/h and passes every strip at 2 of 5 seeds.

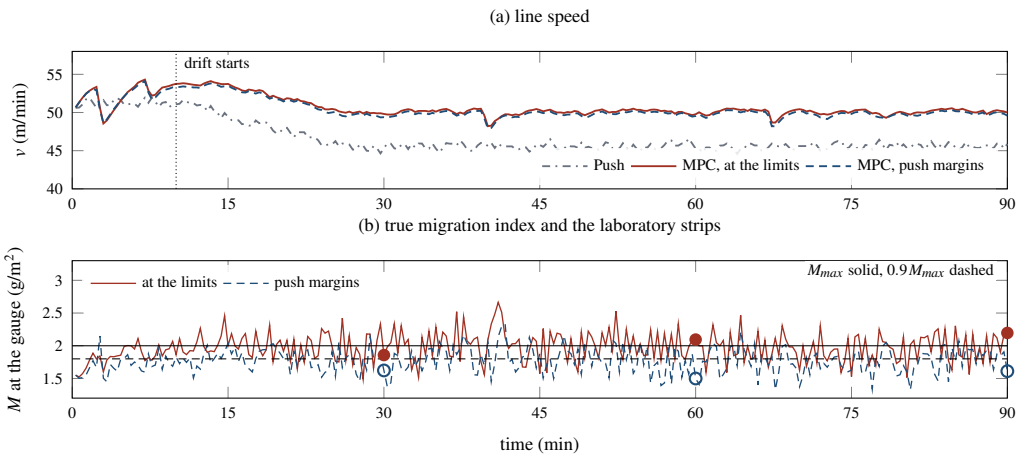


Figure 6.4 Case 9 on its own seed over 90 min, sampled every 20 s. (a) The true line speed under the push (dash-dotted) and under the MPC at its two settings (At the limits solid, Push margins dashed), after the solids drift begins at 10 min. The MPC runs about 4 m/min faster on average. (b) The true migration index at the gauge under the MPC, with the strips the laboratory cut at 30, 60 and 90 min marked (filled circles at the limits, open circles at Push margins). At the limits the index is held near M_{max} and two of three strips test over it, while Push margins holds it near $0.9\,M_{max}$ and every strip passes.

At either setting zone 6 spends about a minute in 90 min over the trip (52 and 54 s, the push never), about half of it on three seeds while the plan accelerates in the first 10 min. At the end of its horizon the plan sits within 2 % of the zone 2 vapor limit in 100 % of its decisions, of zone 6's in 99.4 % and of the migration threshold in 99.1 %, and never near the residual limit. The residual does not bind in case 9. With its limit left out of the plan the line makes 3657 m^2/h, as with it, and the residual passes the limit for under 2 s at one seed.

The failed strips are scatter, not bias. After 40 min the plan's steady prediction of the index at the gauge averages 2.03 g/m^2 and the true index 1.98 g/m^2, so the prediction errs high, while the true index scatters 0.22 g/m^2 (one standard deviation) from parcel to parcel. A plan holding the mean at the threshold fails about half the strips, as shown in Figure 6.4. Slack prices 10 and 100 times higher leave 7 and 4 of 15 strips over, the second with the residual 111 s over its limit at every seed, and the migration slack never exceeds 0.13 g/m^2, so neither the price nor the single slack per output is the cause. A back-off to 95 % of the threshold leaves 3 of 15 and to 90 %, the push's margin, none. It is reported as information, and the default was not retuned.

The other cases of Table 6.4 bound the result. In case 5 with its zone 6 step the residual binds, and the MPC, 11.6 % faster, is over its limit for 1271 s per 90 min at every seed against the push's 103 s (39 s at Push margins, 3681 m^2/h). On the Standard profile, where no setting meets the migration limit, the MPC loses 4.0 and 4.6 % at every seed in cases 6 and 8 while failing fewer strips. The push leaves the unmet limit out, and the plan chases it with a prediction that is low, 1.46 against 2.05 g/m^2 in case 8.

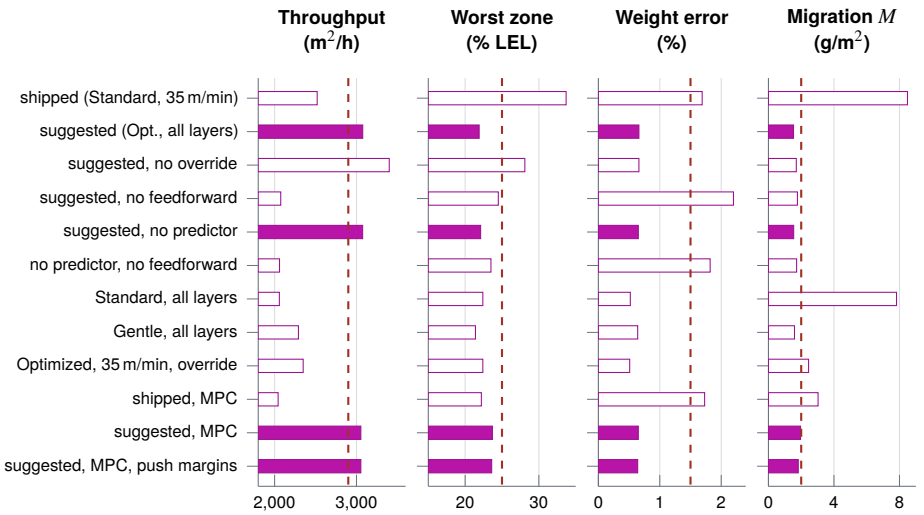


Figure 6.5 Table 6.6 redrawn against the challenge's limits, dashed: at least 2900 m^2/h, every zone at or under 25 % LEL, the dry coat weight within 1.5 % and the migration under its threshold of 2 g/m^2. Solid bars pass and white bars fail. Notice that the run without the override is the fastest and crosses only the dashed limit of the cap, and that the Gentle profile with every layer stays inside every dashed limit except throughput.

> ✦ DID YOU KNOW? **Riding the Limit Buys Half a Percent**
>
> From the simulator: in case 9 the predictive controller at the limits coats 3658 m^2/h, only 19 more than at the push's margins, yet 8 of 15 laboratory strips fail against none, because the index it holds at the threshold scatters from parcel to parcel (Table 6.5).

6.7.6 The Challenge

The challenge coats 5000 m through a solids drift at 20 min, a fan loss at 40 min and a splice at 60 min, and requires every zone at or under 25 % LEL at every instant, the dry coat weight within 1.5 % of the target after the first minute, the residual under its limit, every laboratory sample's true migration under its threshold and at least 2900 m^2/h, judged on the truth with the case's plant as shipped. The configurations are compared in Table 6.6, and Figure 6.5 draws them against the challenge's limits. As shipped, at a fixed 35 m/min on the Standard profile with the push and the override off, the line makes 2520 m^2/h and fails four ways. The suggested settings make 3076 m^2/h, 22 % more, and pass, and on five more seeds they make 3069 to 3084 m^2/h and pass every time, while the shipped settings fail on all six. Each piece earns its place except one. Without the override the line runs faster, 3400 m^2/h, and crosses the cap when the fan weakens. Without the feedforward the drift takes the weight 2.2 % off and the throughput falls to 2075 m^2/h. Without the predictor the run passes at 3075 m^2/h, so the predictor is not what this challenge needs, and its value is the gain of case 2. The line at 3000 s of the suggested run is shown in Figure 6.3. At the fastest playback speed the challenge's 5000 m take 23.4 to 28.7 s of wall-clock time in a browser tab.

For information, with its rules unchanged and over five seeds, the challenge as shipped with the MPC added fails at every seed (2038 to 2044 m^2/h) but keeps the worst zone at 21.8 to 22.2 % LEL. The suggested settings with the MPC pass at 2 of 5 seeds (3053 to 3116 m^2/h, seed 2 also with a residual of 0.503 g/m^2) and at Push margins at all five (3053 to 3115, the push 3076 to 3084 m^2/h).

Table 6.6 The Challenge, 5000 m, Default Seed

Configuration	m^2/h	LEL (%)	Wt. (%)	M (g/m^2)	Verdict
shipped (Standard, 35 m/min)	2520	33.7	1.69	8.49	fails
suggested (Opt., all layers)	3076	21.9	0.66	1.53	passes
suggested, no override	3400	28.1	0.66	1.70	fails
suggested, no feedforward	2075	24.5	2.20	1.77	fails
suggested, no predictor	3075	22.1	0.65	1.54	passes
no predictor, no feedforward	2060	23.5	1.82	1.72	fails
Standard, all layers	2058	22.4	0.52	7.82	fails
Gentle, all layers	2291	21.4	0.64	1.59	fails
Optimized, 35 m/min, override	2349	22.4	0.51	2.45	fails
shipped, MPC	2043	22.2	1.73	3.03	fails
suggested, MPC	3053	23.7	0.65	1.96	passes
suggested, MPC, push margins	3053	23.6	0.64	1.82	passes

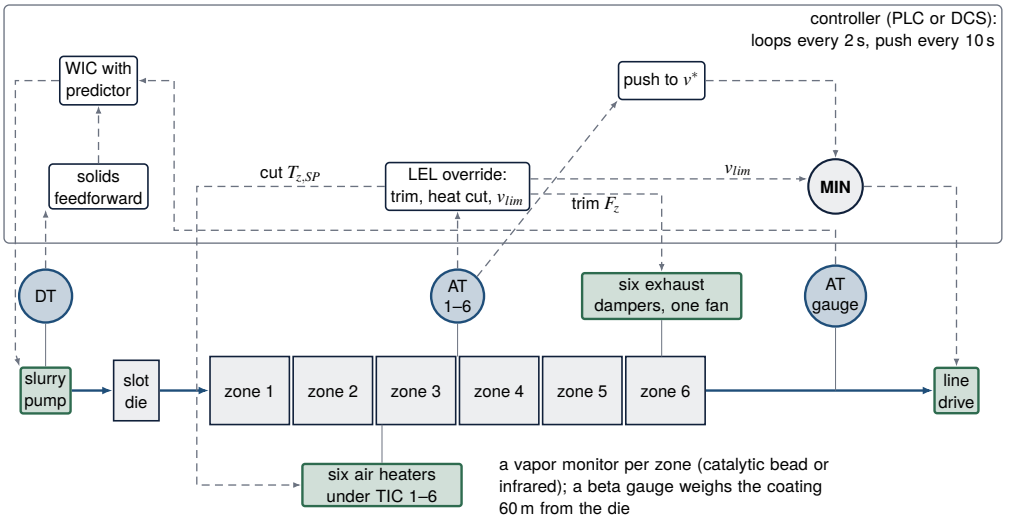


Figure 6.6 The override, the push and the coat-weight loop on real hardware. The vapor monitors AT 1–6 feed the LEL override, which trims the exhaust dampers first, then cuts a zone's air through its heater loop or limits the speed, and the push, whose speed meets the limit in the low selector ahead of the line drive. The beta gauge feeds the coat-weight loop WIC through its predictor, and the densitometer DT feeds the solids feedforward. Notice that every handle of the override is a different device: a damper, a heater and the drive.

6.8 Technology in Practice

A production coater reads the same signals and moves the same handles as the layers of Section 6.5. Figure 6.6 draws the override, the push and the coat-weight loop with line hardware in place of the schematic's symbols.

What Measures It

The constraint of this chapter is read by one vapor monitor per zone. A cost analysis of electrode drying names these instruments as a requirement of an NMP line and puts the limit they guard at a quarter of the lower explosive limit [11]. A national laboratory study mounted laser calipers at the oven inlet of a slot-die coater to read the wet thickness of cathodes and anodes, and found the precision of the in-line measurement to be within ±2 % [22]. The model's monitors read the true vapor through a lag, with no drift and no calibration error, as Limitations states.

TECHNOLOGY Sensor: A Vapor Monitor in Every Zone

Sensors for combustibles in air include the catalytic bead, the thermocouple, the infrared absorber and the flame ionization detector. Bead and thermocouple sensors burn a little of the sample on a heated element and read the heat it gives off. An infrared analyzer reads how much of a beam the vapor absorbs and must reject carbon dioxide and water vapor, which absorb too. Safety analyzers are built for fast response and ruggedness and are usually less accurate than process analyzers [23]. Oven monitors check themselves and recalibrate periodically on a test gas [13]. No open source read gives a range or a response time for an NMP oven monitor. The model's AT is an 8 s lag with 0.2 % LEL of noise and no drift, so a monitor reading low, which would let the push run faster, is not simulated.

What Moves It

The override has three handles. The exhaust trim opens each zone's damper, the heat cut lowers a zone's air setpoint through its heater loop, and the speed limit acts on the line drive through the low selector. A tip sheet on oven efficiency links the vapor monitor to the exhaust, through the fan's drive or its dampers [13], which is the first handle.

TECHNOLOGY Final Element: Exhaust Dampers and the Fan Drive

A damper throttles a large flow of air at low pressure with several vanes turned together, parallel vanes like a Venetian blind across a rectangular duct or radial vanes like petals in a round one [23]. An oven whose vapor monitor sets its ventilation can act through the dampers or, with further savings, through an adjustable-speed drive on the exhaust fan [13]. No open source read gives a stroke time or a rangeability for an oven damper. In the model each zone's exhaust follows its damper command through a 5 s lag, limited by the fan's capacity times its health, so a weakening fan looks on the trend as it does in case 7: every damper wide open and the vapor of the wet zones climbing.

Where the Controller Runs

Programmable logic controllers serve as local controllers within a supervisory scheme, loops are often nested so that the setpoint of one comes from another, and cycle times range from milliseconds to minutes [24]. In the application every loop and the override execute every 2 s, the push every 10 s, and the predictive controller every $T_s = 10\,\mathrm{s}$, so the push and the plan sit naturally in a supervisory layer above the zone loops. The low selector that applies $\min(v_{push}, v_{lim})$ is a standard function block. In one fieldbus standard the control selector block picks among controller outputs and carries back-calculation facilities that modify the response of the deselected controllers, which makes it the block for limit and override strategies [23].

What Is Modernizing It

Two developments bear on the dryer and its limits. The first is ventilation set by measurement rather than by the worst case. Continuous monitoring equipment tracks the solvent load in real time and controls the ventilation air to the real need, and linking it to an adjustable-speed drive on the exhaust fan improves the efficiency further [13]. The second is in-line inspection of the product. The same laboratory study read the homogeneity of the dried electrodes by infrared thermography at the oven outlet, where a rise or fall in the temperature profile showed flaws that optical images missed, and proposed such methods to find flawed electrode before cell assembly [22]. Neither measures the binder in the critical window, which the laboratory peel test still reports half an hour after the strip is cut. The predictive controller of Section 6.5.6 shows what a plan that moves the zones as well as the speed adds once such limits are predicted.

IN PRACTICE One Monitor per Zone, a Quarter of the Limit

A cost analysis of electrode drying from two national laboratories states the rule for NMP. The vapor in the drying chamber must be monitored to stay at or below 25 % of the lower explosive limit, 0.325 volume percent, and LEL monitors in each dryer zone read it in real time, with control logic to keep the operation safe. NMP is a combustible rather than a flammable liquid with a high boiling point, so its slurry mixers need no explosion-proof design, yet a line that coats with it must still be designed to prevent a fire or an explosion [11]. The override of this chapter is that control logic, and its trip at 21 % LEL sits under the cap.

6.9 Limitations

The line is a declared teaching design, not a fit to any coater, and the drying law is a constant rate and an activity law with no transport inside the film, so the residual and the falling-rate tail are plausible rather than predicted. The migration index is a proxy whose window and threshold are teaching values, and it rewards a hot first zone for a reason the sources do not give. The cap, the trip, the residual limit and the peel pass are teaching values. A real oven's limits come from the oven standard and the plant's own safety analysis, and a simulated pass is neither compliance nor a safety case. The zones are well mixed, the monitors read the true vapor through a lag without drift or calibration error, and one fan serves all six dampers.

The push, the override's handle choice and the optimizer share the plant's equations and its declared parameters, so model error reaches them only through a case that introduces it, and the monitors' bias then corrects only the vapor. The override hunts in cases 3, 7 and 8 because its speed handle acts through the web's transit, and the release rules that removed its two resting points were found by measurement on this model and are not proven for other profiles. The second side of the electrode, the calender and the cell that would use the declared coat weight are outside the simulator.

The MPC holds predictions of the residual and the migration index, which are never measured on line, at their limits, and the index's scatter of 0.22 g/m^2 is outside its model, so its default fails half the strips in case 9 and exceeds the residual limit for 1271 s in case 5 with its step. On the Standard profile its migration prediction is about 0.6 g/m^2 low. The push, the override's handle choice and the MPC all use the declared configuration with the measured temperatures, exhaust flows, gauge and recipe or measured solids. A parameter edit therefore introduces model mismatch for each structure. No shipped case edits a parameter, so the nominal comparisons are unchanged. With the critical content edited to 4 g/m^2 in case 9, the push exceeds the residual limit for 815 s at 3364 m^2/h, against 5233 s at 3672 m^2/h under the MPC. The MPC still loses this mismatch case. The override's stepped release when switched off remains the learner's act. Manual starts from the override's output under every structure. The program is larger than the shared solver class is documented for, which 8786 plans without a rejection support but do not prove.

OPEN CHALLENGE Taking the Solvent Out of the Cathode

NMP is toxic, and processing electrodes with water has become an expanding field of research. It has succeeded widely for anodes, but serious challenges remain for the cathode, and a 2024 study found water-based cathodes more sensitive to the drying temperature than NMP-based ones. It points to drying regimes tuned to that sensitivity as the way to capture the savings [25]. A line using water would also do without the LEL monitors and their control logic, and its exhaust could go to the atmosphere [11]. Progress would be a water-based cathode that holds its adhesion under a drying profile fast enough for production, which would trade this chapter's vapor cap for a narrower temperature window.

6.10 Conclusion

This chapter modeled a six-zone NMP cathode dryer with parcels of web that carry their own solvent, temperature and migration, and zones that carry their own air and vapor, with solvent ledgers that close to within 10^{-13} of the solvent fed.

On the Standard profile the wet zones stay near 21 % LEL at any speed while zone 4, where the drying front enters, climbs from 18.57 to 29.7 % LEL between 35 and 40 m/min, so the explosive-limit cap binds at the front. An override that trims the exhaust first and then chooses heat or speed zone by zone holds every zone under the cap through a fan loss, at the cost of a fifth of the output, once two release rules found in review remove its resting points. The same speed and coat weight tested 8.0 or 23.3 N/m depending on the air in the critical window.

With the push, the override, the feedforward and an optimized profile the challenge passes at 3076 m^2/h against 2520 m^2/h as shipped, while the predictor is not needed there. An optional MPC that also moves the zones coats 8.2 % more than the push at the push's margins and fails half the strips at its default limits.

The model is a declared teaching design, and its migration index is a proxy. A fuller model would add transport inside the film, a fitted falling-rate law, drifting monitors and the second side. Within those limits the simulator shows that a vapor limit is held at the drying front, and that the handle for it depends on where that front is.

KEY POINTS

- A faster line does not load every dryer zone a little more. It carries the wet coating into the next zone, so the vapor limit binds where the drying front is.
- An override that trims the exhaust first and then chooses heat or speed zone by zone holds every zone under the cap through a fan loss, at the cost of a fifth of the output.
- The same speed and coat weight tested 8.0 or 23.3 N/m depending on the air in the critical window.
- With the push, the override, the feedforward and an optimized profile the challenge passes at 3076 m^2/h against 2520 m^2/h as shipped.

Where else this applies. Chapter 5 runs a throughput supervisor against torque, pressure and dryer limits, and Volume 5, Chapter 10 pushes a dryer's throughput on inferred limits.

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6.11 Exercises

6.1 Concept check · 2 min

The coater runs at 35 m/min on the Standard profile with the LEL override off, and the line speed setpoint is raised to 40 m/min. Which zone's vapor rises past the 25 % LEL cap?

(a) Every zone a little, since 14 % more solvent enters the dryer each minute

(b) Zone 1, because the faster web arrives hotter and evaporates sooner

(c) Zones 2 and 3, because they evaporate the most solvent of the six zones

(d) Zone 4, because the faster web carries wet coating into the zone the front enters

6.2 Concept check · 2 min

In case 7 the exhaust fan loses 30 % of its capacity at a fixed 35 m/min, every damper is already wide open, and zones 2 and 3, wet from end to end, approach the cap. Which handle lowers their vapor?

(a) A cut in each zone's own air temperature, which lowers its constant drying rate
(b) A lower line speed, which reduces the solvent each zone receives per minute
(c) A wider damper opening, which restores the exhaust each zone receives
(d) A higher push target, which gives the zones more room before the trip

6.3 Concept check · 2 min

Case 2 doubles the coat-weight gain to 0.6 µm per g/m^2. Without the predictor the gauge swings for half an hour, and with it the gauge holds within 1.5 % from 3.0 min. With the predictor off and the shipped gain of 0.3, the loop also settles at 3.0 min. What does the predictor buy?

(a) It makes the gauge report each change sooner than the web can carry it
(b) It allows a higher gain without oscillation, but no faster settling than the detuned loop
(c) It replaces the solids feedforward, since it also corrects a thinning slurry at once
(d) It shortens the transport delay by keying the model to the encoder's web length

6.4 Theory and calculation · 6 min

The slurry has 70 % solids, a solids density of 4430 kg/m^3 and an NMP density of 1028 kg/m^3. The coated width is 1.2 m, the coat weight target is 180 g/m^2 and the gauge is 60 m of web from the die.

(a) Find the slurry density and the wet film thickness at the target. *Checkpoint:* 2223 kg/m^3 and 115.7 µm.

(b) At 35 m/min, find the solvent laid per square meter, the NMP the dryer must remove each second and the pump flow. *Checkpoint:* 77.1 g/m^2, 0.054 kg/s and 4.86 L/min.

(c) The line slows to 30 m/min with the pump held, as in case 1. Find the dry coat weight the die now lays and the time the gauge needs to see it, against the time at 35 m/min. *Checkpoint:* 210 g/m^2, after 120 s against 102.9 s.

6.5 Theory and calculation · 6 min

All solvent the die lays must leave through the exhaust. Use the molar masses 99.13 g/mol for NMP and 28.965 g/mol for air, the lower explosive limit $y_{LEL} = 0.013$, six fans of 1.8 kg/s of air and the solvent load $s_0 = 77.14\,\mathrm{g/m^2}$ on a coated width of 1.2 m.

(a) Find the largest NMP flow the six exhausts can carry with every zone at the 25 % LEL cap. *Checkpoint:* 0.120 kg/s.

(b) Find the line speed above which no profile can keep every zone under the cap. *Checkpoint:* 77.86 m/min.

(c) The fan loses 30 % of its capacity, as in case 7 and the challenge. Find the new bound. *Checkpoint:* 54.5 m/min.

6.6 Theory and calculation · 5 min

The vapor pressure of NMP in the model is the Clausius–Clapeyron line of Equation (6.4), with $P_0 = 101\,325$ Pa, $T_b = 475.2$ K and $B = 6093$ K.

(a) Find the vapor pressure at 120 and 140 °C. *Checkpoint:* 6.98 kPa and 14.8 kPa.

(b) From the slope of $\ln p_{sat}$ at 120 °C, find the temperature rise that doubles the vapor pressure there. *Checkpoint:* 17.6 K.

(c) Find the molar enthalpy of vaporization that B implies, and compare it with the range of 47.7 to 53.4 kJ/mol that the NIST WebBook gives between 345 and 425 K. *Checkpoint:* 50.7 kJ/mol, inside the range.

6.7 App challenge · 8 min

Load scenario 3, Raise the speed: a zone crosses its cap, at the default seed. The LEL override is off as loaded.

(a) Press Run at 10×. When the clock passes about 30 s (any time from 20 to 45 s will do), set Line speed setpoint to 40 m/min, switch to 100× and run to 30 min. Read the Worst zone (true) tile. Export the CSV file and find the time from the first row with `speed_req_mpm` above 35 to the first row with `truth_lel_z4_pct` above 25. *Checkpoint:* 30.3 % LEL in zone 4, within 0.1. About 62 s, within 4 s.

(b) Press the reload button, set LEL override to On, and repeat the same steps. Read the Worst zone (true) tile, and in a new CSV file find the mean of `speed_mpm` from 10 to 30 min. *Checkpoint:* 22.9 % LEL in zone 4, within 0.3, and 35.6 m/min, within 0.2.

Why does the line not settle at a fixed speed in run (b)?

6.8 App challenge · 8 min

Load scenario 4, The profile and the adhesion test, at the default seed. Run at 300× until the run pauses at 60 min. Read the peel test in the Residual · adhesion lab tile, export the CSV file and read `gauge_gm2` at 3600 s and `truth_migration_gm2` at 1800 s, the time the tested strip was cut. Then set Dryer profile to Gentle, press Reset and repeat.

(a) Report the four values for the Standard profile. *Checkpoint:* 8.0 N/m, 179.3 g/m^2 and 6.20 g/m^2, within 0.1.

(b) Report them for the Gentle profile. *Checkpoint:* 23.3 N/m, 179.3 g/m^2 and 0.66 g/m^2, within 0.1.

(c) Use the peel law of Equation (6.7) to find the true peel strength of each strip, and explain why the reports differ from it. *Checkpoint:* 7.32 N/m and 22.56 N/m.

6.9 App challenge · 9 min

Load the challenge, Coat 5000 m at the greatest throughput, at the default seed. For each run below, run at 300× until the run pauses at 5000 m and read the Challenge target tile: the throughput, the worst zone, the coat weight error, the worst migration and the verdict.

(a) Run the challenge as loaded (Standard profile at a fixed 35 m/min, push and override off). *Checkpoint:* 2520 m^2/h, 33.7 % LEL, 1.69 % and 8.49 g/m^2, not met.

(b) Press Reveal suggested tuning, then Reset, and run again. *Checkpoint:* 3076 m^2/h, 21.9 % LEL, 0.66 % and 1.53 g/m^2, met.

(c) Set Solids feedforward (inline density) to Off, press Reset and run again. *Checkpoint:* 2075 m^2/h, 24.5 % LEL, 2.20 % and 1.77 g/m^2, not met.

Name the targets that runs (a) and (c) miss, and explain why run (c) is also slower.

6.10 Application area · 4 min

At 35 m/min the dryer removes 0.054 kg/s of NMP. Each kilogram of air at the 25 % LEL cap carries 0.011 12 kg of NMP, and twice that at the 50 % of the limit that continuous monitors allow under the oven standard.

(a) Find the least total exhaust that could carry this solvent at each margin, and compare it with the design exhaust of 1.53 kg/s per zone. *Checkpoint:* 4.85 kg/s and 2.43 kg/s, against 9.18 kg/s.

(b) Give two reasons why a plant should not simply move to the larger margin to save the exhaust energy, using the chapter's limitations.

6.11 Application area · 4 min

The laboratory cuts a strip at the gauge every 30 min and reports its peel strength 30 min later. The line runs at 35 m/min on a coated width of 1.2 m, and the declared product carries 2.938 mAh/cm^2 per side.

(a) A profile change that harms the adhesion is made just after a strip is cut. Find the longest time before a report can show it and the electrode area coated in that time. *Checkpoint:* 60 min and 2520 m^2.

(b) Find the capacity of one side of that area, and name the one on-line instrument that moves with a quality the line cannot weigh. *Checkpoint:* About 74.0 kAh.

6.12 Review the agent · 5 min

An AI assistant reads Table 6.5 and writes: “At its default setting, At the limits, the MPC coats 3658 m^2/h against the push’s 3364 m^2/h, 8.7 % more. It keeps every zone under the 25 % LEL cap and the residual under its limit, and it uses 6 % less heater energy per square meter. Switch the line to the MPC at its default setting.” Find the flaw in the recommendation and say how you would check it.