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CHAPTER 9

Annealing Line Entry Looper Simulator for Averaging Level Control and Speed Feedforward

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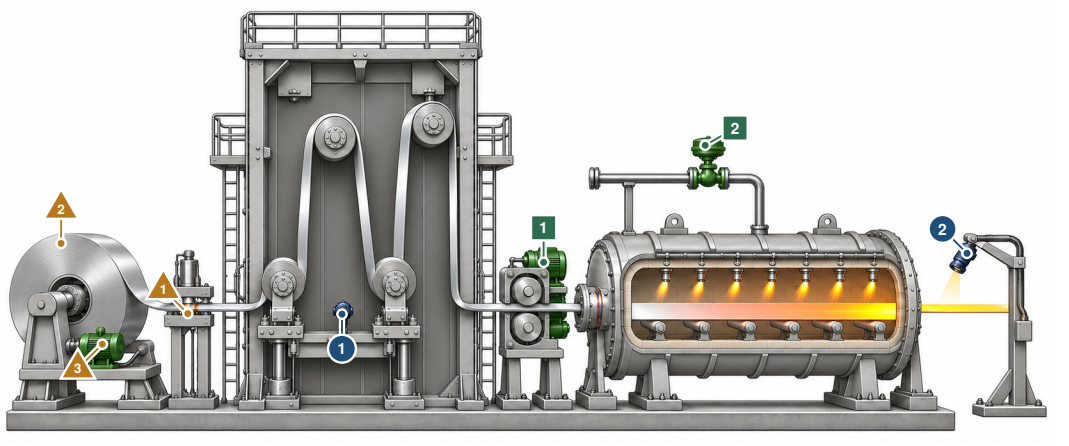
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CHAPTER 9

Annealing Line Entry Looper Simulator for Averaging Level Control and Speed Feedforward



The controller moves 1 speed of the drive rolls that pull strip out of the looper 2 firing of the furnace

The controller reads 1 strip stored in the looper 2 strip temperature at the furnace exit

What disturbs it 1 weld stops, some longer than the looper can carry 2 shorter or thicker coils 3 a slower entry

Notice that the looper stands between the welder and the furnace: the strip it stores lets the furnace run on while the entry stops for each weld. Illustration, not to scale.

IN PLAIN TERMS **Keeping a Furnace Fed While the Entry Stops**

The main idea. An annealing line heats rolled steel strip in a long furnace that must keep running. Every new coil is welded to the last one while the entry stands still, so a tall store of strip in loops feeds the furnace meanwhile.

The challenge. If the speed is pulled down to keep that store full, every weld slows the furnace, and the strip comes out at the wrong temperature. The store can only smooth the supply of strip, and a stop longer than it holds must be seen coming and met by slowing early.

Why it matters. Strip heated to the wrong temperature leaves the line off specification.

THREE WAYS TO READ THIS CHAPTER

⊘	**Explore**	12 min	The first page, the history boxes of Sections 9.1 and 9.2, the fact box of Section 9.3, the try-it and fact boxes of Section 9.5, and the key points
🕮	**Study**	45 min	The whole chapter with its pause points and the twelve exercises
⛰	**Practice**	15 min	The first page, Section 9.5, Section 9.6, Section 9.7 and its open challenge

The control question A looper stores strip between an entry that stops for every weld and a furnace whose strip temperature depends on the line speed. How should the looper loop be tuned so that the welds stay out of the speed, and what must the speed and the firing do when the supply, a stop or the strip thickness changes?

Learning objectives

- Compute the strip one weld draws from the looper and the average speed an interrupted entry can supply.
- Explain why a looper loop resting on its upper clamp leaves the speed untouched when its setpoint lies below the lowest level of a weld.
- Distinguish what a looper absorbs from what only a schedule cap or look-ahead through a stop can fix.
- Scale the line speed with strip thickness from the product $v_p d$ and pair each speed change with a firing feedforward.
- Compare a predictive looper controller with the capped loop over a stated window and name the window that decides the verdict.

Prerequisites Sections 1.4.5 (weld draw and average supply) and 1.4.7 (strip exit temperature on vd), 1.6.2 and 1.6.4 (the PI loops and the scenarios), and 1.6.3 for the looper MPC only. Chapter 6 gives a first integrating level loop.

The app https://apmonitor.com/apps/annealing-line/

See also Volume 6, Chapter 5 for a line whose product answers to its speed and Volume 6, Chapter 7 for level loops inside a recycle. Volume 3, Chapter 6 for a computed feedforward with the feedback left as a slow trim and Volume 3, Chapter 2 for choosing a structure by where the disturbance enters.

9.1 Introduction

An interrupted operation joined to a continuous one needs an inventory between them. Surge drums sit between batch and continuous units, buffer stocks decouple the stations of automatic transfer lines [1], and accumulators store strip and web so that coil changes do not stop a processing line [2, 3]. The level of such an inventory is a means rather than an end. The loop that moves its outflow is judged by how steady it keeps that outflow while the level stays inside its limits, which is the problem posed as averaging level control in the process literature [4, 5].

The misconception this chapter corrects is that every level loop should hold its setpoint. A block diagram of an integrator under PI control rewards tight tuning, because tight tuning gives the smallest level error. The continuous annealing line shows what that error costs downstream. The strip temperature at the furnace exit depends on the line speed, the strip thickness and the furnace temperature [6], so a loop that holds the looper by moving the process speed passes every weld stop into the product. In the simulator the same entry and the same furnace put 71.3 % of the strip outside its temperature window with a tight looper loop and none with an averaging one. The line carries two further lessons that a transfer function does not show. An inventory can smooth a supply but cannot raise its average, and no averaging tuning can carry a stop longer than the inventory holds at full speed.

The line also has two time scales. The strip temperature at the furnace exit answers changes of line speed, strip thickness and furnace temperature with different response times and amplitudes [6]. In the simulator speed acts within one residence time, while the furnace follows its firing over minutes, the two clocks of Section 1.4.7. The freedom the looper gives the process speed is what allows speed to be used as a fast manipulated variable when the strip thickness changes at a weld, and the same speed changes then call for a feedforward to the slow firing. This shape, a fast manipulated variable borrowed from an inventory and a slow one that must be coordinated with it, recurs wherever a buffer feeds a rate-sensitive unit, such as web processing lines [3] like the coating line of Volume 6, Chapter 5, plants whose recycle loops pass through surge tanks [5] like the reactor and column of Volume 6, Chapter 7, galvanizing and coating lines such as Chapter 10, and others.

This chapter compares averaging and tight looper tuning, a schedule cap on speed, look-ahead through entry stops and two feedforwards on the same sequence of coils. Each of these strategies is standard on strip lines. The model covers the entry sequence, the looper, the drive, the strip heating and the furnace, with the controllers written as coded, including a property of the looper loop that follows from its anti-windup and its upper clamp. Twelve scenarios separate what the looper absorbs, what only the schedule can fix, what advance knowledge of a stop can save and what speed can do that the furnace cannot. Section 1.4.5 introduces the weld draw and the average supply on a smaller line, and this chapter measures them on a full one. Section 9.2 reviews the line and its control. Section 9.3 gives the model of the looper, the entry sequence, the drive, the strip heating and the furnace. Section 9.4 describes the looper and strip temperature loops as implemented, their options, the optional looper MPC and manual mode. Section 9.5 reports the measured scenarios, from tight and averaging tuning through short coils, a long weld, firing for the speed and thickness changes to the MPC and the graded challenge. Section 9.6 sets the loops in their real hardware, Section 9.7 states the limitations, Section 9.8 concludes, and Section 9.9 holds the exercises.

> ⧖ HISTORY **From 25 to 600 Meters a Minute (1936 to the 1970s)**
>
> The first vertical continuous annealing line went into operation in 1936. It annealed black plate for tinplate at 25 m/min and heated the strip by electric resistance. Lines spread from the 1940s, and by the first half of the 1950s they ran at 250 to 300 m/min. From the late 1950s through the 1960s the speed jumped to 450 to 600 m/min. Gas jet cooling made a great contribution: it cut the number of strand passes by half and replaced cooling by dipping the strip in water. A review of 1985 judged that the technology had approached a marginal line speed of 600 m/min [7].

9.2 Continuous Annealing and Its Control

Annealing restores the formability of cold-rolled strip, and drawing grades depend on it [8]. Analysis and control of a continuous annealing line were already the subject of a 1964 article in an electrical engineering transactions [9], and a continuous annealing process for drawing-quality strip was reported in the Transactions of the Iron and Steel Institute of Japan in 1977 [8]. Running the strip through the furnace one coil after another is what makes the entry looper necessary. The entry cuts and welds coils at rest, and only the looper allows the furnace section to keep moving while it does.

> ⧖ HISTORY **Sheet for Forming Waits Until 1972**
>
> Continuous annealing of cold-rolled sheet for forming was studied from the 1930s, yet the first commercial vertical line for such sheet started only in October 1972. The obstacle was metallurgical: there was no way to make the carbon dissolved in the steel precipitate in a short time [7]. Earlier work had needed an over-aging treatment of 30 minutes to an hour, too long for a running strip. A process reported in 1977 quenched the strip in water first and so finished the over-aging in less than a minute [8].

Strip temperature control became a named subject as these lines spread. A system for a continuous annealing and processing line was described in 1984 [10], another for a continuous annealing line in 1993 [11], and measurement of the strip temperature with a contact measuring roll was reported for such a line in 1992 [12]. The furnace itself has been modeled in detail. Mathematical models have been published for direct-fired [13] and radiant tube [6] furnaces. The radiant tube model computes the strip temperature distribution from a heat balance and identifies strip thickness, line speed and tube temperature as the dominant influences, with strip width of little effect [6]. The heating of the strip inside an annealing furnace has also been modeled mathematically [14], and low-order identified models now support predictive control of the heating section with an adaptive observer [15]. Energy use is part of the motivation, and furnace models have been applied to improve the energy efficiency of deep-drawing sheet production [16].

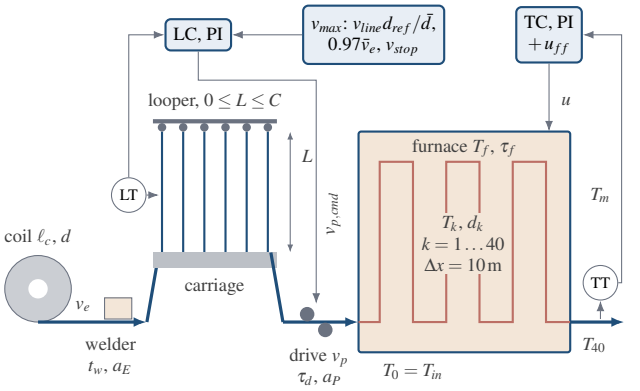


Figure 9.1 Continuous annealing line as modeled. The entry pays out coils of length ℓ_c and thickness d at speed v_e and stops for a weld of duration t_w. The looper stores the strip length L up to its capacity C, the process drive runs the strip at v_p, and the furnace at temperature T_f heats the strip in 40 cells of $\Delta x = 10\,\mathrm{m}$ from T_{in} to the exit temperature T_{40}, measured by the pyrometer TT as T_m. The looper controller LC sets the process speed command within the limit v_{max}, and the temperature controller TC sets the firing u.

Looper control grew up alongside. A strip accumulator is a carriage that moves to lengthen or shorten a set of strands, and its dynamics and control in continuous strip processing lines have been analyzed as a subject of their own [2]. A later model includes the carriage dynamics, the average tension in the accumulator spans and the driven rollers on the process and exit sides, and a controller with a tension observer was compared with the industrial controller of a continuous processing line [3]. The inventory question, how much the stored strip should be allowed to vary and how gently the process speed should respond, is the same one that chemical engineers posed for surge tanks, where averaging level control has been formulated as an optimal control problem for multi-tank systems [4] and systematic PI tuning rules are still being developed for plants with recycle [5].

9.3 Model of the Line

The simulated line pays out coils of 2100 m at up to 420 m/min, stands for 60 s at every weld, stores up to 600 m of strip in the looper and runs the furnace at 300 m/min for 1.0 mm strip, which must leave at 800 °C ±10 °C. Each symbol of the equations that follow is placed on the layout of the line in Figure 9.1.

> **+ DID YOU KNOW? Ten Meters Between Top and Bottom Rolls**
>
> In a vertical annealing furnace the strip runs up and down between rolls more than 10 m apart, and as line speeds rose the span grew to 15 to 20 m. A line started in 1982 was built for more than a million tonnes a year at 450 m/min [7]. This chapter's furnace holds 400 m of strip.

Table 9.1 classifies the variables. The model carries 47 states: the stored strip L, the entry speed v_e, the process speed v_p, the furnace temperature T_f, forty strip cell temperatures T_1 to T_{40}, and three accumulators for strip entered, strip processed and strip off specification. The entry speed is a state only for bookkeeping, because it is set each step by the entry sequence.

9.3.1 Looper and Entry Sequence

The looper is a pure store of strip, Equation (9.1).

$$\frac{\mathrm{d}L}{\mathrm{d}t} = v_e - v_p, \qquad 0 \le L \le C \tag{9.1}$$

Table 9.1 Variables of the Line

Symbol	Type and meaning	Initial	Range
$\ell = 100L/C$	CV, looper level	90 % at start	0–100 %
T_{40}	CV, strip exit temperature	800 °C	SP 720–860
$v_{p,cmd}$	MV, process speed command	300 m/min	60–v_{max}
u	MV, furnace firing	91.5 %	0–100 %
v_e	entry speed (sequence)	300 m/min	0–540
L	state, stored strip	540 m	0–C
v_p	state, process speed	5 m/s	≥ 0
T_f	state, furnace temperature	957.6 °C	—
T_k	states, strip cells 1–40	steady profile	—
ℓ_c	DV, coil length	2100 m	500–4000
t_w	DV, weld stop	60 s	20–240
$v_{e,max}$	DV, entry top speed	420 m/min	180–540
d_{next}	DV, thickness of next coils	1.0 mm	0.5–2.0
σ	DV, pyrometer noise (1σ)	1 °C	0–5

where L is clipped to its bounds after every step. The entry is not a loop but a fixed sequence executed every 0.5 s. While a coil runs, the entry accelerates or decelerates at a_E toward $v_{e,max}$, or toward $\min(v_{e,max}, v_p)$ once $L \geq 0.95C$, and it never exceeds v_p with the looper full. It begins to decelerate when the length R left on the coil satisfies $R \leq v_e^2/(2a_E) + v_e\Delta t$, stops, stands for the weld time t_w, and then starts the next coil. The length of each new coil is drawn as $R = \ell_c(1 + 0.1\xi)$ from a standard normal deviate ξ of the seeded generator, and the first coil starts with $0.55\ell_c$ left.

Two relations follow from the sequence. They are the two halves of Equation (1.8) with this line's symbols. The strip drawn from the looper by one weld, when the entry was running at the process speed before it, is

$$\Delta L_w = v_p \left(t_w + \frac{v_p}{a_E} \right) \tag{9.2}$$

because the entry spends v_p/a_E below the process speed in its deceleration and acceleration together. For the default line this is 350 m, and the measured drop of the level at each weld in case 3 is 347.5 m. A 180 s weld draws 950 m, more than the looper holds. The average rate the entry can supply over a coil cycle is Equation (9.3).

$$\bar{v}_e = \frac{\ell_c}{\ell_c/v_{e,max} + t_w + v_{e,max}/a_E} \tag{9.3}$$

It is 337 m/min for 2100 m coils, 277 m/min for 1000 m coils and 237 m/min for 1000 m coils with the entry derated to 330 m/min. The last two are below the 300 m/min the furnace takes.

9.3.2 Process Drive

The process section follows its speed command through a lag, with a tighter limit on acceleration than on deceleration, Equation (9.4).

$$\frac{\mathrm{d}v_p}{\mathrm{d}t} = \mathrm{clip}\left(\frac{v_{p,cmd} - v_p}{\tau_d},\ -4a_P,\ a_P \right) \tag{9.4}$$

With $a_P = 0.05\,\mathrm{m/s^2}$ the line gains at most 3 m/min per second and loses at most 12 m/min per second. When the looper is empty the process speed is set equal to the entry speed after the step, and the controller limits its command to v_e whenever $L \leq 0.5\,\mathrm{m}$. Each entry into that condition counts as one line stop.

9.3.3 Strip Heating

The 400 m strip path is cut into $N = 40$ cells of length Δx. Each cell is advected by the process speed with first-order upwinding and heated toward the furnace temperature with a time constant proportional to its thickness, Equation (9.5).

$$\frac{\mathrm{d}T_k}{\mathrm{d}t} = -\frac{v_p}{\Delta x}\,(T_k - T_{k-1}) + \frac{T_f - T_k}{\tau_{ref}\, d_k / d_{ref}} \tag{9.5}$$

for $k = 1 \ldots 40$, with $T_0 = T_{in} = 25\,^{\circ}\mathrm{C}$, $\tau_{ref} = 44\,\mathrm{s}$ and $d_{ref} = 1.0\,\mathrm{mm}$. The thickness d_k of each cell is looked up from a list of coil records. When a coil is welded on, its record starts at the strip coordinate $P + L$, where $P = \int v_p\,dt$ is the strip processed, so the new coil reaches the furnace after the strip stored ahead of it. Cell k carries the thickness at coordinate $P - (k - \frac{1}{2})\Delta x$, and $\bar{d}$ is the mean over the forty cells.

At steady state Equation (9.5) gives

$$T_{40} = T_f + (T_{in} - T_f)\,g, \qquad g = \left(\frac{v_p\,\tau_{ref}\,d/d_{ref}}{v_p\,\tau_{ref}\,d/d_{ref} + \Delta x} \right)^N \tag{9.6}$$

so the exit temperature depends on speed and thickness only through their product $v_p d$, as the plug-flow form of Equation (1.12) does. At 300 m/min and 1.0 mm, $g = 0.169$, against $\exp(-80/44) = 0.162$ for exact plug flow with the same 80 s residence time. The furnace temperature that holds 800 °C is 957.6 °C, and one degree of furnace temperature moves the strip by 0.83 °C. With the furnace held, slowing the line by 30 m/min raises the strip to 827.6 °C, and a 1.3 mm strip at unchanged speed leaves at 721.7 °C.

9.3.4 Furnace, Pyrometer and Quality

The furnace is a first-order lag on the firing, loaded by the strip mass rate, Equation (9.7).

$$\tau_f \frac{\mathrm{d}T_f}{\mathrm{d}t} = 500 + 5u - 30\left(v_p \bar{d} - 5\right) - T_f \tag{9.7}$$

with $\tau_f = 240\,\mathrm{s}$, u in percent, v_p in m/s, $\bar{d}$ in mm and temperatures in °C. Full firing at the nominal load gives 1000 °C. A 1.3 mm strip at 300 m/min would need 1062 °C, while full firing at that load reaches only 955 °C. The pyrometer adds Gaussian noise of standard deviation σ to T_{40} and passes it through a first-order filter of 5 s, updated as $T_m \leftarrow T_m + (T_{raw} - T_m)\,\Delta t / (5 + \Delta t)$. Strip leaving the furnace with $|T_{40} - T_{SP}| > 10\,^{\circ}\mathrm{C}$ accumulates at the rate v_p into the off-specification length, which is judged on the true exit temperature rather than the measurement.

The two time scales appear in open-loop step tests in manual mode, drawn in Figure 9.2. Slowing the process from 300 to 270 m/min raises the strip temperature by 40.5 °C, with 63 % of the change after 75 s, because the strip heats longer at once and the furnace, less loaded, then rises by 15 °C. Raising the firing by 5 % raises the strip by 20.8 °C, with 63 % after 270 s. Speed is the faster handle by more than a factor of three.

Table 9.2 lists the parameters. The line starts with $L = 0.9C$, both speeds at 5 m/s, the furnace at the temperature that puts the strip at 800 °C, the strip cells on the steady profile of Equation (9.6) and the firing at 91.5 %, the value that holds that furnace temperature. All states advance together under the fourth-order Runge-Kutta method, stepped every 0.5 s (Section 1.6.1).

9.3.5 Assumptions

The looper is a store of strip without carriage inertia or tension. Real accumulators couple carriage motion to strip tension and to the speeds of the rolls on either side, which limits how fast they fill and empty [3].

The entry sequence is ideal, with one acceleration, a weld time that changes only by event, and coil lengths scattered by 10 %. Coil preparation, threading and variable weld times are absent.

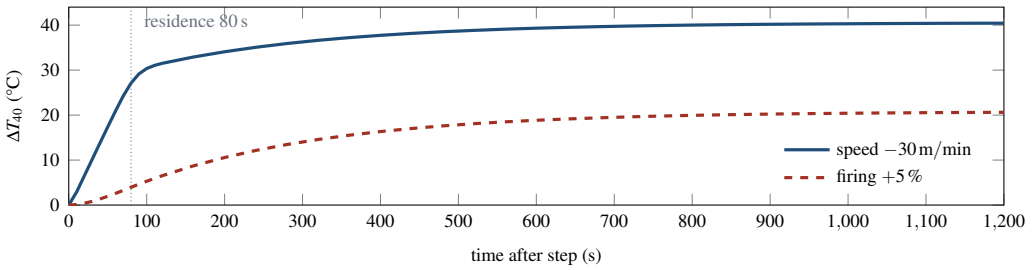


Figure 9.2 Strip exit temperature after a step in process speed and after a step in firing, from 300 m/min, 1.0 mm strip and 800 °C in manual mode, as simulated. The speed response (solid) reaches most of its change within one residence time and then creeps up as the furnace temperature follows the lighter load. The firing response (dashed) follows the 240 s furnace lag.

Table 9.2 Parameters and Their Status in the Interface. Disturbances Are Listed in Table 9.1

Symbol	Meaning	Value	Class
C	looper capacity	600 m	adjustable
a_E	entry acceleration	0.5 m/s^2	adjustable
a_P	process acceleration limit	0.05 m/s^2	adjustable
τ_d	process drive lag	2 s	adjustable
τ_{ref}	strip heating time at 1.0 mm	44 s	adjustable
τ_f	furnace time constant	240 s	adjustable
T_{in}	strip entry temperature	25 °C	hidden
—	strip temperature window	±10 °C	adjustable
N, Δx	cells, cell length	40, 10 m	fixed
d_{ref}	reference thickness	1.0 mm	fixed
—	coefficients of (9.7)	500, 5, 30	fixed
—	pyrometer filter	5 s	fixed
—	coil length scatter (1σ)	10 %	fixed

The strip heats toward one furnace temperature. Real furnaces have heating, soaking and cooling sections with several zones, and radiant heat exchange that is nonlinear in temperature [6, 13].

Strip width is constant, so thickness alone sets the mass per meter, which the radiant tube study supports for the strip temperature itself [6]. The upwind cells add numerical dispersion to what is physically a pure transport, which rounds the front of a thickness change.

Quality is judged by exit temperature alone. Annealing quality also depends on the soaking time and the cooling rate, which are not modeled.

9.4 Controllers as Implemented

Both loops execute every 0.5 s, the same step as the physics, with the velocity-form PID of Section 1.6.2. The derivative time is zero in both loops and no output slew limit is set, so each scan reduces to the PI recursion of Equation (9.8).

$$
\begin{aligned}
e_k &= \alpha\,(r_k - y_k), \qquad P_k = K_c e_k \\
s_k &= s_{k-1} + (P_k - P_{k-1}) \\
c_k &= u_{b,k} + s_k + I_{k-1} \\
u_k &= \mathrm{clip}\,(c_k,\ u_{min},\ u_{max}) \\
I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{u_k - c_k}{T_t}\right]\Delta t
\end{aligned}
\tag{9.8}
$$

where $\alpha = \pm 1$ is the action, $T_t = \tau_I$ and $\Delta t = 0.5\,\text{s}$. These are Equations (1.13) to (1.16) without the derivative, with α for a, s_k for S_k and c_k for v_k, since v is a speed in this chapter. The sum s_k telescopes to P_k and is never clipped, and the clip acts on the emitted output alone. Anti-windup is back-calculation with a tracking time equal to the integral time [17], so at a limit only I is corrected, toward the value that reproduces the applied output.

9.4.1 Looper Loop

The looper loop measures the level ℓ in percent and sets the process speed command. Its action is direct ($\alpha = -1$) in the convention of Section 1.6.2, because a higher level must raise the outflow, so $e = \ell - \ell_{SP}$. The bias u_b is zero, the integral is initialized to the starting speed of 5 m/s, and the output is clipped between 1 m/s and a time-varying upper limit v_{max}, Equation (9.9).

$$v_{max} = \min\left(v_{line}\frac{d_{ref}}{\bar{d}},\ 0.97\,\bar{v}_e,\ v_{stop} \right) \tag{9.9}$$

The line speed v_{line} is 300 m/min. The thickness factor $d_{ref}/\bar{d}$ is applied when the thickness feedforward is on, the schedule cap $0.97\bar{v}_e$ from Equation (9.3) when the schedule option is on, and the look-ahead limit v_{stop} only during a deceleration or a weld with look-ahead on. With the thickness feedforward off the first term is v_{line} itself, and the other two terms drop out when their options are off. The loop can therefore only slow the line below the limit, never speed it up. The default tuning is $K_c = 0.75\,\text{m/min}$ per percent, $\tau_I = 30\,\text{min}$ and $\ell_{SP} = 30\,\%$.

The upper clamp and the back-calculation together give the loop a property that decides its behavior. While the output rests on v_{max}, the last line of Equation (9.8) with $u_b = 0$, $s_k = K_c e_k$ and $T_t = \tau_I$ reduces to

$$I_k - I_{k-1} = \frac{\Delta t}{\tau_I}\left(v_{max} - I_{k-1}\right) \tag{9.10}$$

in which the error has cancelled. The integral relaxes toward the limit, and once it is there the command stays at v_{max} for as long as $\ell > \ell_{SP}$. Below the setpoint the command is close to $v_{max} - K_c(\ell_{SP} - \ell)$, with integral action too slow to matter within one weld. The speed dip at a weld is therefore about K_c times the depth to which the level falls below the setpoint, and a setpoint below the lowest level of a normal weld leaves the process speed untouched whatever the gain.

The look-ahead limit uses the known duration of the entry stop, Equation (9.11).

$$v_{stop} = \max\left(0.5\,\text{m/s},\ \frac{L - 0.05C}{\max(1\,\text{s},\ t_{left})} \right) \tag{9.11}$$

where t_{left} is the weld time remaining plus $v_p/(2a_E)$ during a weld, and the next weld time plus v_e/a_E plus $v_p/(2a_E)$ during the deceleration before it. The term $v_p/(2a_E)$ is the standstill equivalent to the entry's acceleration back to the process speed. The stored strip less a reserve of 5 % of capacity then lasts until the entry has caught up.

9.4.2 Strip Temperature Loop

The temperature loop measures T_m and sets the firing with reverse action ($\alpha = +1$) in the same convention, output limits 0 and 100 %, $K_c = 0.25\,\%$ per °C and $\tau_I = 4\,\text{min}$. Its integral is initialized to the starting firing. With the firing feedforward on, the bias is the steady-state firing for the present speed and mean thickness, measured from the base case, Equation (9.12).

$$\begin{aligned} u_{ff} &= u^*(v_p, \bar{d}) - u^*(5\,\text{m/s}, 1\,\text{mm}) \\ u^*(v,d) &= \frac{T_f^*(v,d) - 500 + 30(vd - 5)}{5} \end{aligned} \tag{9.12}$$

where $T_f^* = (T_{SP} - T_{in}g)/(1-g)$ inverts Equation (9.6) and g is evaluated with the uniform thickness $\bar{d}$. When the option is switched, the integral is moved by the change in u_{ff} so that the firing does not

jump. The feedforward is exact at steady state for uniform strip, because it inverts the same equations the plant uses, and the pyrometer loop is left to trim what it misses, as the settled water measurement trims the computed coagulant dose in Volume 3, Chapter 6. For 1.0 mm strip it asks for 55.4 % firing at 174 m/min and 81.5 % at 268 m/min, against 91.5 % at 300 m/min.

The thickness feedforward on speed is exact in the same sense. Because the exit temperature of Equation (9.6) and the furnace load of Equation (9.7) both depend on $v_p\bar{d}$, scaling the speed by $d_{ref}/\bar{d}$ leaves both unchanged, and 1.3 mm strip at 231 m/min needs the same 957.6 °C furnace as 1.0 mm strip at 300 m/min.

9.4.3 Looper Model Predictive Controller

A model predictive controller (MPC) can replace the looper loop as an option, set up as Section 1.6.3 describes. The looper PI stays the default, in the application and in all scenarios but scenario 11, and it is the fallback. Every $T_s = 4\,\mathrm{s}$, or eight scans, it solves one quadratic program for the process speed command over $N_p = 120$ steps, or 480 s, in 16 move blocks. The first four span one step each and the remaining twelve span 2, 2, 3, 4, 5, 6, 8, 10, 12, 15, 20 and 29 steps. The first move alone is applied and held until the next decision, the receding-horizon form [18, 19].

The controller's model is written from Equations (9.1) and (9.4) rather than identified, because a step test would return the same integrator behind the same lag with fitting error added. It is Equation (9.13).

$$\frac{\mathrm{d}L}{\mathrm{d}t} = v_e - v_h - v_p + q, \quad \frac{\mathrm{d}v_p}{\mathrm{d}t} = \frac{v_{p,cmd} - v_p}{\tau_d}, \quad \frac{\mathrm{d}q}{\mathrm{d}t} = 0 \tag{9.13}$$

Here q is an unexplained net inflow supplied by the estimator, and $v_h \geq 0$ is the rate at which the entry holds strip back while the looper is full, a second decision because the full-looper rule is not linear. The lag takes its declared value $\tau_d = 2\,\mathrm{s}$, copied when the application loads, so an edit of the drive changes the plant and not the model. With a zero-order hold the model becomes Equation (9.14).

$$\begin{aligned} L_{k+1} &= L_k - \tau_d(1-\phi)\,v_{p,k} + T_s\left(v_{e,k} - v_{h,k} + q_k\right) \\ &\quad - \left[T_s - \tau_d(1-\phi)\right] v_{p,cmd,k} \\ v_{p,k+1} &= \phi\, v_{p,k} + (1-\phi)\, v_{p,cmd,k} \end{aligned} \tag{9.14}$$

where $\phi = \mathrm{e}^{-T_s/\tau_d} = 0.135$. The application's sampled matrices equal this closed form to 3×10^{-15}. Run open loop for 120 s after a 30 m/min step of the command in manual mode and fed the measured entry speed, the model stays within 0.111 m/min of the plant's process speed and 0.025 m of its stored strip, a residual caused by the drive's deceleration clip in the first second of the step.

The decisions are the moves of the command, measured from the command applied now, and the held-back rate, both constant within each block. Each plan minimizes Equation (9.15), in which $\hat{L}_k$ and $\hat{v}_{p,k}$ are predictions, j counts the blocks and n_j is the length of block j in steps, with $n_0 = 1$ for the step from the applied command.

$$\begin{aligned} \mathscr{J} &= \sum_{k=1}^{N_p} \left(\frac{\hat{v}_{p,k} - v_{max}}{0.1\,\mathrm{m/s}}\right)^2 + \lambda \sum_{j=1}^{16} \left(\frac{\Delta v_{p,cmd,j}}{0.05\,\mathrm{m/s}}\right)^2 \\ &\quad + w_h \sum_{k=0}^{N_p-1} v_{h,k}^2 + \kappa\,\varepsilon_1^2 + \nu\,\varepsilon_1 + \nu_{SP}\,\varepsilon_2 \\ \text{s.t. } & 0.05C - \varepsilon_1 \leq \hat{L}_k \leq 0.97C + \varepsilon_1, \quad \hat{L}_k \geq \frac{\ell_{SP}C}{100} - \varepsilon_2 \\ & 1\,\mathrm{m/s} \leq v_{p,cmd,j} \leq v_{max}, \quad 0 \leq v_{h,j} \leq v_{e,max}, \quad \varepsilon_o \geq 0 \\ & -4a_P T_s n_{j-1} \leq \Delta v_{p,cmd,j} \leq a_P T_s n_{j-1} \end{aligned} \tag{9.15}$$

The speed term prices the shortfall from the present line-speed limit v_{max}, because the furnace is fired for that speed. With $\lambda = 1$ a move of 3 m/min costs as much as 6 m/min of shortfall for one step, and

$w_h = 0.01$ per $(\text{m/s})^2$. The level limits are soft with one slack per output, so ε_1 is the deepest predicted crossing of the 5 % reserve that look-ahead also keeps or of a top above the entry's 95 % fill rule, with $\kappa = 10^3$ per m^2 and $\nu = 10^3$ per m. The level setpoint is a cheap second floor, $v_{SP} = 10$ per m, kept against what the plan is not told. A limit already crossed is re-entered along a funnel with a 20 s time constant. The command box is the looper PI's own clamp, so the schedule cap and look-ahead bound the MPC when they are on, and the rate rows are the drive's 12 m/min up and 48 m/min down per decision. A dual active-set method [20] solves the program, and any plan the solver does not report optimal, or whose values are not finite or whose command leaves its box, is rejected.

The entry speed over the horizon comes from a preview with three settings. Sequence, the default, runs the entry sequence forward at 0.5 s with its own rules from its present phase and speed, the strip R left on the coil being paid out, known from the entry's coil tracking, and the weld time left or the next weld's time, 60 s until the welder announces a longer one, and then the scheduled coils. It never sees an event before its announcement or a coil before it is drawn, which tests on every case with events confirm. Schedule gives only what the cap and look-ahead know, the rate $\bar{v}_e$ of Equation (9.3) while the entry runs and, once it decelerates for a weld, the time until it runs again, and Off holds the entry speed measured now. Neither the cap nor look-ahead reads what Sequence reads, so Schedule is the like-for-like setting.

A steady-state Kalman filter on (L, v_p, q) runs every 4 s under both looper options. It predicts with the mean command and entry speed of the last period and corrects with the measured stored strip and process speed, with measurement variances of $0.25\ \text{m}^2$ and $2.5 \times 10^{-5}\ \text{m}^2/\text{s}^2$ and process variances per decision of $0.25\ \text{m}^2$, $4 \times 10^{-4}\ \text{m}^2/\text{s}^2$ and $\rho \times 10^{-4}\ \text{m}^2/\text{s}^2$ for q, $\rho = 0.01$. The random-walk inflow makes the plan offset-free [21], although with a model this close to the plant ρ changes nothing measurable.

A first design, $T_s = 1$ s with 180 steps, solved but left 21.20 % of scenario 11 and 13.74 % of the short coils of case 4 with the firing feedforward off specification. A 4 s period at 120 steps, inside the solver's documented limit, is a horizon design, the shortest period that spans a long weld from its announcement through the stop, about 410 s, and two short-coil cycles, 434 s by Equation (9.3). A 2 s period scored better on scenario 11, 17.22 against 17.46 %, and was not chosen. The setpoint floor was added before tuning, after a probe outside the comparison case, and it lowers scenario 11's share from 18.05 to 17.46 %. One pass over nine values of λ and five of ρ on scenario 11 then scored the speed shortfall and the strip temperature IAE relative to the looper PI with the schedule cap and look-ahead. The pass was to admit only settings that move the command no more than that structure, but none did, 339 against 205.5 m/min at best, so the condition was dropped, and the largest λ within 10 % of the best score is $\lambda = 1$.

A rejected plan hands the command to the looper PI, which tracks the applied command every scan, and the next valid plan takes it back. A forced rejection with the pyrometer noise off moves the command by 0.279 m/min against the PI's own move of 0.283 m/min on that scan, and no plan was rejected in any measured run. The entry sequence with its full-looper rule, the empty-looper limit and the temperature loop behave under the MPC as they do under the PI, and a weld extended by 360 s without notice in case 3 empties the looper under both, where the empty-looper rule stops the line. The controller reads the measured stored strip and speeds, the entry sequence's state, the schedule and its declared model, and a test that replays one plant's measurements into a second plant with other drive, strip and furnace parameters finds identical commands and plans over 3000 steps. A plan takes 0.87 to 0.89 ms in Chrome, 6.5 to 6.7 % of a core at 300 times real time, at 59.9 frames per second.

9.4.4 Manual Mode

In manual mode the operator sets the process speed command, clipped to 0 to 420 m/min, and the firing directly. Both PI loops track the applied values, the looper loop its command limited to v_{max}, by setting $I_k = u_k - u_{b,k} - s_k$ in Equation (9.8), so the transfer to automatic is bumpless, as Section 1.6.2 describes. The entry sequence and the empty-looper limit apply in both modes.

9.5 Results

Table 9.3 gives the twelve scenarios in order. All numbers in Table 9.4 and in this section come from runs of the application engine at its default seed unless ten seeds are stated, each over the window given with it, with any setting changed before the run starts, and they agree with the figures quoted in the application's own scenario notes. At the default speed of 60 times real time a one-hour case runs in one minute. Figure 9.3 draws the off-specification shares and line stops of Table 9.4 as a chart.

Table 9.3 Scenarios in Order

#	Scenario	Event and setting
1	Fixed process speed (manual)	1000 m coils at 30 min
2	Holding the looper tightly	ℓ_{SP} 75 %, K_c 2, τ_I 5 min
3	Averaging level control	ℓ_{SP} 30 %, K_c 0.75, τ_I 30 min
4	Short coils	1000 m coils at 10 min
5	Schedule cap	as 4, cap $0.97\bar{v}_e$
6	A weld longer than the looper	180 s weld near 10 min
7	Look-ahead	as 6, v_{stop} on
8	Firing for the speed	as 7, u_{ff} on
9	Thicker strip at a weld	1.3 mm coils at 5 min
10	Speed feedforward	as 9, $d_{ref}/\bar{d}$ on
11	Fill the looper or cap the speed	1000 m coils, MPC, long weld
12	Challenge, two hours	four events, tight tuning

Table 9.4 Measured Scenarios. Off Spec Is the Share of Strip Processed Outside ±10 °C, Speed Is the Time Mean and Standard Deviation

# (min)	Stops	Off spec	Speed (m/min)	Level (%)	T_{40} (°C)
1 (90)	5	18.8 %	287.6 ± 49.9	0–96	800–953
2 (60)	0	71.3 %	287.2 ± 22.4	43–96	782–845
3 (60)	0	0.0 %	300.0 ± 0.0	38–96	800–800
4 (90)	7	53.1 %	278.9 ± 57.4	0–96	753–910
5 (90)	0	6.6 %	271.9 ± 9.9	33–96	800–828
6 (40)	1	30.9 %	285.0 ± 60.0	0–96	736–947
7 (40)	0	31.3 %	288.8 ± 34.3	5–96	749–903
8 (40)	0	18.5 %	288.8 ± 34.3	5–96	732–861
9 (60)	0	77.5 %	300.0 ± 0.0	38–96	718–800
10 (60)	0	2.5 %	245.8 ± 28.2	38–97	778–821
11 (90)	0	7.6 %	274.9 ± 21.5	5–97	744–843
12 (120)	1	76.0 %	251.1 ± 40.8	0–96	716–939

9.5.1 Fixed Speed, Tight and Averaging Tuning

With the process fixed at 300 m/min and 2100 m coils, the looper swings between 38 and 96 % and nothing else moves. After the switch to 1000 m coils the entry supplies 277 m/min on average, the looper first runs empty at 42.5 min, and the line stops five times in 90 min. The tight loop of case 2, set at 75 %, cuts the speed at every weld, to as low as 223 m/min, and the strip runs between 782 and 845 °C with 71.3 % off specification, although the entry could supply the furnace at full speed throughout. The averaging loop of case 3 lets the level fall 347.5 m at each weld without reaching its setpoint, the speed stays at 300 m/min with zero standard deviation, and no strip is off specification.

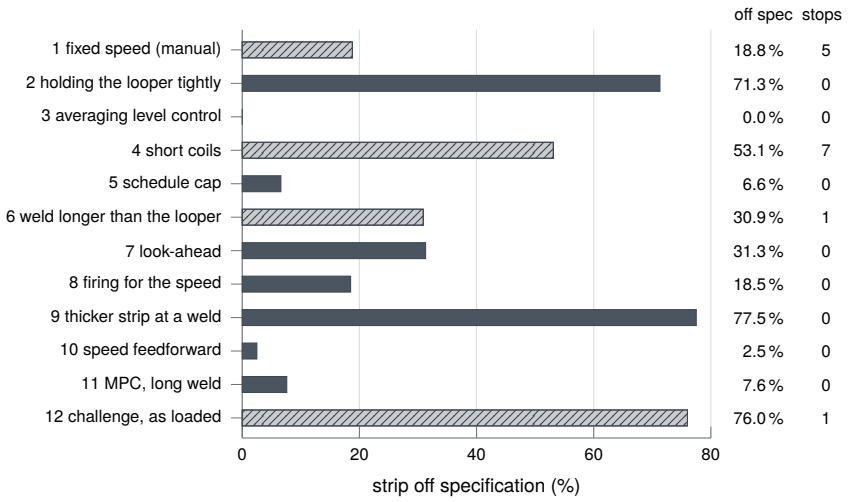


Figure 9.3 The twelve scenarios of Table 9.4 as a chart: the share of strip off specification (bars and first column) and the line stops (second column). Hatched bars mark runs in which the looper ran empty and stopped the line at least once, solid bars runs without a stop. Notice two pairs: tight against averaging tuning (rows 2 and 3), and a speed held against a speed scaled by thickness (rows 9 and 10). Each pair runs on the same entry and the same furnace and goes from one of the longest bars of the chart to one of the shortest.

TRY IT IN THE APP **3 · Averaging Level Control**

Load scenario 3 and press Run. Watch the looper level and the process speed on the trends. At every weld the level falls by about 347.5 m of strip, to no lower than 38 %, while the process speed stays at 300 m/min for the whole hour and no strip leaves off specification.

Table 9.5 separates the setpoint from the gain, which cases 2 and 3 change together. The tight gain and integral time of case 2 with the 30 % setpoint give exactly the result of case 3, because the level never falls below 38 % and Equation (9.10) keeps the command on its limit. With the 75 % setpoint the dip scales with the gain, 31, 77 and 11 m/min for gains of 0.75, 2 and 0.25. These are somewhat above the proportional estimate $K_c(\ell_{SP} - \ell_{min})$ of 27, 65 and 9 m/min, because the integral adds to the cut. A setpoint of 40 %, two points above the lowest level, already gives a dip of 2 m/min. In this loop the setpoint decides whether the welds reach the speed at all, and the gain decides by how much.

Pause. Try Exercise 9.1 before reading on.

Table 9.5 Setpoint Versus Gain in Case 3, One Hour. Gain in m/min per Percent, Dip Is the Lowest Process Speed Below 300 m/min

ℓ_{SP} (%)	K_c	τ_I (min)	Dip (m/min)	Off spec
30	0.75	30	0	0.0 %
30	2	5	0	0.0 %
40	0.75	30	2	0.0 %
50	0.75	30	10	0.0 %
75	0.25	30	11	0.0 %
75	0.75	30	31	17.5 %
75	2	5	77	71.3 %

9.5.2 A Supply That Is Too Small

Short coils defeat the averaging loop. At 30 % the looper holds 180 m, less than one weld draws, so by the time the level is low enough for the loop to act the next weld empties it. Case 4 stops the line seven times, first at 22 min, with 53.1 % of the strip off specification. The schedule cap of case 5 brings the speed to 268 m/min at the schedule change, $0.97 \times 277\,\mathrm{m/min}$, the looper never falls below 33 %, and the line never stops. The single speed change overheats the strip to 828 °C while the furnace follows, leaving 6.6 % off specification, and the firing feedforward reduces that to 2.3 %.

Pause. Try Exercise 9.2 before reading on.

9.5.3 A Stop Longer Than the Looper

A 180 s weld draws about 950 m by Equation (9.2). In case 6 the looper runs empty at 12.4 min, the line stands with the entry for 70 s, and strip that waited in the furnace leaves at up to 947 °C, with 30.9 % off specification over 40 min. Doubling the capacity to 1200 m carries the same weld with no stop and no strip off specification. Look-ahead in case 7 lowers the speed limit as soon as the entry decelerates for the weld and holds it at 174 m/min while the entry stands. The looper bottoms at 5 %, and the line never stops. The furnace is still fired for 300 m/min, so the slow strip peaks at 903 °C and 31.3 % is off specification, about as much as with the stop. After the weld the process accelerates at its limit to 268 m/min and then creeps, reaching 290 m/min about 80 s after the entry restarts, because the level is far below its setpoint and the integral has relaxed toward the look-ahead limit while the entry stood still.

> **DID YOU KNOW? Saving the Stop Did Not Save the Strip**
>
> From the simulator: look-ahead keeps the line running through the 180 s weld that stopped it in case 6, yet the share of strip off specification rises from 30.9 to 31.3 % (Table 9.4). The furnace is still fired for the full speed while the line runs slow.

9.5.4 Firing for the Speed

Adding the firing feedforward in case 8 cuts the firing to a low of 35.1 % during the weld, against 54.4 % with the PI loop alone, and the strip peaks at 861 °C instead of 903 °C. The furnace cannot return as fast as the line, so after the weld the strip falls to 732 °C, below the 749 °C of case 7, while the firing sits at 100 % for 133 s. Over 40 min the off-specification share falls from 31.3 to 18.5 %, with both the hot and the cold strip reduced, from 826 to 616 m and from 2786 to 1521 m. The moment of Figure 9.4 is 30 min into this run, when all of the off-specification strip has already been made. The same feedforward applied to the tight loop of case 2 lowers its off-specification share from 71.3 to 55.1 %, which shows that a feedforward softens speed changes but does not excuse creating them.

9.5.5 Thickness Changes at a Weld

With the speed held, 1.3 mm strip needs a furnace hotter than full firing gives. In case 9 the firing is saturated for 46.3 min, the strip falls to 718 °C and 77.5 % of it is off specification, and adding the firing feedforward changes nothing (77.5 %). Scaling the speed by $d_{ref}/\bar{d}$ in case 10 ramps the process from 300 to 231 m/min as the weld travels through the furnace, the looper absorbs the difference between entry and process, and the strip stays between 778 and 821 °C with 2.5 % off specification. All of that strip leaves in the 100 s while the weld is inside the furnace and $\bar{d}$ lies between 1.16 and 1.30 mm, because the speed set from the mean thickness is exact only when the furnace holds one thickness.

Pause. Try Exercise 9.3 before reading on.



Figure 9.4 Scenario 8, firing for the speed through a 180 s weld with look-ahead and averaging tuning, at $t = 29.83$ min with a 30 min trend window, cropped to the plant view and the trends. The looper is back at 96 % (574 of 600 m), the entry and process run at 300 m/min, the strip leaves at 802 °C, and the furnace is at 960 °C with 92 % firing. The trends show four weld stops of the entry. During the long one, from about 10 to 13.5 min, the dashed line limit steps down and the process speed follows it, the level falls to about 5 %, the firing is cut and then saturates at 100 % as the line speeds up again, and the strip temperature rises above and then falls below its setpoint while the furnace temperature dips. The badge row and the status line show no line stops and 2136 m (25.1 %) of strip off specification. Callouts: (1) the badge row, (2) the looper and its stored strip, (3) the furnace with its firing and the exit temperature, (4) the entry and process speed bars above the status line, (5) the long weld on the trends, where the line limit and the process speed step down.

TRY IT IN THE APP **10 · Speed Feedforward on Thickness**

Load scenario 10 and run past the weld at five minutes, where the coils turn 1.3 mm thick. As the weld travels through the furnace the process speed ramps from 300 to 231 m/min and the looper takes up the difference. The strip stays between 778 and 821 °C, and the 2.5 % off specification all leaves while the weld is inside the furnace.

9.5.6 Predictive Control Through an Announced Long Weld

Scenario 11 runs 1000 m coils from the start with the averaging tuning and the firing feedforward of case 8, and at 680 s the welder announces that the next weld will take 180 s, a stop that the looper cannot carry at 300 m/min. Table 9.6 compares the MPC with the looper PI under the schedule cap and look-ahead, the strongest structure without the MPC, called the capped loop below, at the same seed, noise and duration, with no case retuned and 600 plans in 2400 s, none rejected. Two windows are needed, because the case starts at 300 m/min with the furnace fired for that speed, so a window from $t = 0$ holds a start-up term unrelated to the weld.

Under the MPC the line runs at 288 m/min with the looper at 46.3 % when the weld is announced. The plan then holds the line between 194 and 285 m/min, so the entry, still at 420 m/min, fills the

Table 9.6 Scenario 11 Under Five Looper Structures, Default Seed and Mean of Ten Seeds. Speed SD and Command Travel in m/min Over 0 to 2400 s

	0–2400 s		680–3600 s				
Structure	Off (%)	km	Off (m)	Off (%)	km	SD	Travel
PI, cap, look-ahead	21.60	10.427	1690	13.25	12.752	25.1	205
MPC, Sequence	17.46	10.752	1877	14.43	13.006	30.6	428
MPC, Schedule	40.48	10.767	5291	40.71	12.997	42.6	1071
MPC, Off	87.69	8.448	9598	94.17	10.192	99.6	3840
PI, hindsight[a]	16.17	10.667	1724	13.49	12.781	34.3	472
Mean of ten seeds							
PI, cap, look-ahead	21.85	10.41	1713	13.45	12.74	—	—
MPC, Sequence	19.42	10.77	2268	17.40	13.03	—	—
MPC, Schedule	31.78	10.79	4951	38.05	13.02	—	—
PI, hindsight[a]	17.77	10.53	—	14.84	12.62	—	—

[a] The best of 1080 fixed settings of the looper PI chosen after the run: look-ahead, no cap, $v_{line} = 290$ m/min, $\ell_{SP} = 90$ %, $K_c = 0.25$ m/min per percent, $\tau_I = 30$ min.

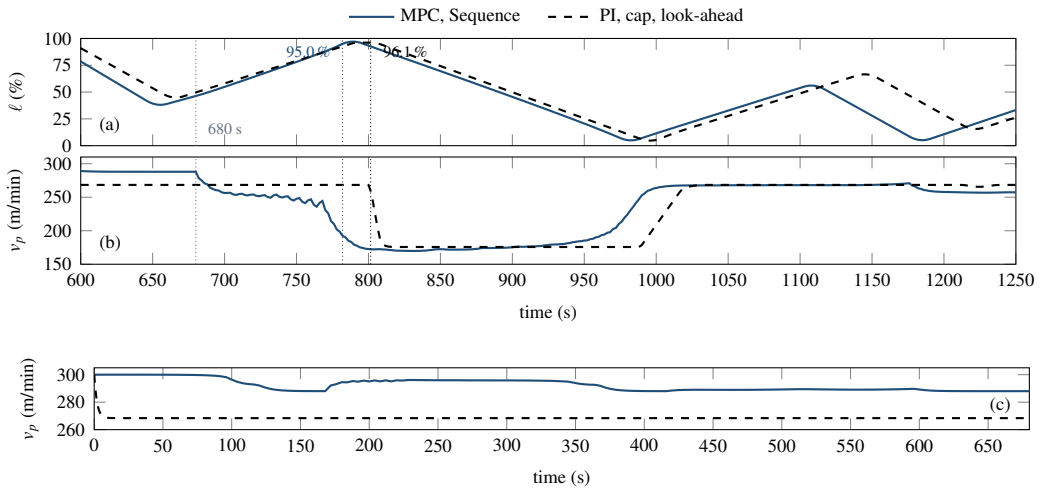


Figure 9.5 Scenario 11 under the MPC with the Sequence preview (blue, solid) and the capped loop (black, dashed). (a) Looper level and (b) process speed from 600 to 1250 s, with dotted marks at the announcement (680 s) and at the entry's deceleration for the long weld under each structure, 782 s at 95.0 % for the MPC and 801.5 s at 96.1 % for the capped loop. (c) Process speed from 0 to 680 s, where the schedule cap steps the line from 300 to 268 m/min at $t = 0$.

looper to 95.0 % by the time it decelerates for the weld at 782 s. The capped loop runs at 268 m/min throughout and arrives as full, 96.1 % at 801.5 s, as shown in Figure 9.5, and neither stops. The fill is itself a slowdown, so the strip leaves its window at 720.5 s under the MPC against 819.5 s, and from 680 to 1200 s the MPC puts 1685 against 1301 m off specification.

Over the first 2400 s the MPC puts 17.46 % of the strip off specification against 21.60 % and processes 10.752 against 10.427 km. That lead comes from the start of the run. The cap steps the speed limit to 268 m/min at $t = 0$, which puts 563 m of strip off specification before the announcement, while the MPC slows gradually to 288 m/min on the strip stored at the start and puts none, as Figure 9.5c shows. From the announcement to one hour, 680 to 3600 s, the MPC puts more strip off specification, 1877 against 1690 m (14.43 against 13.25 %), while carrying 2.0 % more strip. Over ten seeds it puts more off specification in that window at all ten, 17.40 against 13.45 % on average with 2.3 % more strip, and less over the first 2400 s at all ten, 19.42 against 21.85 %.

A fixed setting of the looper PI chosen with hindsight beats the MPC on its own headline. Of 1080 fixed settings of the loop's options and tuning, 587 run without a stop, and the best over the first 2400 s puts 16.17 % off specification with 10.667 km, lower than the MPC at 9 of 10 seeds in both windows. It is a bound rather than a design, chosen after the run was seen.

The fill is the preview's doing. Told only what the cap and look-ahead know, the Schedule preview reaches the weld at 78.6 %, slows to 127 m/min and puts 40.48 % off specification, and told nothing, the Off preview puts 87.69 %. With the level limits and the setpoint floor unpriced, the Sequence plan stops the line three times.

The MPC loses elsewhere too. It moves the speed more, a standard deviation of 30.6 against 25.1 m/min and 428 against 205 m/min of command travel. On steady short coils with the firing feedforward, case 5 over 90 min, the cap's single speed change suits the strip better, 2.29 against 6.15 % off specification, although the MPC carries 2.8 % more strip. A long weld announced 40 s into an ordinary weld stop halts the line under the MPC in 3 of 3 runs and never under the capped loop or look-ahead alone, because Equation (9.11) lets look-ahead slow the line to 30 m/min, below the MPC's 60 m/min floor. On the long coils of cases 6 to 8 the looper is at 95.6 % at the long weld under every structure, and the MPC and look-ahead tie, 30.34 against 31.29 %. Under the MPC the looper of case 4 never empties, 0 stops against 7, so the application's instructions run cases 1 to 10 on the looper PI.

9.5.7 The Graded Challenge

The challenge runs two hours with 1000 m coils from 10 min, 1.2 mm strip from 30 min, a 180 s weld at 60 min and the entry derated to 330 m/min from 80 min, starting from the tight tuning of case 2 with every option off. It is met with no line stops, at most 15 % of the strip off specification and the strip within ± 20 °C over the last 40 min, the last row of Table 9.7, and the outcomes are collected in Table 9.8.

As loaded the line stops once and puts 76.0 % of the strip off specification. The suggested configuration meets all three targets, with no stops, 10.1 % off specification and the strip between 797 and 815 °C over the last 40 min. Removing any one element breaks a target. Without look-ahead the long weld stops the line once, and without either feedforward or the schedule cap the off-specification share rises above 15 %. The schedule cap has a price in throughput, 29.87 against 30.77 km of strip processed without it. Keeping the tight tuning with every option on gives 57.5 %, so the feedforwards cannot compensate for a looper loop that passes the welds into the speed.

With the rules unchanged, the MPC alone still fails the challenge at 43.5 % off specification, because the tight 75 % setpoint becomes its floor and both feedforwards stay off. With the suggested settings and the MPC in place of the looper PI the target is met at 10.2 %, and with the cap and look-ahead also off at 8.0 % with 2.4 % more strip, the last rows of Table 9.8. Under the suggested settings the difficult weld is announced while a weld is already in progress. The event then extends that weld alone by 120 s, and the following weld keeps its scheduled duration. An earlier version of the app also lengthened the following weld, which raised the suggested configuration's off-specification share from 10.1 to 14.2 %.

9.6 Technology in Practice

The two loops of Section 9.4 run on a level measurement, a pyrometer, a speed drive and the firing of the furnace. Figure 9.6 draws them with that hardware in place of the schematic's symbols.

What Measures It

On a real line the strip temperature is measured in more places than the exit. In one furnace of five zones the strip readings, taken together during operation, were judged indispensable for the control of each zone and of the line as a whole [22]. The chapter has one reading at the exit, TT-902. The speed of a roll can be measured by a tachogenerator, a small generator whose voltage is proportional

Table 9.7 Scenarios and Completion Requirements

#	Scenario	Kind	Required to complete
1	Fixed process speed	Demonstration	Run in manual mode with the speed at 300 m/min and the firing at 91.5 % through two welds, then on to 60 min, past the switch to 1000 m coils at 30 min.
2	Holding the looper tightly	Demonstration	With the tight tuning ($\ell_{SP} = 75\,\%$, $K_c = 2$ m/min per %, $\tau_I = 5$ min), run until a weld cuts the process speed below 270 m/min, then 30 min more with the tuning unchanged.
3	Averaging level control	Experiment	With the averaging tuning ($\ell_{SP} = 30\,\%$, $K_c = 0.75$ m/min per %, $\tau_I = 30$ min), hold the process speed at or above 299.4 m/min for 30 min, then run to 60 min with the same tuning.
4	Short coils	Demonstration	With the averaging tuning and no schedule cap, run through three welds of short coils after the switch at 10 min, then on to 60 min.
5	Schedule cap	Experiment	With the schedule cap on, run until the speed limit falls below 276 m/min after the switch at 10 min, then on to 60 min.
6	A weld longer than the looper	Demonstration	With the averaging tuning, run until the 180 s weld empties the looper and stops the line, then 5 min more with the tuning unchanged.
7	Look-ahead	Experiment	With look-ahead on, run until the speed limit falls below 240 m/min at the long weld, then 10 min more with look-ahead on.
8	Firing for the speed	Experiment	With the firing feedforward on, run until the process speed is below 270 m/min with the firing below 70 %, then 10 min more with the feedforward on.
9	Thicker strip at a weld	Demonstration	With the thickness feedforward off, run until the mean thickness in the furnace exceeds 1.29 mm, then 15 min more with it off.
10	Speed feedforward	Experiment	With the thickness feedforward on, run until the process speed falls below 252 m/min, then 15 min more with it on.
11	Fill the looper or cap the speed	Experiment	With the MPC setting the process speed, run in automatic mode to 1100 s, past the weld announced at 680 s and the stop it causes. Restart with the looper PI, the schedule cap and look-ahead, run to 1100 s again, and confirm a comparison of the looper level at the stop, the strip processed and the strip off specification.
12	Challenge, two hours	Challenge	At 2 h, no line stops, at most 15 % of the strip off specification, and $\lvert T_{40} - T_{SP}\rvert \le 20\,^{\circ}\mathrm{C}$ over the last 40 min, with the model parameters and disturbances as given.[a]

[a] With the shipped settings (tight tuning, every option off) the run has one line stop, 76.0 % of the strip off specification and a worst deviation of 46.7 °C over the last 40 min, so all three criteria fail. With the suggested settings (averaging tuning, schedule cap, look-ahead and both feedforwards) it has no stop, 10.1 % off specification and a worst deviation of 15.0 °C, inside the limits by 4.9 percentage points and 5.0 °C.

Table 9.8 Challenge, Two Hours. Suggested Is Averaging Tuning With the Schedule Cap, Look-Ahead and Both Feedforwards. MPC Replaces the Looper PI

Configuration	Stops	Off spec	Last 40 min (°C)
as loaded	1	76.0 %	753–843
suggested	0	10.1 %	797–815
suggested, no schedule cap	0	17.1 %	781–817
suggested, no look-ahead	1	10.2 %	797–815
suggested, no thickness ff	0	16.5 %	794–829
suggested, no firing ff	0	22.1 %	799–820
all options, tight tuning	0	57.5 %	786–824
as loaded, MPC	0	43.5 %	773–822
suggested, MPC	0	10.2 %	797–815
suggested, MPC, no cap or look-ahead	0	8.0 %	792–806

to speed, or by an optical encoder [23]. In the model the level LT-901 is the stored length itself, with no noise and no lag.

line controller: in the chapter both PI blocks execute every 0.5 s, the step of the physics; the optional MPC replaces LC-901 and plans every 4 s

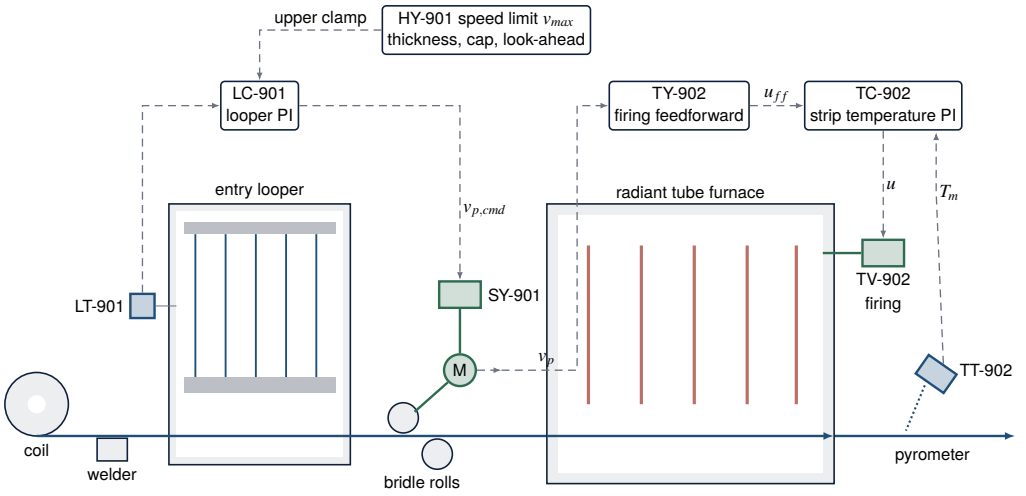


Figure 9.6 The two loops of the line drawn with their hardware. The looper level LT-901 feeds the looper controller LC-901, whose speed command goes to the process drive SY-901, a motor and the bridle rolls that pull the strip out of the looper. The limit HY-901 is the loop's upper clamp, set by the thickness feedforward, the schedule cap and look-ahead. The pyrometer TT-902 reads the strip at the furnace exit and feeds the strip temperature controller TC-902, which sets the firing TV-902 of the radiant tubes, and the feedforward TY-902 adds the firing that the present speed and mean thickness need. Notice that the only path from the looper to the strip temperature runs through the process speed.

TECHNOLOGY **Sensor: A Pyrometer Looking at Bright Strip**

A radiation pyrometer infers a surface temperature from the light the surface emits, so it must know the surface's emittance [23]. Cold-rolled strip in a reducing atmosphere is bright: one study measured an average emissivity of 0.22. The strip is also colder than the furnace walls, so wall radiation reflected off the strip adds to the reading. In one test this back radiation was about 14 °C. A water-cooled shielding flange near the strip, a gas-purged optical filter and a contact thermometer for intermittent correction brought the estimated error below 1 %. A weld has a rougher surface and a higher emissivity, so it shows on the trend as a short pulse of false high temperature [22]. The chapter's pyrometer adds noise and a 5 s filter and has no bias of this kind.

What Moves It

In the heating section of a vertical furnace the strip is heated by radiant tubes arranged in several zones, and the furnace temperature of each zone is controlled independently [7]. Measurements on a working furnace found the line speed the most effective variable in controlling the strip temperature [22], the fast handle of Figure 9.2. The chapter lumps the zones into one furnace temperature with a 240 s lag.

TECHNOLOGY Final Element: The Bridle Roll Drive

The bridle roll drive plays the main role in strip speed control on an annealing line. Its motor, gears and rolls form a torsional spring, and backlash in reducers and couplings lowers the natural frequency of that spring until the speed loop can vibrate. Direct-current motors needed new brushes and commutator parts every two to three years, and for helper rolls inverter-fed alternating-current motors were expected to replace them [7]. Such a variable frequency drive sets the speed by the frequency of the power it feeds the motor [23]. The chapter's drive is a 2 s lag with an acceleration limit of 0.05 m/s^2.

Where the Controller Runs

A line of this kind is run from a layered control system. A supervisor sends set points to distributed controllers, which drive the actuators from sensor feedback, and loops at both levels run with cycle times from milliseconds to minutes [24]. On an annealing line an operation optimization layer sits between the production scheduling layer and the process control layer and sets the process control variables [25]. The chapter's PI blocks execute every 0.5 s, the step of the physics, and the optional MPC plans every 4 s. Both loops, the limit HY-901 and the feedforward TY-902 belong to the process control layer. The schedule cap reads the coil schedule, which belongs to the layer above.

IN PRACTICE Watching the Strip Track

Operators of continuous annealing furnaces know that poor tracking often ends in a broken strip. A temperature difference across the width deforms the strip and changes how it touches the rolls. The rolls are given a crown or a thick middle so that the strip centers itself, but too much crown buckles the center and too strong a centering force wrinkles the strip. The roll profile and the strip tension must therefore be set to suit each operating condition [7]. The model of this chapter has neither tension nor tracking.

What Is Modernizing It

Three developments touch the loops of this chapter. Predictive control of the heating section has moved to linear low-order models identified from the furnace, with parameter estimation and an adaptive observer standing in for quantities that have no sensor. In simulation near actual operating conditions it was compared with a PI controller and with nonlinear predictive control [15]. Data-driven models predict the strip temperature from the operating data of a large furnace: a neural network whose parameters are tuned by an improved swarm optimization was verified on data collected at the production site [26]. Operation optimization now predicts the range of the next disturbances from a time series and adjusts how robust the settings must be, which in tests on actual production data improved strip quality and capacity utilization and reduced the total energy consumption [25].

9.7 Limitations

The looper has no carriage dynamics or tension loops, which in practice limit the rate at which strip can be stored and released [3].

The furnace is one lumped temperature with a linear firing gain. Multi-zone furnaces with radiant exchange respond differently in each zone and nonlinearly in temperature [6, 13], and practical strip temperature control uses their models directly [15].

There is no exit looper and no exit section, so the shears and the coiler at the exit never constrain the process speed.

The feedforwards use the same equations as the plant and so have no model error. The look-ahead knows the weld duration exactly and the schedule cap knows the coil length on average.

Quality is judged on exit temperature alone, and the soaking and cooling that decide the final properties are absent.

The MPC's model omits the strip temperature and the furnace, so its only route to the strip is the price on the speed shortfall, and it also omits the drive's acceleration clip and the scatter of the

coils still to come. Its Sequence preview takes the coil tracking and the announced weld time as exact. A long weld announced while the entry already stands finds the plan unable to slow below 60 m/min where look-ahead may go to 30 m/min. The tuning pass and the headline comparison both use scenario 11, whose start at 300 m/min favors a gradual slowdown in any window that begins at $t = 0$. Manual mode entered during an empty-looper stop starts from the loop's request (277 m/min under the looper PI), not from the limited 0 m/min.

OPEN CHALLENGE A Strip Temperature Model That Holds On Line

The strip temperature in an annealing furnace depends on tube and furnace temperatures, strip width and thickness, line speed and material. The process has a large time delay and a strongly coupled nonlinearity, which limits controllers designed on a mechanism model, and data-driven models trained on production data are now a research focus [26]. Detailed nonlinear models cost much computation in a large furnace, and some quantities have no sensor [15]. Progress would be a model that stays accurate across sizes and speeds and runs inside the controller on a working line.

9.8 Conclusion

The annealing line places a surge inventory between an entry that stops for every weld and a furnace whose product temperature depends on speed. Holding the looper tightly puts 71.3 % of the strip off specification, and letting it swing through its range puts none. Because the loop can only slow the line and its integral relaxes to the limit, the setpoint relative to the lowest level of a weld decides whether any weld reaches the speed. When short coils lower the average supply to 277 m/min the averaging loop lets the looper empty seven times, and a cap at 97 % of the supply removes every stop. A 180 s weld empties the 600 m looper unless look-ahead slows the line to 174 m/min, and firing for the speed then lowers the off-specification share from 31.3 to 18.5 %. A change to 1.3 mm strip saturates the firing and leaves 77.5 % of the strip cold, against 2.5 % with the speed scaled by thickness. A looper MPC fills the looper before an announced long weld, but from the announcement on it leaves 14.4 against 13.3 % of the strip off specification. Carriage and tension dynamics, a multi-zone furnace, an exit section and model error in the feedforwards would make the line more realistic. The line as it stands is a lesson in using an inventory for what it is for.

KEY POINTS

- A looper is a store of strip that lets the furnace keep running while the entry stops for each weld.
- Holding the looper tightly puts 71.3 % of the strip off specification, and letting it swing through its range puts none.
- The setpoint relative to the lowest level of a weld decides whether any weld reaches the speed, because the loop can only slow the line.
- An inventory can smooth a supply but cannot raise its average.
- A change to 1.3 mm strip saturates the firing and leaves 77.5 % of the strip cold, against 2.5 % with the speed scaled by thickness.

Where else this applies. Averaging level control also governs the surge levels inside the recycle of Volume 6, Chapter 7, and a store between an interrupted entry and a rate-sensitive process recurs in the coating line of Chapter 10.

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9.9 Exercises

9.1 Concept check · 2 min

In scenario 3 the looper level falls from about 96 to about 38 % at every weld, yet the process speed stays at 300 m/min with zero standard deviation for the whole hour. Which explanation is right?

(a) The gain of 0.75 m/min per percent is so small that each speed dip is below the resolution of the tile

(b) The integral time of 30 min is long against a weld, so the loop cannot move the speed within one

(c) The level never falls below the 30 % setpoint, so the output rests on its upper limit whatever the gain

(d) The schedule cap holds the speed command at 97 % of the average rate the entry can supply

9.2 Concept check · 1 min

After the switch to 1000 m coils in scenario 4 the entry can supply about 277 m/min on average while the furnace section takes 300 m/min. Which statement about the looper is right?

(a) A higher looper gain keeps the process at 300 m/min, because the loop reacts before the level is low

(b) A looper of twice the capacity removes the line stops for good, because it can carry two welds at once

(c) A looper setpoint of 90 % removes the line stops, because more strip is held back before each weld

(d) The mean process speed must fall to the mean supply, because a looper smooths a supply but cannot raise it

9.3 Concept check · 2 min

From the weld after 5 min in scenario 9 the coils are 1.3 mm thick, the line stays at 300 m/min and 77.5 % of the strip leaves off specification, with or without the firing feedforward. Scenario 10 scales the speed by $d_{ref}/\bar{d}$ and leaves 2.5 % off specification. Why does the speed succeed where the firing fails?

(a) The exit temperature and the furnace load depend on $v_p d$ only, and at 300 m/min the strip needs a furnace above full firing

(b) The firing feedforward is switched off whenever the thickness feedforward is off, so scenario 9 runs on the PI loop alone

(c) The pyrometer reads the thicker strip low, so the firing loop acts on a measurement that is wrong by 30 %

(d) The furnace lag of 240 s is too long for the firing to reach a new furnace temperature within the hour

9.4 Theory and calculation · 6 min

The default line runs the process at $v_p = 5\,\mathrm{m/s}$ (300 m/min). The entry accelerates and decelerates at $a_E = 0.5\,\mathrm{m/s^2}$, a normal weld stands $t_w = 60\,\mathrm{s}$ and the looper holds $C = 600\,\mathrm{m}$. In scenario 3 the looper holds 574 m when the entry begins to slow for a weld.

(a) Use Equation (9.2) to find the strip a normal weld draws and the strip a 180 s weld draws. *Checkpoint:* 350 m and 950 m.

(b) Find the lowest stored strip after a normal weld, in meters and in percent of capacity, and say which looper setpoints keep the welds out of the process speed. *Checkpoint:* 224 m, 37.3 %; any setpoint below about 37 %.

(c) Find the longest weld the looper can carry from 574 m at 300 m/min without slowing the line. *Checkpoint:* 104.8 s.

9.5 Theory and calculation · 6 min

The entry runs at up to $v_{e,max} = 420\,\mathrm{m/min}$, a weld stands $t_w = 60\,\mathrm{s}$ and $a_E = 0.5\,\mathrm{m/s^2}$.

(a) Use Equation (9.3) to find the average supply for coils of 2100 m and of 1000 m, in m/min. *Checkpoint:* 336.9 m/min and 276.7 m/min.

(b) The schedule cap is $0.97\,\bar{v}_e$. Find the cap for 1000 m coils, and the coil length below which the entry cannot feed 300 m/min on average. *Checkpoint:* 268.4 m/min; 1295 m.

(c) From 80 min of the challenge the entry is limited to 330 m/min with 1000 m coils. Find the new average supply and the cap. *Checkpoint:* 237.3 m/min and 230.2 m/min.

9.6 Theory and calculation · 7 min

Use Equation (9.6) with $N = 40$, $\Delta x = 10\,\mathrm{m}$, $\tau_{ref} = 44\,\mathrm{s}$, $d_{ref} = 1.0\,\mathrm{mm}$ and $T_{in} = 25\,^\circ\mathrm{C}$, and Equation (9.7) at steady state.

(a) Find g and the furnace temperature T_f^* that gives 800 °C at 300 m/min and 1.0 mm. *Checkpoint:* $g = 0.169$, $T_f^* = 957.6\,^\circ\mathrm{C}$.

(b) With the furnace held there, find the exit temperature of 1.3 mm strip at 300 m/min, and the speed at which 1.3 mm strip leaves at 800 °C. *Checkpoint:* 721.7 °C; 230.8 m/min.

(c) Find the furnace temperature that 1.3 mm strip at 300 m/min needs and the firing that holds it. Compare with the firing range. *Checkpoint:* 1062.4 °C; 121.5 %, above the 100 % limit.

9.7 App challenge · 9 min

Run the app at the default seed and the default speed of 60×, at which one simulated hour takes one minute. Read the scorecard tiles at 60 min.

(a) Load scenario 2, *Holding the looper tightly*, and run 60 min. Read the *Off-spec strip* and *Process speed* tiles, and the lowest process speed on the *Entry and process speeds* trend or as the minimum of `vp_mpm` in the exported CSV, to within 2 m/min. *Checkpoint:* 71.3 %; $287 \pm 22.4\,\mathrm{m/min}$; lowest about 224 m/min.

(b) Load scenario 3, *Averaging level control*, and run 60 min. Read the same two tiles and the *Looper range used* tile. *Checkpoint:* 0.0 %; $300 \pm 0.0\,\mathrm{m/min}$; 38 to 96 %.

(c) Load scenario 3 again, set *Looper level setpoint* to 75 % before Run, keep the gain and integral time as loaded, and run 60 min. Read the *Off-spec strip* tile to within 0.2 % and the lowest process speed to within 2 m/min, and explain the result with Equation (9.10). *Checkpoint:* 17.5 %; lowest about 269 m/min.

9.8 App challenge · 8 min

Run scenarios 4, *Short coils: an inventory cannot fix a supply*, and 5, *Capping the speed at what the entry can supply*, at the default seed for 90 min each, at the default speed of 60× (90 s each).

(a) Run scenario 4 to 90 min and read the *Line stops* and *Off-spec strip* tiles. *Checkpoint:* 7 stops; 53.1 %.

(b) Run scenario 5 to 90 min. After the switch at 10 min, read on the *Line speed* card what the entry can supply and the speed limit. At 90 min read *Line stops*, *Off-spec strip*, *Looper range used* and *Strip temperature range*. Compare the card with your answer to Exercise 9.5. *Checkpoint:* 277 m/min and 268 m/min; 0 stops; 6.6 %; 33 to 96 %; 800 to 828 °C.

(c) Load scenario 5 again, set *Fire for the speed (feedforward)* On before Run, run to 90 min and read *Off-spec strip* to within 0.2 %. Say where the off-specification strip of (b) came from. *Checkpoint:* 2.3 %.

9.9 App challenge · 8 min

Run scenarios 6, *A weld longer than the looper*, 7, *Looking ahead through the stop*, and 8, *Firing for the speed*, at the default seed for 40 min each, at the default speed of 60× (40 s each). Read the scorecard tiles at 40 min.

(a) Scenario 6: read *Line stops*, *Off-spec strip* and *Strip temperature range*. *Checkpoint:* 1; 30.9 %; 736 to 947 °C.

(b) Scenario 7: read the same tiles, *Looper range used*, and the lowest process speed during the long weld on the *Entry and process speeds* trend, to within 2 m/min. *Checkpoint:* 0; 31.3 %; 749 to 903 °C; 5 to 96 %; 174 m/min.

(c) Scenario 8: read *Off-spec strip* and *Strip temperature range*. Explain why scenario 7 leaves as much strip off specification as scenario 6 and what the firing feedforward changes. *Checkpoint:* 18.5 %; 732 to 861 °C.

9.10 Application area · 4 min

(a) Doubling the looper to 1200 m carries the 180 s weld of scenario 6 with no stop and no strip off specification. Explain with Equation (9.2) why, and say whether the larger looper would also remove the line stops of scenario 4. *Checkpoint:* 950 m fits; no, it only postpones them.

(b) The briefing of scenario 1 notes that a line stop can break the strip and cost an hour of rethreading. Give two reasons from the chapter why a line prefers the slowdown of scenario 7 to the stop of scenario 6, although both leave about 31 % of the strip off specification. *Checkpoint:* Strip that stands in the furnace overheats most, and only a slowdown can be paired with a firing feedforward.

9.11 Application area · 3 min

The Limitations section notes that the feedforwards use the plant's own equations and that look-ahead knows the weld duration exactly.

(a) Look-ahead keeps a reserve of 5 % of the 600 m looper. At the look-ahead speed of 174 m/min, how long an overrun of the announced weld does that reserve cover, and what happens after it? *Checkpoint:* About 10 s; the looper empties and the line stops.

(b) On a real line the thickness and firing feedforwards would carry model error. Which loop removes what they miss, and on what time scale? *Checkpoint:* The strip temperature loop on the firing, over minutes.

9.12 Review the agent · 5 min

An AI assistant, shown Table 9.6, writes: "Over 40 min of scenario 11 the MPC puts 17.46 % of the strip off specification against 21.60 % for the looper PI with the schedule cap and look-ahead, and it processes 3 % more strip. The MPC is the better looper controller, and the line should run every case on it." Find the flaw and say how you would check it with the app.