INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 19 Control of Biological Systems and Human Performance

CHAPTER 13

Greenhouse Climate Simulator for Temperature Integration Under a Humidity Limit

Pages 326–350

Edited by John D. Hedengren

How to cite this chapter. "Greenhouse Climate Simulator for Temperature Integration Under a Humidity Limit," in *Control of Biological Systems and Human Performance*, John D. Hedengren, Ed., vol. 19 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 13, pp. 326–350.

The page numbers in this file are those of the printed volume.

The app for this chapter
https://apmonitor.com/apps/greenhouse-climate/

The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v19-biological-human/#greenhouse-climate

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CHAPTER 13

Greenhouse Climate Simulator for Temperature Integration Under a Humidity Limit



The controller moves 1 roof vent drive 2 thermal screen drive 3 boiler firing 4 fog valve 5 carbon dioxide dosing valve

The controller reads 1 measuring box, air temperature and humidity 2 carbon dioxide sample point 3 weather station

What disturbs it 1 sun, wind and outside cold

Two glasshouse spans of tomatoes with a roof vent, a thermal screen at the gutter, heating pipes along the rows, overhead fog and a carbon dioxide line from the plant room: notice that every handle acts on the one body of air that the measuring box samples. Illustration, not to scale.

IN PLAIN TERMS A Daily Heat Budget Under an Hourly Limit

The main idea. A tomato crop grows by the average warmth of its whole day, not by the warmth of each hour. So a glasshouse can let the free afternoon sun do some of the heating and burn less fuel at night.

The challenge. The air must also stay dry enough every hour, or water settles on the leaves. Opening a window or heating to dry the air uses up the saving, and the same window lets out the gas the plants feed on.

Why it matters. A glasshouse heated for most of the year saves fuel only if it also keeps its leaves dry.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on an energy target (Section 13.1), the two history segments (Section 13.2), the two try-it segments and the fact on the dark day (Section 13.6), and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the cases and the graded week (Section 13.6), Technology in Practice (Section 13.7), Limitations (Section 13.8) and the open challenges

The control question A tomato crop answers the mean temperature of its day, so a glasshouse can spend its heat where it is cheapest, while the humidity under a closed screen must hold hour by hour. How much does a planner over the weather forecast save against fixed setpoints, and what does the humidity limit cost once one air exchange carries heat, water and carbon dioxide together?

Learning objectives

- Explain why a daily-mean recipe makes the heating setpoint a budget and the humidity limit a constraint.
- Compute the screen's insulation, its gap and the air exchange time of the house from the model's coefficients.
- Describe the pipe cascade with external reset and the three stages of the humidity override.
- Compare fixed setpoints with the receding-horizon planner on gas, daily mean and humid minutes in the app.
- Decide which combination of planner, override and cap meets the graded week, and price a point of humidity limit.

Prerequisites Sections 1.6.2 (velocity form and action), 1.6.1 and 1.6.4 (engine and scenarios) and 1.4.6 (overrides on limits). Chapter 11 for an economic supervisor above regulatory loops.

The app https://apmonitor.com/apps/greenhouse-climate/

See also Volume 9, Chapter 9 for a comfort band spent against a tariff, Volume 9, Chapter 6 for heat stored ahead of demand and Volume 9, Chapter 7 for a forecast whose error grows with lead time. Volume 4, Chapter 2 for a protective override and Volume 4, Chapter 4 for selectors on limits measured late.

13.1 Introduction

A glasshouse that grows tomatoes in a temperate climate is heated for most of the year, and its crop does not need every hour to be warm. Development and yield of a glasshouse tomato crop were found to depend mainly on the 24-hour average temperature, and a control program that let the air range between 14 and 26 °C around the same mean grew the crop no differently from a fixed regime [1]. The heating setpoint of such a house is therefore a budget for the day. A degree that the afternoon sun supplies for nothing can stand in for a degree the boiler would buy at night, provided the day's mean comes out right, and with a weather forecast the trade becomes a planning problem. Humidity does not trade that way. Water settles on the leaves in the hour the air saturates, whatever the afternoon was like, so the humidity limit has to hold hour by hour, and the three things that hold it, a gap in the screen, an open vent and more heat, all spend the budget.

A common reading of a climate computer is that it has done its job once its setpoints hold. On fixed setpoints of 19.5 by day and 17 °C at night it holds both, apart from a dawn dip of 1.4 K with the boiler at its limit, and the day's mean comes out at 19.02 °C on a bright Monday with 19.7 MJ/m^2 of sun and 18.57 °C on a dull Tuesday with 11.4 MJ/m^2, against a recipe of 19 °C. A planner that spends the same recipe over the forecast heats the bright Monday on 865 m^3 of gas instead of 1040 m^3, 17 % less, for a mean of 18.91 °C. The thermal screen that saves 622 of the 1188 m^3 a night would otherwise burn keeps the house above 85 % relative humidity for all twelve hours of that night, and opening every vent at noon cools the house by 3.2 K, dries it by 17 points of humidity and takes 85 ppm of carbon dioxide (CO_2) out within 15 min. Each handle on the climate moves all three of its variables.

The class of problem reaches well beyond glass. A product that responds to the integral of a variable, under hard limits on that variable and on others that share its actuators, is planned over a prediction and re-planned as measurements arrive, which is the receding-horizon structure of model predictive control, already surveyed in theory and in industrial practice by 1989 [2]. Horticulture made the structure explicit as a hierarchy in which an upper layer manages the crop and a lower one the climate, with predictions of the weather and of the auction price among its inputs [3], and a receding-horizon controller of a solar greenhouse was designed to keep temperature and humidity

within limits while satisfying a temperature integral [4]. A building held inside a comfort band, as in Volume 9, Chapter 9, or a store charged against a tariff has the same shape, an amount that can be moved between hours bound to a limit that cannot, and a transfer function from boiler to air contains neither.

> **+ DID YOU KNOW? A Target of 65 Percent**
>
> Under agreements between the Dutch grower association and the government, glasshouse horticulture aimed to cut its energy efficiency index by 65 % between 1980 and 2010. Climate regimes such as temperature integration were designed to reach savings with the equipment growers already had [5].

However, optimal control of a greenhouse needs a quantitative model of how its crop production responds to the controls and the weather [3], while the climate computers growers buy come with hundreds of settings and courses on how to adjust them but no account of when or why [6], so there is no open plant on which the budget, the limit and the forecast can be set against one another while the gas meter keeps count. This chapter supplies one. It balances temperature integration against a humidity limit and counts the cost, on a browser glasshouse whose ledgers of energy, water, CO_2 and assimilates close to round-off and whose planner sees only the forecast and what the climate computer has measured. The climate and crop model reduces the Vanthoor models [7, 8], the vent law follows de Jong [9], the stomatal resistance follows Stanghellini [10], and temperature integration is established practice. The chapter gives a 41-state model in enough detail to rebuild, a climate computer that reads only its instruments, and a planner written as a linear program of 165 to 286 variables whose cost curves come from a quasi-steady model of each hour. Its results are comparisons on one plant. Among them, the planner lowers the cost of the graded week by \$656 to \$725 against fixed setpoints under the same humidity override at every limit from 78 to 90 %, each point of limit costs between \$76 and \$113, and in that week the CO_2 cap the challenge suggests changes nothing once the planner and the override run.

Section 13.2 follows the domain from hand-set vents to a planned daily mean. Section 13.3 gives the model of the house, the crop, the supply and the instruments, with the time scales its equations imply. Section 13.4 describes the climate computer: the pipe cascade with external reset, the vents under a three-stage humidity override, the screen, the CO_2 loop and the fog. Section 13.5 sets out the planner's linear program, Section 13.6 reports the nine cases and the graded week, and Sections 13.8 and 13.9 state the limitations and the conclusions, after Section 13.7 names the devices and the controller platform of a real glasshouse. The exercises of Section 13.10 run the cases in the app.

13.2 From Hand-Set Vents to a Planned Daily Mean

Control of the glasshouse climate began as the grower's own work. A review of heating and ventilation control in 1968 found many English growers still without automatically fired boilers or controlled heating, judged automatic ventilation hard to justify on the labor it saved, and reported that the automatic systems of the day held the dry-bulb temperature reasonably precisely while the grower still chose the temperature level from the weather and the state of the plants and corrected what those systems did to the humidity [11]. The same review found each factor of the climate controlled in isolation, because growers added equipment piecemeal as plant research advanced and capital allowed. Heat loss then became a subject of its own. A symposium on energy saving in greenhouses heard in 1977 that thermal screens drawn over the crop at night cut the thermal transmittance of glasshouse compartments by 28 to 43 % at zero wind speed, depending on the film, the largest saving coming from an aluminized polyester not yet durable enough for commercial use [12]. The first climate computers reached growers in the same decade, as the segment below tells.

> ⧖ HISTORY **A Computer at the Growers' Fair (1974)**
>
> A computer was first shown to Dutch growers as the heart of a greenhouse climate control system at the annual horticultural fair of 1974 in Bleiswijk. Research at that moment was still aimed mostly at analog control, and seventeen electronic firms were selling analog controllers to growers. The first systems sold so well that competitors at the fair started at once to develop digital climate computers of their own. Within two years systems from five producers were on sale, and by the 1980 report eleven firms, nine of them Dutch, competed for the market [13].

Research took a system view. A paper of 1978 described greenhouse culture as three levels, the instantaneous climate, short-term plant growth and long-term crop development, each controlled through relatively simple models, with the computer essential at the first level and the third, where predictions of cost and return seemed attractive, left to the grower's final decision [14]. Theses at the agricultural university in Wageningen then supplied the physics, among them the ventilation of large multi-span houses through windows on the lee and windward sides, driven by the wind and by the temperature difference and measured at full scale [9], and a model of the transpiration of a tomato crop offered as the quantitative basis for controlling the air's humidity [10]. A thesis of 1994 on CO_2 measured in greenhouse fruit vegetable crops that each additional 100 µmol/mol raised the light-use efficiency by about 10 to 15 %, and that intermittent supply raised the average concentration only a little under normal ventilation [15], which is the coupling between the vents and the dosing line.

Temperature integration grew from the energy question, as the segment below tells.

> ⧖ HISTORY **Temperature Integration (1988 to 2003)**
>
> Experiments had shown that the development and yield of a glasshouse tomato depend mainly on the 24-hour average temperature. A control program of 1988 let the air range between 14 and 26 °C, not limited to a 24-hour period, and December-sown tomatoes grew no differently from a fixed regime with the same mean [1]. A thesis of 2003 nested the integration in windows of 24 hours and six days, predicted up to 9 % less energy than regular integration for a year-round tomato crop, and found the potential limited by humidity control on fixed setpoints. A humidity regime built on the processes of cut chrysanthemum saved 18 % of the energy of a fixed 80 % setpoint in simulation, the two combined more than 33 %, and the only addition was a computer acting as a setpoint generator above the existing climate computer [5].

Model-based optimal control of the crop took the same path. A thesis of 1994 found the optimal management systems of the literature presented as two-layer hierarchies and set out to include humidity explicitly and to cope with errors in the model and in the predictions of weather and price [3]. A receding-horizon optimal controller meant to hold a solar greenhouse within temperature and humidity limits and a temperature integral used 77 % less gas, in simulations of a simplified version, than a conventional greenhouse under optimal control [4], and a monograph collected the methods of the optimal control of greenhouse cultivation [6]. Energy balances of a reference tomato house in the Netherlands put the savings of a higher humidity setpoint, a stepwise screen gap and temperature integration at about 5 % each, against 23 % for a better-insulated cover [16]. The humidity limit and the temperature budget stayed in tension throughout, and the simulator of this chapter puts a price on that tension. Staffing is a further pressure. The greenhouse industry finds it hard to staff the management of its crops, and in an international competition five teams grew cucumbers remotely on setpoints chosen by their own artificial intelligence, one of them outperforming the manually grown reference [17].

13.3 One Hectare Under Glass

The simulated house is one hectare of Venlo glasshouse growing tomatoes at a leaf area index of 3, modeled per square meter of floor as a single well-mixed air node of mean height $h = 5\,\mathrm{m}$ under a single-glass cover, as shown in Figure 13.1. A boiler of 150 $\mathrm{W/m^2}$ heats water in pipes along the crop

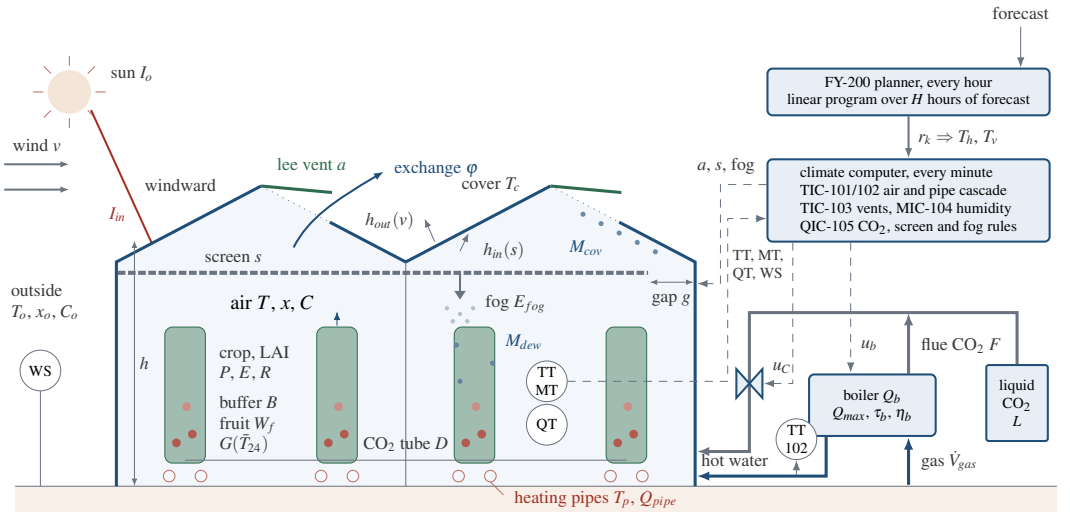


Figure 13.1 The simulated glasshouse in cross-section, two of its Venlo spans with the wind v from the left, beside the plant room and the climate computer. The air node at T, x and C, of mean height h, exchanges φ with the outside air at T_o, x_o and C_o through the vents of aperture a (lee side first) and the leaks, and loses heat through the cover at T_c by $h_{in}(s)$ inside and $h_{out}(v)$ outside, where water condenses as M_{cov}. The screen closes to s at the gutter with a humidity gap g. Sunlight I_o enters as I_{in}, the crop transpires E, photosynthesizes P, respires R, fills the buffer B and grows fruit W_f at a rate $G(\bar{T}_{24})$ set by its trailing daily mean, and dew M_{dew} settles on it when the air saturates. The boiler fires at u_b to deliver Q_b into pipes at T_p that give Q_{pipe} to the air, and the dosing valve u_C draws the dose D from the flue gas F first and the liquid store L for the rest. The climate computer reads the measuring box (TT, MT), the CO_2 analyzer (QT), the pipe sensor (TT-102) and the weather station (WS), and the planner above it writes the hourly temperatures r_k. Not to scale.

rows, roof vents open on the lee side first and then on the windward side, a thermal screen draws across at the gutter, a dosing line of 130 kg/(ha h) brings CO_2 from the boiler's flue gas and from a liquid store, and high-pressure fog evaporates up to 150 g/(m^2 h). The ten physical states are the air, cover and pipe temperatures T, T_c and T_p, the boiler's heat Q_b, the vapor concentration x, the CO_2 concentration C, the screen closure s, the vent aperture a, the assimilate buffer B and the fruit dry matter grown W_f. Thirty-one more states integrate every flux into a ledger, so the energy, vapor, CO_2 and assimilate balances and the costs are exact integrals of the model. Table 13.1 gives each signal's role and its value at a settled start.

13.3.1 Heat in the Air, the Cover and the Pipes

The air node gains the heat of the pipes, the sun it absorbs and the latent heat of any dew, and loses heat to the cover, to the exchange and to the water the crop and the fog evaporate, as shown in Equation (13.1).

$$C_{air}\frac{\mathrm{d}T}{\mathrm{d}t} = Q_{pipe} + \alpha_s I_{in} + \lambda M_{dew} - h_{in}(s)\,(T - T_c) - \rho c_p\,\varphi\,(T - T_o) - \lambda\,(E + E_{fog}) \quad (13.1)$$

where every flux is per square meter of floor, t is in seconds (the application integrates in hours and applies the factor of 3600 in one place), C_{air} lumps the air, the crop and the light structure, α_s is the share of the transmitted sun the house absorbs, λ the latent heat of water and ρc_p the volumetric

Table 13.1 Role and Starting Value of Each Signal, From the Settled Start of Case 2

Signal	Role	Start	Range
T	state, CV, TT-101	17.00 °C	band 16–26
T_c	state, cover	9.97 °C	—
T_p, Q_b	states, CV of TIC-102	42.8 °C, 50.0 W/m^2	15–90, 0–150
x	state, MT-101 reads RH	82.5 % RH	limit 85, 90
C	state, CV, QT-101	978 ppm	SP to 800
s, a	states, drives	98.9 %, 0	0–100 %
B, W_f	states, crop	4 g/m^2, 0	—
—	31 ledger states	0	—
$T_{p,SP}$	MV of TIC-101	—	15–90 °C
u_b	MV of TIC-102, firing	—	0–100 %
a_T, a_H	MVs of TIC-103, MIC-104	—	0–100, 0–50
s_{cmd}, fog	MVs of the rules	—	0–100, on/off
u_C	MV of QIC-105, dosing	—	to the supply
T_h, T_v	heating, vent setpoints	17.0, 19.0	—
r_k	planner's hourly temperature	—	16–26
T_o, I_o, v	DVs, weather station	6.11 °C, 0, 2.48 m/s	a week
—	DVs, offsets	0	±10 K, 0–150 %
—	DVs, events	—	7 kinds
p_{gas}, p_C	DVs, prices	0.40 $/m^3, 0.15 $/kg	—

heat capacity of air. The cover warms from the air inside, from the water condensing on it and from the share α_c of the sun it absorbs, and it loses to the outside by wind and radiation lumped in one coefficient, as shown in Equation (13.2).

$$C_{cov}\frac{\mathrm{d}T_c}{\mathrm{d}t} = h_{in}(s)(T - T_c) + \lambda M_{cov} + \alpha_c I_o - h_{out}(v)(T_c - T_o) \tag{13.2}$$

where $h_{out} = 7 + 2v$ in W/(m^2 K) with the wind v in m/s. The screen is a resistance R_s in the inside path, and a gap costs more than its area because warm air escapes through it, as shown in Equation (13.3).

$$\begin{aligned} h_{in}(s) &= \left[\frac{1}{h_{in,0}} + \left(1 - (1-s)^{0.7}\right)R_s\right]^{-1} \\ h_{in,0} &= \left[\frac{1}{U_{open}} - \frac{1}{h_{out}(4)}\right]^{-1}, \qquad R_s = \frac{1}{U_{scr}} - \frac{1}{U_{open}} \end{aligned} \tag{13.3}$$

so the declared cover coefficients of 7.5 with the screen open and 4.0 W/(m^2 K) under it at a 4 m/s wind give $h_{in,0} = 15\,\mathrm{W/(m^2\,K)}$ and $R_s = 0.117\,\mathrm{m^2\,K/W}$, and a 10 % gap keeps 80 % of the screen's insulation. The sun reaching the crop is $I_{in} = \tau_c\,(1 - s\,(1 - \tau_s))\,I_o$. The boiler delivers its firing behind a lag, and the pipes give heat to the air by natural convection and radiation lumped together in Equation (13.4).

$$\begin{aligned} \tau_b\frac{\mathrm{d}Q_b}{\mathrm{d}t} &= u_b\,Q_{max} - Q_b, \qquad C_{pipe}\frac{\mathrm{d}T_p}{\mathrm{d}t} = Q_b - Q_{pipe} \\ Q_{pipe} &= k_p\,|T_p - T|^{1.25}\,\mathrm{sgn}(T_p - T), \qquad \dot{V}_{gas} = \frac{Q_b}{\eta_b\,\mathrm{LHV}} \end{aligned} \tag{13.4}$$

where $u_b \in [0, 1]$ is the firing command, which a boiler outage overrides with zero heat whatever TIC-102 asks, and k_p is set so that pipes at 80 °C give 150 W/m^2 to air at 18 °C. Burning the gas makes 1.78 kg of CO_2 per cubic meter, so a firing boiler offers its flue gas to the dosing line at $f_g Q_b$ with f_g equivalent to 2.20 kg/(ha h) per 1 W/m^2, up to $F_{max} = 50\,\mathrm{kg/(ha\,h)}$, which it reaches at 22.7 W/m^2. A boiler at full fire makes 330 kg/(ha h), and at night, when nothing is dosed, all of it goes up the stack.

13.3.2 Water, Carbon Dioxide and the Exchange

The exchange φ, in cubic meters of air per square meter of floor per second, enters the vapor and the CO_2 balance alike in Equation (13.5).

$$\begin{aligned} h\frac{\mathrm{d}x}{\mathrm{d}t} &= 10^3\,(E + E_{fog} - M_{cov} - M_{dew}) - \varphi\,(x - x_o) \\ h\,\kappa\frac{\mathrm{d}C}{\mathrm{d}t} &= D - \mu_C P + R - \varphi\,\kappa\,(C - C_o) \end{aligned} \tag{13.5}$$

where x is in g/m^3, the water fluxes in kg/(m^2 s), C in ppm with $\kappa = 1.829\,\mathrm{mg/m^3}$ per ppm, D the dose and R the crop's respiration in mg/(m^2 s), and $\mu_C P$ the CO_2 taken up by a gross photosynthesis P in µmol/(m^2 s), with $\mu_C = 44.01 \times 10^{-3}$ mg/µmol. Condensation on the cover and dew on the crop follow Equation (13.6).

$$\begin{aligned} M_{cov} &= 6.4 \times 10^{-9} \cdot 4 \cdot \pi(s)\left(e(x,T) - e_s(T_c)\right)^+ \\ M_{dew} &= \frac{h}{1.2 \times 10^5}\left(x - x_s(T)\right)^+ \end{aligned} \tag{13.6}$$

in which the vapor pressure e and the saturation pressure e_s come from Tetens' formula in Pa, the coefficient of four is a heat exchange coefficient in W/(m^2 K) in the form the application takes from the Vanthoor model [7], x_s the saturation concentration and $(\cdot)^+ = \max(0,\cdot)$. Dew is a numerical stand-in that removes any supersaturation within about two minutes. The exchange is the vents' law, reduced from the measurements of Venlo windows [9], plus the leaks, both scaled by what the screen lets through, as shown in Equation (13.7).

$$\begin{aligned} \varphi &= \varphi_v + \varphi_l \\ \varphi_v &= \frac{\pi(s)\,\varphi_{max}}{3600}\left(0.4 f(a_l) + 0.6 f(a_w)\right) \\ &\quad \times \frac{1}{4}\sqrt{v^2 + 0.5\,(T - T_o)^+} \\ \varphi_l &= \pi(s)\,\frac{n_l h}{3600}\,\frac{v + 0.5}{4.5} \\ f(a) &= \frac{1 - \mathrm{e}^{-3a}}{1 - \mathrm{e}^{-3}} \\ a_l &= \min(1, 2a), \qquad a_w = (2a - 1)^+ \\ \pi(s) &= p_s + (1 - p_s)(1 - s)^{0.4} \end{aligned} \tag{13.7}$$

where the lee window opens over the first half of the aperture and the windward one over the second, $\varphi_{max} = 60\,\mathrm{m^3/(m^2\,h)}$ is the exchange at full aperture in a 4 m/s wind, 24 m^3/(m^2 h) of it through the lee windows alone, the buoyancy term carries a calm day, $n_l = 0.5$ air changes an hour is the leakage at 4 m/s, and a closed screen passes $p_s = 15\,\%$ of the exchange. A 10 % gap passes 49 %.

13.3.3 The Crop

Equation (13.8) gives the transpiration, the Penman–Monteith combination with the canopy at the air temperature and Stanghellini's stomatal resistance [10].

$$\begin{aligned} \lambda E &= \frac{\Delta R_n + \rho c_p\left(e_s(T) - e\right)/r_a}{\Delta + \gamma(1 + r_s/r_a)}, \qquad r_a = \frac{r_b}{2\,\mathrm{LAI}} \\ r_s &= \frac{r_{min}}{\mathrm{LAI}}\,\frac{I_l + 4.3}{I_l + 0.54}\left(1 + 2\,\mathrm{e}^{-I_l/2}\right) f_C(C) \end{aligned} \tag{13.8}$$

with Δ the slope of the saturation curve, $\gamma = 66.5\,\mathrm{Pa/K}$, $S_c = 0.85\,(1 - \mathrm{e}^{-0.7\,\mathrm{LAI}})\,I_{in}$ is the sunlight the canopy absorbs, $R_n = S_c + f_p Q^{+}_{pipe}$ adds the pipes' radiation, $I_l = S_c/\mathrm{LAI}$, the stomata close three times further in the dark, and $f_C = 1 + 6.08 \times 10^{-7}(\tilde{C} - 200)^2$ while S_c exceeds $5\,\mathrm{W/m^2}$, with $\tilde{C}$ the CO_2 clipped to 200 to 1100 ppm, and $f_C = 1$ otherwise. Gross photosynthesis is a big-leaf light response whose ceiling saturates in CO_2 and whose slope falls toward the compensation point, as shown in Equation (13.9).

$$\begin{aligned} P &= \sigma(B)\,P_c\Big[1 - \exp\Big(-\frac{\varepsilon\,\Phi}{P_c}\Big)\Big] \\ P_c &= P_m f_T(T)\,\frac{C^*}{C^* + K_C}, \qquad \varepsilon = \varepsilon_0\,\frac{C^* - \Gamma}{C^* + 2\Gamma} \\ C^* &= \max(C, \Gamma), \qquad \Gamma = 2T + 5 \\ \Phi &= 2.3 \cdot 0.93\,(1 - \mathrm{e}^{-0.7\,\mathrm{LAI}})\,I_{in} \end{aligned} \tag{13.9}$$

where the absorbed photosynthetically active radiation Φ is in $\mu\mathrm{mol/(m^2\,s)}$, $f_T(T) = \mathrm{clip}\big((T - 6)/10\big)\,\mathrm{clip}\big((38 - T)/8\big)$ with clip limiting to $[0, 1]$, and $\sigma(B) = 1 - \mathrm{clip}\big((B - 20)/10\big)$ stops the uptake as a full buffer runs out of sinks. At $500\,\mathrm{W/m^2}$ outside and 21 °C the canopy photosynthesizes 23.6 % faster at 800 ppm than at the outdoor 420 ppm. The assimilates fill the buffer, and growth draws on it at a rate set by the trailing 24-hour mean $\bar{T}_{24}$, as shown in Equation (13.10).

$$\begin{aligned} \frac{\mathrm{d}B}{\mathrm{d}t} &= m_H P - R_m - G, \qquad \frac{\mathrm{d}W_f}{\mathrm{d}t} = f_f\,\eta\,G \\ R_m &= \frac{r_m W_c}{86400}\,2^{(T-25)/10}\,\frac{B}{B + 0.2} \\ G &= \frac{g_{19}}{86400}\,\mathrm{clip}_{16/9}\Big(\frac{\bar{T}_{24} - 10}{9}\Big)\,\frac{B}{B + 2} \\ &\quad \times \mathrm{clip}\Big(\frac{T - 8}{4}\Big)\,\mathrm{clip}\Big(\frac{36 - T}{4}\Big) \end{aligned} \tag{13.10}$$

where B is in $\mathrm{g/m^2}$ of assimilates, $m_H = 30.03 \times 10^{-6}\,\mathrm{g/\mu mol}$, $\mathrm{clip}_{16/9}$ limits to $[0, 16/9]$, and the respiration in Equation (13.5) is $R = (R_m + (1 - \eta)G)\,\mu_C/m_H$ in $\mathrm{mg/(m^2\,s)}$, maintenance plus the share of growth not converted to dry matter. The demand is $18\,\mathrm{g/(m^2\,d)}$ at a mean of 19 °C, 12 at 16 and 24 at 22, so the crop answers the mean, not the hour. The mean $\bar{T}_{24}$ is the average of the last 288 five-minute means of the true air temperature.

🕮 **Pause.** Try Exercise 13.1 before reading on.

13.3.4 Supply, Costs, Weather and Instruments

The dosing line takes flue gas first and buys liquid CO_2 for the rest, $D = \min(u_C D_{max}, F + L)$ with $F = \min(F_{max}, f_g Q_b)$ while the boiler fires and $L = D_{max}$ when liquid is allowed, of which $\min(D, F)$ is free. The cost integrates $p_{gas}\dot{V}_{gas}$, p_C times the liquid dosed, and electricity at 0.15 $/kWh for $0.5\,\mathrm{W/m^2}$ of base load, $0.6\,\mathrm{W/m^2}$ of pumps once the boiler delivers $20\,\mathrm{W/m^2}$, $1.5\,\mathrm{W/m^2}$ while the fog runs and $0.2\,\mathrm{W/m^2}$ for the dosing fan at full rate.

The weather is a synthetic spring week at 52° N in mid-April. Each day of a table of nine sets a dawn minimum and an afternoon maximum joined by half-cosines at 05:00 and 15:00, a mean sky transmissivity with seeded smooth variation, a wind and a dew point below the dawn minimum, and the sun is clear-sky radiation from the solar elevation scaled by the transmissivity, near $700\,\mathrm{W/m^2}$ at a clear noon. A front blends one day's air mass into the next over about an hour and a half with a band of rain. The forecast issued at hour t_0 for hour t is the truth plus an error of seeded smooth noise in t whose size grows as $\min(t - t_0, 48)/24$ times 1.2 K, 0.18 of transmissivity and 1.2 m/s at the declared size, so successive forecasts of one hour converge as it nears. A missed front is a forecast that places it

Table 13.2 Model Constants by Group, Marked V When the Show Model Dialog Offers a Slider, H When Hidden From It and C When Written Into the Code

Symbol	Meaning	Value	Class
House			
h	mean air height	5.0 m	H
C_{air}, C_{cov}	air with crop and structure, cover	30, 10 kJ/(m^2 K)	V, H
U_{open}, U_{scr}	cover, screen open and closed	7.5, 4.0 W/(m^2 K)	V
τ_c, τ_s	light transmission, cover and screen	0.78, 0.80	V
p_s	exchange a closed screen passes	0.15	V
α_s, α_c	sun absorbed in the house, cover	0.90, 0.05	H
n_l, φ_{max}	leakage, vents at full	0.5 h^{-1}, 60 m^3/(m^2 h)	V
—	vent and screen drive lags	2, 3 min	H
Heating and CO_2			
Q_{max}, η_b, τ_b	boiler capacity, efficiency, lag	150 W/m^2, 0.92, 5 min	V, V, H
C_{pipe}, k_p	pipe water and steel, transfer	12, 0.862	V, H
$T_{p,max}$, f_p	highest pipe, pipe radiation share	90 °C, 0.2	V, H
LHV	natural gas, lower heating value	31.65 MJ/m^3	C
D_{max}, F_{max}	line capacity, flue share	130, 50 kg/(ha h)	V
C_o	outdoor CO_2	420 ppm	V
Crop			
LAI	leaf area index	3	V
P_m, K_C	photosynthesis ceiling, half point	55 µmol/(m^2 s), 400 ppm	V
ε_0	light-use efficiency	0.08 mol/mol	V
r_m, W_c	maintenance at 25 °C, standing crop	0.01 d^{-1}, 800 g/m^2	V, H
g_{19}	growth demand at 19 °C	18 g/(m^2 d)	V
f_f, η	fruit share, conversion	0.6, 0.7	H
r_{min}, r_b	stomatal, boundary-layer resistances	82, 275 s/m	H
Fog, prices and constants			
—	fog capacity	150 g/(m^2 h)	V
p_{gas}, p_C	gas, liquid CO_2	0.40 $/m^3, 0.15 $/kg	control
ρc_p, λ, γ	air, latent heat, psychrometer	1206, 2.45 MJ/kg, 66.5	C

k_p in W/(m^2 K$^{1.25}$), C_{pipe} in kJ/(m^2 K), ρc_p in J/(m^3 K), γ in Pa/K.

Δ hours late until it is three hours away and blends toward the truth from six hours away. The climate computer reads the air temperature and humidity in an aspirated box behind a 1 min first-order lag with 0.05 K and 0.5 points of noise, the CO_2 behind the 2 min lag of its sample line with 5 ppm of noise, the pipe water with 0.1 K, the weather station with 0.1 K, 2 % of radiation, 0.2 m/s and one point of humidity, and the drives' own positions and the boiler's meter without error, the noise given as standard deviations and drawn, like the weather's, from a generator seeded at 20261009.

13.3.5 Starting State and Numerics

Every case starts at midnight with the air at its night setpoint and a trailing mean of 19 °C, and the rest of the house is solved at rest for the weather of that instant. The cover, the vapor, the CO_2 and the pipe temperature that hold the air still are found by a Gauss–Seidel sweep with a bisection for the vapor, the screen is set by its rules, and where the screen is closed and the override is on, its humidity gap is placed at the fixed point of its proportional rule. Case 2 starts this way at 17.00 °C and 82.5 % with the screen 98.9 % closed, a gap of 1.06 %, 978 ppm of CO_2 gathered from the night's respiration and the boiler at 50.0 W/m^2. A fixed 30 s step of the fourth-order Runge–Kutta method advances the 41 states, the climate computer runs every minute, the planner every simulated hour, and the historian logs a row every 5 min, 2017 rows for a week, on the engine of Section 1.6.1. A week runs in 28 s at the top speed. Halving the step changes the cost of the graded week with the suggested settings by 0.0003 %, its gas by 0.0007 % and no day's mean by more than 0.000 03 K, and over that week the seven balances close to 3.6×10^{-14} of their throughput, 1.3×10^{-14} as shipped. The application passes its 35 verification checks.

13.3.6 What the Equations Imply

The exchange sets the clock of the house. At a 4 m/s wind and a 5 K difference, h/φ is 120 min with the vents shut, 10.6 min with the lee windows open and 4.5 min with every window open, while under a closed screen the shut house exchanges its air once in 800 min. Water and CO_2 follow that clock, which is why a closed screen traps the crop's night transpiration and a wide roof empties the CO_2 in minutes. The air node against the cover and the exchange answers in 60 min shut, 121 min screened and 17 min with the vents full, the cover in 5.6 min, and the pipes, whose transfer coefficient is $\mathrm{d}Q_{pipe}/\mathrm{d}T_p = 2.3$ to 3.0 W/(m^2 K) at 20 to 60 K above the air, in 88 to 67 min, so heat bought now keeps arriving for an hour after the boiler stops. The crop answers a day.

13.3.7 Assumptions

One air node. The house has no vertical gradients, no separate canopy, soil or structure temperature and no cold air falling through a screen gap, and the space above the screen is lumped with the cover. The lumped capacity makes the house answer a little faster and more evenly than a real one.

A reduced crop. The crop is one big leaf at a fixed leaf area index, after the Vanthoor tomato model [8] reduced to a buffer and a growth rate on the daily mean. Fruit set, truss development, leaf picking, quality and the crop's tolerance of several days off its mean are absent, and the integration window is the calendar day.

Reduced vents, screen and cover. One law serves the lee windows and one the windward, the screen's exchange and gap are concave fits rather than a buoyant flow through the gap, and the cover loses heat to the outdoor air temperature, so a clear night's colder sky is absent.

A synthetic week and a declared forecast. The weather is generated, fronts are blends between air masses and the forecast error is declared, not learned, and a real forecast fails in more ways than a front placed late.

An idealized climate computer. Sensors are aspirated and seeded, actuators do what they are told within their drive times, and the boiler fails only when the outage is fired. Every limit, price and coefficient is a teaching value, not a calibration of any house.

13.4 The Climate Computer as Implemented

The climate computer executes every minute from its instruments alone, in the order of the instruments, the temperature strategy, the heating cascade, the vents with the humidity override, the screen, the CO_2 loop and the fog. Five loops run the framework's velocity-form proportional-integral-derivative (PID) law of Equation (13.11), none with derivative action and TIC-101 with its integral replaced by the external reset of Section 13.4.1.

$$\begin{aligned} e_k &= \gamma_a\,(\mathrm{SP}_k - \mathrm{PV}_k), \qquad P_k = K_c\,e_k \\ S_k &= S_{k-1} + (P_k - P_{k-1}), \qquad v_k = u_0 + S_k + I_{k-1} \\ u_k &= \mathrm{clamp}(v_k, u_{min}, u_{max}) \\ I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I}\,e_k + \frac{u_k - v_k}{\tau_I}\right]\Delta t_c \end{aligned} \tag{13.11}$$

which is the law of Section 1.6.2 with no derivative term, written with γ_a for the action a, $u_0 = 0$ for the bias u_b, $\Delta t_c = 1$ min for the control period and the integral time as the tracking constant. The limit acts on the output alone and the anti-windup on the integral alone, and a return from MANUAL to AUTO causes no jump. The loops and their tunings are listed in Table 13.3, where $\gamma_a = +1$ is reverse acting and -1 direct acting, the convention of Section 1.3. The vent loops are direct acting because an open vent lowers both the air temperature and the humidity.

13.4.1 Temperature Strategy and the Heating Cascade

On fixed setpoints the heating setpoint is $T_h = T_{night} + (T_{day} - T_{night})\,\mathrm{clip}(\theta - 6)\,\big(1 - \mathrm{clip}(\theta - 19)\big)$ at clock hour θ, ramped over an hour at 06:00 and 19:00, and the vents work at $T_v = T_h + \Delta T_v$ with

Table 13.3 The Loops as Executed, Each on the Law of Equation (13.11) With No Derivative and a 1 min Period

Loop	CV → MV	K_c	τ_I	Limits	γ_a
TIC-101	$T \to T_{p,SP}$	8	60 min	15–90 °C	+1
TIC-102	$T_p \to u_b$	8	15 min	0–100 %	+1
TIC-103	$T \to a_T$	15	15 min	0–100 %	−1
MIC-104	RH → a_H	4	20 min	0–50 %	−1
QIC-105	$C \to u_C$	0.3	10 min	0–supply	+1

K_c in K/K, %/K, %/K, % per point and %/ppm. TIC-101 uses external reset.

$\Delta T_v = 2\,\mathrm{K}$, so between the two the house floats on the sun. With the planner on, the setpoints come from Section 13.5. The air loop TIC-101 does not fire the boiler. It asks the pipe loop TIC-102 for a water temperature, and its reset is a lag of the pipe temperature the slave achieves rather than of its own output, the external reset feedback of Equation (13.12).

$$\begin{aligned} I_k &= I_{k-1} + \frac{\Delta t_c}{\tau_{I,T}}\left(\tilde{T}_{p,k} - I_{k-1}\right) \\ T_{p,SP,k} &= \mathrm{clamp}\left(K_{c,T}\left(T_{h,k} - \hat{T}_k\right) + I_k,\ 15,\ 90\right) \end{aligned} \tag{13.12}$$

where $\hat{T}$ is the measuring box and $\tilde{T}_p$ the measured pipe temperature clipped to 15 to 90 °C. While the pipes follow, the loop is an ordinary PI controller. While the boiler is at its limit, out, or slower than asked, the reset follows the pipes there are, so the master cannot wind up while the water takes an hour to heat. Volume 3, Chapter 4 uses the same external reset feedback behind a high select. With the slave in MANUAL the master tracks the measured pipe temperature, so the cascade closes without a bump.

🕮 **Pause.** Try Exercise 13.3 before reading on.

13.4.2 Vents, the Humidity Override and the Screen

TIC-103 opens the vents as the measured air rises above T_v, and MIC-104 opens the lee windows, up to half the aperture, as the measured humidity rises above a limit RH_{sp} that is $\mathrm{RH}_{lim} = 85\,\%$ in the dark and rises linearly to $\mathrm{RH}_{day} = 90\,\%$ as the measured radiation outside goes from 50 to 150 W/m^2. A high select drives the vents with $a = \max(a_T, a_H)$, and the loop not selected has its integral set so that its output is the command plus its own proportional term, $I_T = a$ while MIC-104 is selected and $I_H = \min(a, 50)$ otherwise, so either can take over without a bump. The override has three stages. While the screen is closed, a gap opens in it in proportion to the humidity from three points below the limit, $g = \mathrm{clamp}\left(K_g(\widehat{\mathrm{RH}} - \mathrm{RH}_{lim} + 3),\ 0,\ g_{max}\right)$ with $K_g = 2$ and $g_{max} = 10\,\%$. The lee vent is the second stage, and the third is heat, as shown in Equation (13.13).

$$\begin{aligned} \Delta T_{h,k} = \mathrm{clamp}\Big(&\Delta T_{h,k-1} + 2\Delta t_c\big[\sigma_H\,\mathrm{clip}(\widehat{\mathrm{RH}} - \mathrm{RH}_{sp}) \\ &- \mathrm{clip}(\mathrm{RH}_{sp} - 1 - \widehat{\mathrm{RH}})\big],\ 0,\ 5\Big) \end{aligned} \tag{13.13}$$

where Δt_c is in hours here, $\sigma_H = \mathrm{clip}\left((a_H - 45)/5\right)$ engages the stage as the lee vent nears its half-open limit, and ΔT_h raises both T_h and T_v by up to 5 K at up to 2 K/h, letting the humidity outrank the recipe. With the override off, or the heating or the vents in MANUAL, the term falls at 2 K/h. The screen closes when the radiation outside is under $I_{scr} = 10\,\mathrm{W/m^2}$ and the air outside under $T_{scr} = 14\,^\circ\mathrm{C}$, opens when the radiation passes $5I_{scr}$ or the air outside passes $T_{scr} + 2\,\mathrm{K}$, moves at most once in 20 min, opens in proportion to the light from 5 to 15 times I_{scr} while it is cold outside, and never opens faster than over half an hour.

13.4.3 Carbon Dioxide and Fog

QIC-105 doses toward a setpoint C_{sp} that rises with the measured radiation from the outdoor 420 ppm above 20 W/m^2 to $C_{SP} = 800$ ppm at 200 W/m^2, and it doses nothing below 20 W/m^2. With the cap on and the vents open past $a_{cap} = 50\,\%$, the setpoint falls toward 50 ppm above outdoors over the next 30 points of aperture, $C_{sp} \leftarrow C_{sp} - (C_{sp} - \min(C_{sp}, C_o + 50))\,\mathrm{clip}((a - a_{cap})/0.3)$. The output is limited to what the line can deliver at that moment, flue gas while the boiler fires and liquid when it is allowed. The fog runs while the measured air is 2 K above T_v with the vents past 90 % and the humidity under 80 %, stops 1 K lower or three points wetter, and switches at most once in 5 min.

13.5 The Planner: A Receding-Horizon Linear Program

Every simulated hour, and whenever a price, the recipe or a limit changes, the planner FY-200 chooses one planned temperature r_k for each of the next $H = 24$ hours of a fresh forecast, uses only the first, and solves again an hour later from the hours already measured. Its house model is quasi-steady for each hour of the forecast, as shown in Equation (13.14).

$$\begin{aligned} q(r) &= \big(U(s,v) + \rho c_p \varphi_l\big)(r - T_o) + \lambda E - \alpha_s I_{in} \\ Q &= q(r) + \rho c_p\,(\varphi_H - \varphi_l)^+ (r - T_o)^+ \quad \text{if } q \geq 0 \\ \varphi_V &= -q(r)/\big(\rho c_p\,(r - T_o)\big) \quad \text{if } q < 0 \\ c_k(r) &= 3.6 \times 10^7 \Big[p_{gas} \frac{Q}{\eta_b\,\mathrm{LHV}} + 10^{-6}\, p_C\,(D_k - F)^+ \Big] \\ D_k &= \min\big(D_{max},\ \mu_C P + (\varphi_l + \varphi_V)\,\kappa\,(C_{sp} - C_o)^+\big) \end{aligned} \tag{13.14}$$

where the screen s is the one the rules would set for the hour, $U(s,v) = [1/h_{in}(s) + 1/h_{out}(v)]^{-1}$ the cover's overall coefficient, φ_l the leakage, E the transpiration at the humidity limit, φ_H the exchange the limit would need to remove the crop's water, capped at what the gap and the lee windows can pass, φ_V the venting that throws away the sun's surplus, D_{max} the line's 130 kg/(ha h), and F the flue gas a firing boiler makes, all per square meter and second, so that the factor of 3.6×10^7 gives dollars per hour for the hectare when D_k and F are in mg/(m^2 s). Each curve is sampled every 0.5 K between the lowest temperature full vents can reach and the band's top, 26 °C in daylight and 20 °C in the dark, and replaced by its lower convex hull, so it becomes a sum of segments of rising slope. The program is Equation (13.15).

$$\begin{aligned} \min\ & \sum_j c_j \delta_j + 10^5 \sum_d (\sigma_d^+ + \sigma_d^-) \\ & + \sum_k \left[u_k^+ + u_k^- + 500\,(w_k^+ + w_k^-) + 0.05\,(z_k^+ + z_k^-) \right] \\ \text{s.t. } & r_k = L_k + \sum_{j \in k} \delta_j, \qquad 0 \leq \delta_j \leq \ell_j \\ & \textstyle\sum_{k \in d} \omega_k r_k + \sigma_d^+ - \sigma_d^- \in [N_d - 24\delta_T,\ N_d + 24\delta_T] \\ & r_k - r_{k-1} = (u_k^+ - u_k^-) + (w_k^+ - w_k^-) \\ & 0 \leq u_k^{\pm} \leq \rho_r \\ & r_k - \hat{r}_k = z_k^+ - z_k^- \end{aligned} \tag{13.15}$$

where segment j of hour k has width ℓ_j and slope c_j (weighted by $1 + 0.001k$ so that ties go to the nearer, surer hour), L_k is the hour's lowest reachable temperature, ω_k is one except for the part of the present hour already gone, N_d is the day's sum $24\bar{T}$ less the hours already measured, held loosely for a day the horizon only reaches part of, $\delta_T = 0.2$ K is the tolerance, $\rho_r = 3$ K/h the ramp with r_{-1} the present plan, and $\hat{r}_k$ the previous plan's value for the same hour. Every variable is nonnegative. Because the slopes rise, the cheap segments fill first and no integer variable is needed. A shortfall on a

Table 13.4 The Nine Cases and the Graded Week

#	What differs from the reference	What it shows
1	cap off, $\Delta T_v = 4$ K, every vent open 12:00 to 13:00	one exchange, three variables
2	none, Monday and Tuesday	a setpoint is not the recipe
3	override off, two nights	the screen traps the water
4	cap off, a bright Wednesday	dosing into open vents
5	planner on, case 2's days	temperature integration
6	planner on, a front 9 h early	the forecast and the band
7	planner on, a dark saturated day	no setting wins
8	planner on, gas $\times 3$ for a day	price against the mean
9	a heat wave, 12 K warmer	fog as the last handle
10	the week, 20/18 °C, override and cap off	graded challenge

day's mean is priced at \$100 000 per kelvin-hour, so it is reported rather than taken quietly, a change between hours costs \$1 per kelvin so nearly equal hours are planned level, and the hold term of \$0.05 per kelvin keeps a plan in force against a fourth-digit change of an input. The bounded-variable simplex of the framework's shared linear programming module solves it, and over the graded week with the suggested settings each of the 168 solves had 165 to 286 variables and 25 to 49 rows, ended optimal in 54 to 269 pivots and bound flips, and the application logs the count in place of a solve time, which varies from run to run. The plan becomes setpoints by its hour's free temperature T_f, where the sun alone holds the house, as heating to r venting at $r + \Delta T_v$ when $r \geq T_f + 0.3$, heating at $r - \Delta T_v$ and venting at r when $r \leq T_f - 0.3$, and the band split around r in between, and the climate computer moves to each hour's setpoints at the ramp rather than in one step.

The plant, the planner and the loops each have a model of their own. The plant's is Equations (13.1) to (13.10). The planner's internal model is Equation (13.14) on the forecast, which omits the dawn and dusk transients, the override's third stage and the fog, and prices the CO_2 that holds the setpoint by light up to the line's capacity but without the cap. Summed over the present hours it plans, it expects \$4498 of gas and CO_2 where the house buys \$5351, 16 % less, and \$1040 against \$1282 over case 5. The loops are tuned on no identified model, and the application identifies none.

13.6 Nine Cases and a Spring Week

Table 13.4 lists the cases. Each starts from a reference line with the fixed setpoints of Section 13.4, the humidity override on at 85 %, the cap on, both CO_2 sources and gas at 0.40 \$/m^3, and alters it as its row states. Headless engine runs at the default seed, with every changed setting made before Run as a learner makes it, supplied every number below, and Table 13.5 collects what each case scored. A day counts as dark below 50 W/m^2 outside and as bright above 14 MJ/m^2, and its bright hours are those above 400 W/m^2. One seed draws both the synthetic weather and the sensor noise, so a case replays the same weather in every run, and the spreads quoted over other seeds of the noise keep that weather fixed. A Reset restarts a case from midnight with the learner's settings kept, as Section 1.6.1 describes, and a setting changed before Run gives the same run as the same setting carried through a Reset, the settled start included.

13.6.1 One Exchange, Three Variables

Case 1 runs a bright Monday with the vents 4 K above a 19.5 °C heating setpoint and the cap off. At 11:57 the house is at 23.50 °C, 83.4 % and 584 ppm, its vents 51 % open and its air changing 6.4 times an hour, and the line doses its full 130 kg/h, of which 96 kg/h already leaves by the vents and leaks. At noon the vent loop goes to MANUAL with every window open, the exchange more than doubles to 13.7 air changes an hour, and by 12:15 the air is at 20.30 °C, the humidity at 66.6 % and the CO_2 at 499 ppm. The boiler is asked to fire from 12:21, the air reaches the heating setpoint at 12:24, and at 12:57 the boiler burns 51 W/m^2 against the open roof with the air at 19.24 °C. The hour

Table 13.5 Results by Case. Mean, Gas and Cost Are the First Day's, and RH Is the Minutes Above 85 % in That Day's Dark Hours

Case and configuration	Mean (°C)	Gas (m^3)	Cost ($)	RH (min)	CO_2 (ppm)
2 fixed, Monday	19.02	1040	651	64	585
2 fixed, Tuesday	18.57	1547	787	89	—
3 screen, override off[a]	—	566	—	720	—
3 screen never closed[a]	—	1188	—	130	—
3 screen, override on[a]	—	781	—	108	—
4 cap off	19.14	850	581	172	550
4 cap on	19.14	850	557	172	530
5 planner, Monday	18.91	865	577	68	632
5 planner, Tuesday	18.79	1501	774	92	—
6 front missed	18.68	1743	883	81	—
6 perfect forecast	18.79	1624	866	43	—
7 override on	20.69	1965	900	601	—
7 override off	18.80	456	283	931	—
8 gas ×3	18.80	1456	1933	85	—
8 normal price[b]	18.79	1521	785	84	—
9 fog on	22.24	197	251	162	470
9 fog off	22.97	197	234	162	469

[a]Gas and RH over the second night, 18:00 to 06:00, all minutes above 85 %.
[b]The scripted price spike removed, a counterfactual run.
CO_2 is the mean over the bright hours of a bright day.

costs 41.6 m^3 of gas ($17) that goes straight out, and the vents and leaks carry off 103 of the 130 kg dosed, 79 % against 74 % in the hour before noon at half aperture, while gross photosynthesis falls 5.4 %. Back in AUTO the house is at 22.30 °C, 85.1 % and 578 ppm by 13:30. The heating loop sees only its own temperature and fights the vent with gas.

🕮 **Pause.** Try Exercise 13.2 before reading on.

13.6.2 A Setpoint Is Not the Recipe

Case 2 runs Monday and Tuesday on 19.5 °C from 06:00 to 19:00 and 17 °C at night. On bright Monday the sun carries the air to 21.7 °C by 09:19, the vents open from 21.5 °C and hold it there, standing 56 % open at 12:30 with 96 kg/h of CO_2 leaving, and the day's mean is 19.02 °C on 1040 m^3. On dull Tuesday there is no sun to float on and the mean falls to 18.57 °C, 0.43 K short, on 1547 m^3. The boiler sits at its limit for 1.68 h on Monday and 3.57 h on Tuesday, 186 of those 315 minutes between 05:00 and 08:00, when the screen opens over a cold house and the setpoint ramps up, and the air falls to 15.58 °C, 1.42 K under the night setpoint, before the pipes catch up. The setpoints are held on both days and the recipe on one.

13.6.3 The Screen and the Water It Traps

Case 3 runs from Monday 00:00 to Tuesday 06:00 with the override off. Over the second night, 18:00 to 06:00, the closed screen holds the gas to 566 m^3 against 1188 m^3 with the screen never closing, and it keeps the house above 85 % for all 720 minutes, reaching saturation and wetting the leaves for 26 min. With the override on, the gap opens to its 10 % limit and MIC-104 asks for up to 42.1 % of lee vent, which keeps the night under 85 % for all but 108 min at a peak of 88.5 % on 781 m^3, 215 m^3 more than the closed screen and 407 m^3 less than no screen. The third stage never acts that night. The screen saves more than half of a night's gas and the override returns a third of the saving to keep the leaves dry.

> **TRY IT IN THE APP 3 · The Screen at Night**
>
> Load the case and press run to Tuesday 06:00. Watch the humidity badge through the second night: under the closed screen the house stays above 85 % for all 720 minutes. Reload the scenario, turn the Humidity override on and run again: the gap and the lee vent keep the night under 85 % for all but 108 min.

13.6.4 Dosing Into Open Vents

Case 4 runs a bright Wednesday with the cap off. For 8.02 h the vents are more than half open while the line doses, and of the 1043 kg it doses in those hours, 784 kg leave by the vents. Over the day the line doses 1460 kg and the bright hours average 550 ppm. With the cap on the day doses 1305 kg, the CO_2 bill falls from \$210 to \$186, the bright hours average 530 ppm and the crop banks 240 kg of assimilates against 243. Widening the vent band to 4 K instead keeps 592 ppm through the bright hours, for a day 0.88 K over the recipe at 19.88 °C. The cap saves CO_2 only where the vents stand wide, and anything that keeps the vents closer is also a CO_2 strategy.

13.6.5 Temperature Integration

Case 5 runs case 2's days with the planner on. On Monday it lets the middle of the day run warm on the sun, planning 24.7 °C from 11:00 to 16:00 with the air peaking at 24.89 °C at 11:18, and holds the night at the floor of 16 °C, for a mean of 18.91 °C on 865 m^3, against 19.02 °C on 1040 m^3 for the fixed setpoints. The closer vents also keep 632 ppm through the bright hours against 585. On dull Tuesday there is less sun to bank, and the planner spends 1501 m^3 against 1547 and holds 18.79 °C where the fixed setpoints let the day fall to 18.57 °C. Over the two days it uses 8.5 % less gas, 2366 m^3 against 2587, for \$1351 against \$1438 and 406 kg of assimilates against 400. The band constrains the plan and not the air. The plan sits at the 16 °C floor for 15.0 h of the two days, the air below it for 11.6 h of those, but below 15.5 °C for only 1.08 h, all of it between 05:00 and 09:00, when the screen opens over a cold house and the boiler spends 88 minutes of the two dawns at its limit, and the lowest air is 14.63 °C at 05:57. Figure 13.2 shows the planner at the end of Monday.

> **TRY IT IN THE APP 5 · Temperature Integration**
>
> Load the case and press run. Watch the air and the violet plan in the Climate view through bright Monday: the plan lets the middle of the day run warm, near 24.7 °C, and holds the night at the 16 °C floor. The day ends at a mean of 18.91 °C on 865 m^3 of gas, against 1040 m^3 for the fixed setpoints of case 2.

13.6.6 A Forecast That Misses a Front

Case 6 runs Friday with a cold front at 12:00 that the forecast places at 21:00 until it is three hours away. Trusting a bright afternoon, the planner holds the night at 16.0 °C. From 06:00 the forecast catches up, and with the front coming the planner raises the morning's heating setpoint to 22.5 °C, unscreened, to bank the mean before the cold, and the air reaches 21.6 °C by noon. The day ends at 18.68 °C, 0.12 K short of the 18.8 °C the planner aims for at the cheap edge of its tolerance, on 1743 m^3 and \$883. On a perfect forecast the planner heats the screened night to its 20 °C ceiling instead and makes 18.79 °C on 1624 m^3 and \$866, so the miss costs 119 m^3, \$17 and a tenth of a kelvin. The band's floor kept the night at 16 °C however bright the afternoon looked. Widening the band from 17 to 24 to 15 to 28 °C cuts Monday's gas in case 5 from 969 to 794 m^3, while what the missed front of case 6 costs falls from \$22 to \$17, so in this case the band's floor, not its width, sets what a bad forecast spends.

13.6.7 A Dark Day No Setting Wins

Case 7 runs Thursday under overcast and drizzle, about 14 °C outside, saturated and calm, with 2.5 MJ/m^2 of sun, the planner on and the CO_2 setpoint asking for its full 800 ppm from 50 W/m^2. Saturated air at 14 °C holds 98 % of the water the 85 % limit allows at 17 °C, so venting barely dries the house. The override holds the 90 % line, never crossing it, but not the limit, which the house



Figure 13.2 Temperature integration in case 5 at day 1 23:55, in the Climate view with no control changed. (1) The badges read 15.8 °C, 84 %, 634 ppm, a trailing mean of 18.92 °C, $575 today and 251 kg banked. (2) The summary line reads that FY-200, re-solved at 23:00, plans today's mean at 18.92 °C against the 19.0 °C recipe and 16.0 °C for this hour, beside the browser's own solve time. Monday's air climbs to about 25 °C around noon and sits just under the 16 °C floor through the night, and (3) Tuesday's plan, the stepped solid line in violet, holds 17.0 °C until 08:00, reaches 26.0 °C at 12:00 and 13:00 under a free-sun forecast, dotted in amber, that peaks at 29.3 °C, and is back at 16.0 °C from 17:00. (4) The humidity strip holds the night at the 85 % limit, and (5) the CO_2 strip shows what the night's respiration gathers, near 1000 ppm, falling as the screen opens and about 630 ppm through the bright hours.

exceeds for 17.6 h with the heating raised the full 5 K for 9.53 h and the lee windows at half. That heat sends the mean to 20.69 °C, 1.7 K over the recipe, and from 16:00 the planner reports that the day's mean cannot come down to 19 °C inside the band. The CO_2 is held within 22 ppm of its setpoint only by dosing 985 kg into vents that carry 96 % of it out, for 19 kg of assimilates, and the day costs $900. With the override off it costs $283 and keeps the mean at 18.80 °C, while the house sits above 90 % for 21.8 h and wets the leaves for 16.5 min. The override ranks the humidity above the recipe and the CO_2, and the planner says what that costs instead of widening its band.

> ✦ **DID YOU KNOW? Drying a Saturated Day Buys Little**
>
> From the simulator: on the dark, saturated Thursday of case 7 the humidity override raises the day's gas from 456 to 1965 m^3 and its cost from $283 to $900, and the house still spends 601 dark minutes above 85 %, against 931 without it (Table 13.5).

13.6.8 Gas Prices and Fog

Case 8 runs a dull Tuesday with the gas price tripled from midnight. The planner moves heat out of the day and into the screened night, 19.50 °C before dawn where it averaged 18.44 at the normal price and 20.37 °C on average from 09:00 to 17:00 instead of 21.86, the normal-price figures coming from a counterfactual run with the scripted spike removed. The boiler fires less in daylight, the flue gas falls from 295 to 276 kg and the line buys 994 kg of liquid CO_2 instead of 928. The day costs $1933 against $785 at the normal price, and since the unchanged plan would have cost $2001, re-planning wins back $68 of the $1217 the spike adds ($52 to $74 over five other seeds of the sensor noise), while

Table 13.6 The Graded Week in Every Combination of the Planner (P), the Override at 83 % (O) and the Cap (C)

Changes	Cost ($)	Gas (m^3)	Worst (K)	RH (min)	CO_2 (ppm)	Fails
none	4292	6447	1.00	775	578	mean, RH, CO_2
C	4271	6447	1.00	775	559	mean, RH, CO_2
P	3780	5306	0.22	715	617	RH
P and C	3778	5306	0.22	715	615	RH
O	6312	10500	0.83	92	573	mean, CO_2, cost
O and C	6290	10500	0.82	92	553	mean, CO_2, cost
P and O, or all	5594	9184	0.33	78	611	none
all at 85 %	5398	8780	0.33	192	611	RH

Worst is the largest miss of a day's mean, RH the most humid day's dark minutes, CO_2 the lowest bright day. Gas costs 0.40 \$/m^3, 1.20 \$/m^3 on Wednesday.

a recipe of 18.5 °C would save \$125. Case 9 runs a cloudless Monday 12 K warmer with the vents wide for 15.92 h. The fog runs for 7.90 h from 09:16 and takes the peak from 29.63 °C to 27.78 °C, while the humidity at the peak rises from 64 to 78 % with 36 % outside, and the crop banks 213 kg against 207 for \$18 more electricity.

13.6.9 The Graded Week

The challenge runs the spring week, bright, dull, bright, dark, a front, bright and bright, with the gas price tripled for Wednesday and Friday's front arriving nine hours before the forecast says. The target is every day's mean within 0.5 K of 19 °C, no more than 150 min above 85 % in any day's dark hours, at least 600 ppm through the bright hours of every bright day and at least 1200 kg of assimilates, for at most \$6100. Shipped on 20 and 18 °C with no planner, no override and no cap, the week costs \$4292 and fails three parts, six days off the recipe with the worst by 1.00 K, a day with 775 min of humid dark hours and a bright day at 578 ppm. Table 13.6 adds the three suggested changes in every combination.

The planner and the override pass together, at \$5594 with every day within 0.33 K, at most 77.5 min of humid dark hours, 611 ppm on the worst bright day and 1227 kg banked, margins of 0.17 K, 72.5 min, 11 ppm, 27 kg and \$506 on the five targets, the same week whether the settings are made before Run or carried through a Reset. That is more than the shipped \$4292 because dry nights cost gas. Each fails alone. The planner alone gives the cheapest week, \$3780, but leaves 715 min of humid dark hours in its worst day, and the override alone costs \$6312 and leaves three days off the recipe and a bright day at 573 ppm. The same pattern holds over five other seeds of the sensor noise, with the passing week at \$5595 to \$5606. Once the planner and the override run, the cap changes nothing in this week. It engages for 6.55 h, but the measured CO_2 stays below the lowered setpoint with the line at its limit, so the two weeks are identical state for state. With the planner alone the cap lowers the worst bright day from 617 to 615 ppm, and without the planner to 553 ppm. The planner is the CO_2 strategy here, because its warm afternoons keep the vents closed. Figure 13.3 draws the rows of Table 13.6 against the cost and humidity targets.

The humidity limit is the price setter, as shown in Figure 13.4. With the planner, moving the limit from 83 to 85 % saves \$196 a week and lets the worst night rise from 77.5 to 192 min, and each point of limit from 78 to 90 % is worth between \$76 and \$113. At every limit the planner's week is \$656 to \$725 cheaper than the same override on fixed setpoints, and only the planner's weeks at 80 to 84 % pass, since at 78 % the dry nights cost \$6140. The horizon has to reach a day ahead. With horizons of 24 to 48 h the suggested week costs \$5594 to \$5597 and passes, while at 18 h Wednesday's bright hours hold 598 ppm and fail the CO_2 target. At 12 and 6 h a plan that sees only part of the day holds Wednesday's bright hours cooler, venting at 23.1 and 21.3 °C against 23.5 °C, so the vents stand 55 and 72 % open against 52 and the bright hours hold 596 ppm and 535 ppm. Volume 9, Chapter 7 meets the same question of how far a forecast should reach on a slower plant. A perfect forecast

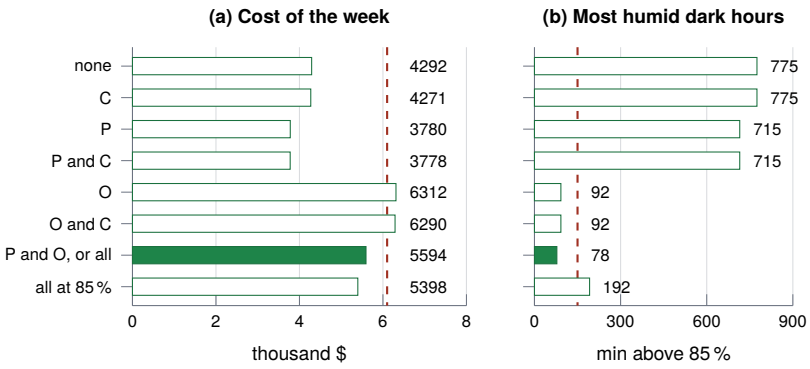


Figure 13.3 The graded week of Table 13.6 in every combination of the planner (P), the override at 83 % (O) and the cap (C): the week's cost against the $6100 the challenge allows and the most humid day's dark minutes against its 150 min (dashed lines). The solid bar passes every target, white bars fail at least one. Notice that the planner alone is the cheapest week and the override alone the driest, and that only the two together sit inside both lines.

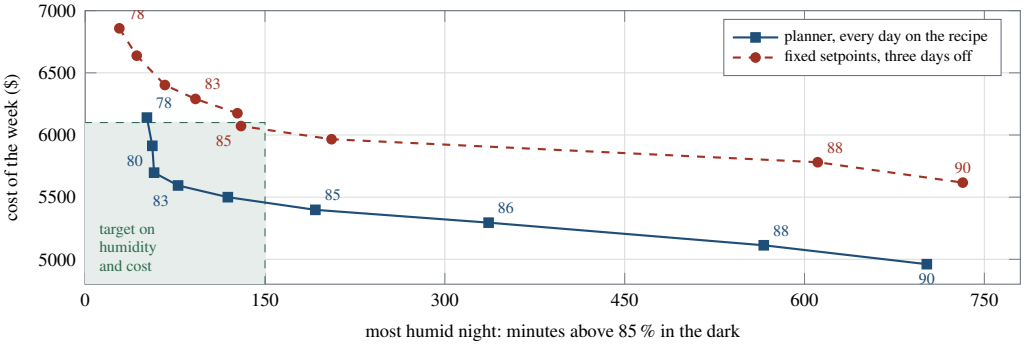


Figure 13.4 The price of a humidity limit over the graded week, with the override and the cap on and the limit at 78 to 90 % as labeled, with the planner (solid line, squares) and on fixed setpoints (dashed line, circles). With the planner every day stays within 0.35 K of the recipe, and on fixed 20 and 18 °C setpoints three days miss it by up to 0.84 K and the worst bright day holds 551 to 554 ppm, so the shaded box covers two of the five targets.

makes the suggested week $30 dearer, at $5625, with its worst day 0.21 K off rather than 0.33 and Friday, the day of the front, only $2 cheaper, and an error three times the declared size makes it $28 dearer.

The external reset of TIC-101 earns its place. Replacing it, in a copy of the source, with the shared law's own back-calculation on the same tuning raises the overshoot of an unramped 3 K step of the night setpoint at 01:00 in case 2 from 0.21 to 1.26 K, and that of the step that opens case 6 on a perfect forecast, where the plan starts at 20 °C over the settled 17 °C night, from 0.22 to 0.41 K at the shipped ramp of 3 K/h and from 0.31 to 0.98 K at the fastest planned ramp of 8 K/h, because the master's integral, which external reset ties to the pipe temperature achieved, otherwise grows through the hour the pipes take to heat and then has to unwind.

13.7 Technology in Practice

The climate computer of Section 13.4 reads a handful of instruments and moves five kinds of handle, and the planner of Section 13.5 sits above it. Figure 13.5 draws them as a glasshouse would install

them.

What Measures It

The loops that matter most read one measuring box in the crop for the air temperature and the humidity, a CO_2 analyzer behind its sample line, a sensor in the pipe water and a weather station outside. CO_2 sensors of the nondispersive infrared type measure the absorption of infrared light by the CO_2 molecules and correlate it with the concentration [18]. In the chapter the box reads behind a 1 min lag and the analyzer behind the 2 min lag of its sample line.

> **TECHNOLOGY Sensor: Air Temperature and Humidity**
>
> The standard measurements of a glasshouse climate computer include the air temperature and the humidity deficit inside, the heating pipe temperature, the screen positions and an outside weather station [17]. Temperature elements are thermistors, sensitive over a limited range, or platinum resistance detectors, accurate and linear over a wider one. Humidity sensors use a capacitive or resistive element with a hygroscopic material whose capacitance or resistance changes with the humidity. Accuracies of 0.5 °C and two points of relative humidity are reported for sensors in greenhouse systems, which still need calibration and maintenance, and dew is a known source of interference with a humidity sensor [18]. The chapter's measuring box reads the true air behind a 1 min lag with 0.05 K and 0.5 points of noise.

What Moves It

The heating loop fires a boiler into pipes along the rows, the vent loops open roof windows lee side first, a drive draws the screen at the gutter, a valve sets the dose of CO_2 and the fog runs on and off. A test facility equipped like a commercial house had the same set: continuous roof ventilation with an opening of 0.3 m^2 per square meter of floor, movable screens, a fogging system and a CO_2 supply [17]. Every handle acts on the same air.

> **TECHNOLOGY Final Element: Boiler and Heating Pipe Rail**
>
> The compartments of a test facility, equipped with actuators available in commercial high-tech greenhouses, had two pipe heating systems, a rail pipe on the floor with a peak capacity of 180 W/m^2 and a pipe at crop height with 30 W/m^2, each on its own setpoint, and growers set a minimum rail pipe temperature among their climate setpoints [17]. The pipe water is a store of heat between the burner and the air. In the chapter the boiler of 150 W/m^2 fires behind a 5 min lag into pipes held at 15 to 90 °C by TIC-102, and an outage shows on the trend as a firing request at its limit while the pipe temperature falls.

Where the Controller Runs

In the competition of Section 13.2 the teams' setpoints reached a standard commercial process computer, and setpoints and measurements were exchanged every five minutes [17]. Such controllers hold logic, timing, counting and three-mode PID control, and supervisory and lower loops run continuously with cycle times from milliseconds to minutes [19]. The chapter's climate computer executes every minute and the planner every hour, so the scan of the platform is never the limit. In a function block program the heating cascade is two PI blocks with the master's reset fed from the measured pipe temperature, the vents take a high select of two PI blocks, and the planner is a supervisory layer that writes the heating and vent setpoints.

What Is Modernizing It

Three lines of work bear on this chapter. The first puts learned models inside predictive control. A neural network that predicts the inside temperature from 15 inputs served an optimizer of six roof windows on a strawberry house, and in a six-day field test its root mean square temperature error was 2.45 °C against 3.01 °C for conventional ventilation control [20]. The second is autonomous growing. One team of the competition ran three layers: a crop model set average climate targets, a

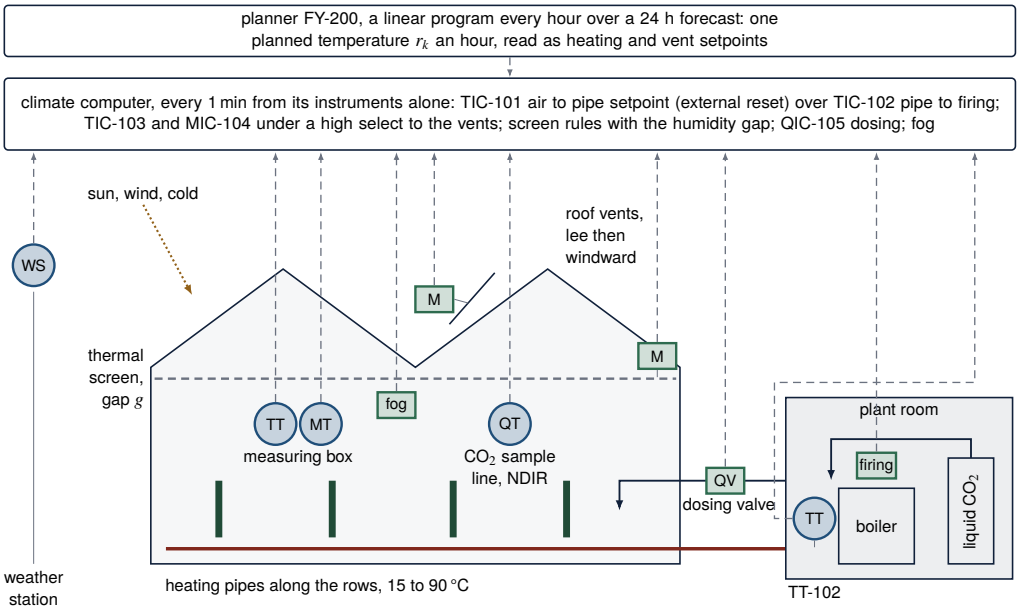


Figure 13.5 The chapter's loops with the devices a commercial glasshouse would install. The thick line is the hot water of the pipes, thin dark arrows the carbon dioxide, dashed gray lines the signals and the dotted amber arrow the weather. Notice that every handle (the boiler, the vents, the screen, the fog and the dosing valve) acts on the one body of air that the measuring box samples, and that the planner writes setpoints, never a valve position.

middle layer turned them with the weather forecast into ideal climate trajectories, and a bottom layer set the setpoints [17], the hierarchy of this chapter's planner over its climate computer. The third is dense sensing. Networks of temperature, humidity, CO_2 and light sensors capture the variation of the microclimate across the house, and Kalman filtering and the wavelet transform reduce their measurement errors [18]. None of them removes the coupling of one air exchange that carries heat, water and CO_2 together.

> **IN PRACTICE** **Drying a House With Heat and Vents**
>
> Humidity is held for the health of the crop: appropriate relative humidity prevents fungal infections and controls transpiration [21]. In the remote growing competition of 2018, a team that found small spots of fungal disease in its cucumber compartment was advised to lower the humidity. It stopped the misting, opened the vents on both the lee and the wind side, and set the minimum temperature of the pipe rail to 40 °C, which held the air at its night and day temperatures while the house ventilated. The heating energy rose steeply [17]. Heating and venting at once is the third stage of this chapter's override.

13.8 Limitations

The house is one air node with a big-leaf crop, a reduced vent law and a lumped screen, so it shows the couplings between temperature, humidity and CO_2 but not the gradients inside a real house, the cold air that falls through a screen gap or a clear sky's radiation. The crop answers the calendar day's mean with no tolerance of a mean held over several days, which real temperature integration exploits [1, 5], and fruit set and quality are absent. The weather is synthetic and the forecast error declared.

OPEN CHALLENGE Sensing the Crop Instead of the Air

In the remote growing competition, the extra sensors the teams chose showed no clear link with yield or net profit. Robust sensors giving direct information on the crop's performance, rather than indirect information on its air and root zone, might improve such control substantially [17]. A review adds that the calibration, maintenance and interoperability of sensors remain significant concerns [18]. Progress would be a measured crop state, such as the leaf wetness duration and the transpiration that a crop-based humidity regime set targets for [5], held by the planner in place of the air's humidity.

The planner's model is quasi-steady per hour and prices CO_2 without the cap, so it expects 16 % less than the house buys over the suggested week, and it holds each day's mean separately. There is no heat buffer, no combined heat and power unit and no artificial light, which are how real growers move gas in time and make CO_2 on demand. Volume 9, Chapter 6 prices heat from such a unit and a stored tank. Every threshold and price is a teaching value, and none of the numbers is a measurement of a commercial glasshouse.

OPEN CHALLENGE One Box for a Hectare

A greenhouse is traditionally monitored by sensors placed with no guarantee that they represent the house, and most methods proposed for placing them do not approach the problem from a control perspective. One study took the mean of 56 paired temperature and humidity sensors as the reference and found that eight well-chosen sensors, aggregated by a learned formula, estimated it with a correlation of 0.999 [21]. The chapter's house is one air node read by one box. Progress would be a placement chosen for the loop it serves.

13.9 Conclusion

A glasshouse spends a temperature budget against a humidity limit through one air exchange that also carries its CO_2, and the simulator of this chapter measures each side of the trade from ledgers that close to 3.6×10^{-14}. Fixed setpoints of 19.5 and 17 °C make the 19 °C recipe on a bright day and miss it by 0.43 K on a dull one, the screen saves 622 of 1188 m^3 on a night while keeping the house above 85 % for twelve hours, and a vent opened at noon costs 41.6 m^3 of gas and 79 % of the CO_2 dosed. The receding-horizon linear program over the forecast heats the bright Monday on 17 % less gas and holds the dull Tuesday 0.22 K nearer the recipe, a missed front costs it \$17, and on a dark saturated day it reports a mean 1.7 K over the recipe rather than widen its band. Over the graded week the planner and the override pass together at \$5594, each fails alone, the cap changes nothing once both run, and the planner is \$656 to \$725 cheaper than fixed setpoints at every humidity limit from 78 to 90 %. The house is lumped, its crop reduced and its weather synthetic. A fuller model would add a canopy temperature, a screen gap with its own buoyant flow, integration over several days, a heat buffer and lighting. The simulator makes temperature integration a measurable trade against the humidity limit that every glasshouse has to hold.

KEY POINTS

- A tomato crop answers the mean temperature of its day, so the heating setpoint is a budget while the humidity limit holds hour by hour.
- The planner heats the bright Monday on 865 m^3 of gas instead of 1040, 17 % less.
- The thermal screen saves 622 of the 1188 m^3 a night would burn and keeps the house above 85 % for all twelve hours.
- Over the graded week the planner and the override pass together at \$5594, each fails alone, and the cap changes nothing once both run.

Where else this applies. Volume 9, Chapter 11 plans pumps over the same 24-hour horizon.

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13.10 Exercises

13.1 Concept check · 2 min

The planner of Section 13.5 lets a bright afternoon run warm and holds the night at the floor of its band. Why can this meet the same 19 °C recipe on less gas than fixed setpoints?

(a) Growth rises with the hourly temperature, so the warm afternoon adds yield that pays for the gas

(b) A warm house loses less heat through its cover, so a warm afternoon costs less than a warm night

(c) Growth follows the trailing daily mean, so a degree the sun supplies can replace one the boiler buys at night

(d) The humidity limit is looser in daylight, so the night can run cooler without wetting the leaves

13.2 Concept check · 1 min

In case 1 every vent opens wide at noon for an hour. What happens to the air temperature, the humidity and the CO_2 in the first quarter of an hour?

(a) The air cools and the humidity rises, while the CO_2 holds because the line keeps dosing

(b) The air cools and dries, while the CO_2 rises because cooler leaves take up less of it

(c) Only the air temperature moves, because the vent loop acts on temperature alone

(d) All three fall together, because one exchange carries heat, water and CO_2 out

13.3 Concept check · 2 min

At dawn the boiler of the glasshouse sits at its limit for most of an hour while the air is below its heating setpoint. Why does the air loop TIC-101 not wind up?

(a) Its reset is a lag of the measured pipe temperature, so it follows the pipes the slave achieves

(b) Its output is clamped at 15 to 90 °C, and the clamp alone stops the integral from growing

(c) The pipe loop TIC-102 is fast enough that the pipes reach every request within a minute

(d) The heating setpoint ramps over an hour, so the error never grows large enough to wind up

13.4 Theory and calculation · 6 min

The cover has $U_{open} = 7.5\,\mathrm{W/(m^2\,K)}$ with the screen open and $U_{scr} = 4.0\,\mathrm{W/(m^2\,K)}$ under it, both at a 4 m/s wind, where $h_{out} = 7 + 2v$. A closed screen passes $p_s = 0.15$ of the exchange.

(a) Use Equation (13.3) to find $h_{in,0}$ and R_s. *Checkpoint:* 15 W/(m² K), 0.117 m² K/W

(b) The screen closes to $s = 0.90$, a 10 % gap. What share of the closed screen's resistance R_s does it keep, and what is the overall cover coefficient $U = [1/h_{in}(s) + 1/h_{out}]^{-1}$ at 4 m/s? Give the coefficient to two decimals. *Checkpoint:* 0.800, 4.41 W/(m² K)

(c) What share of the open-house exchange does the screen pass with the 10 % gap, from $\pi(s)$ of Equation (13.7)? *Checkpoint:* 0.488

13.5 Theory and calculation · 8 min

Take the house of Section 13.3 with $h = 5$ m, a 4 m/s wind and the air 5 K warmer than outside, so that the factor $\frac{1}{4}\sqrt{v^2 + 0.5\,(T - T_o)^+}$ of Equation (13.7) is 1.075. Note $f(1) = 1$ and $f(0) = 0$.

(a) With the vents shut and the screen open, find the leakage φ_l in m³/(m² h) and the time h/φ in minutes. *Checkpoint:* 2.5 m³/(m² h), 120 min

(b) With the aperture at $a = 0.5$, so that only the lee windows are fully open, find φ and h/φ. *Checkpoint:* 28.3 m³/(m² h), 10.6 min

(c) With every window open ($a = 1$), and with the vents shut under a fully closed screen, find h/φ in each case. *Checkpoint:* 4.5 min, 800 min

13.6 Theory and calculation · 6 min

Fixed setpoints hold 19.5 °C by day and 17 °C at night, the heating setpoint ramping over an hour from 06:00 and from 19:00 as in Section 13.4.1. The recipe is a 19 °C mean.

(a) Find the 24-hour mean of the heating setpoint, to two decimals. *Checkpoint:* 18.35 °C

(b) Find the growth demand $g_{19}\,\mathrm{clip}_{16/9}\big((\bar{T}_{24} - 10)/9\big)$ of Equation (13.10) at that mean, with $g_{19} = 18\,\mathrm{g/(m^2\,d)}$. *Checkpoint:* 16.7 g/(m² d)

(c) Case 2's bright Monday ends at a mean of 19.02 °C. How many kelvin-hours above the setpoint's own mean did the sun supply, to the nearest whole number? *Checkpoint:* 16 K h

13.7 App challenge · 8 min

Run scenario 2 (Heating and venting on fixed setpoints) with its default settings at the default seed to its end, Tuesday midnight (48 h), at 6 h/s, then export the CSV file. Repeat with scenario 5 (Temperature integration).

(a) For each scenario, read Monday's mean and gas from the CSV row at 24 h (columns `T_day_C` and `metric_gas_m3`). Give the means to 0.01 K and the gas to the nearest $\mathrm{m^3}$. *Checkpoint:* 19.02 °C and 1040 $\mathrm{m^3}$, 18.91 °C and 865 $\mathrm{m^3}$

(b) At the end of each run, read Tuesday's mean from the *24 h mean* badge and the two-day gas from the *Gas* tile. What share of Tuesday's gas does the planner save, and what share of Monday's? *Checkpoint:* 3 %, 17 %

(c) Explain the difference between the two days in one or two sentences.

13.8 App challenge · 7 min

Run scenario 7 (The humid dark day) at the default seed with its default settings to midnight (24 h) at 2 h/s. Read the *Cost* tile, the *24 h mean* badge and the worst night on the *Humid minutes at night* tile. Then press Reset, turn the *Humidity override* off before pressing Run, and run to midnight again.

(a) Give the three readings for both runs (cost to the dollar, mean to 0.01 K, minutes to the nearest whole minute). *Checkpoint:* \$900, 20.69 °C, 601 min; \$283, 18.80 °C, 931 min

(b) Which target does each run give up, and why can no setting hold all of them on this day?

13.9 App challenge · 10 min

Run the challenge (a spring week) at the default seed to its end (168 h) at 6 h/s, three times, each time making the changes before pressing Run: (1) as shipped, (2) with the planner on, the Humidity override on with a humidity limit of 83 % and the $\mathrm{CO_2}$ cap on, and (3) as in (2) with the limit at 85 %. For each run read the *Cost*, *Days off the recipe*, *Humid minutes at night* and *Bright-day CO_2* tiles.

(a) Which parts of the target does run (1) fail, and by how much? *Checkpoint:* mean (6 of 7, worst 1.00 K), 775 min, 578 ppm

(b) Does run (2) meet the target, and at what cost? *Checkpoint:* yes, \$5594

(c) What does run (3) save, and which part does it fail? *Checkpoint:* \$196, humidity at 192 min

13.10 Application area · 3 min

The crop of this chapter answers the calendar day's mean, with no tolerance of a mean held over several days. Real temperature integration has used windows of 24 hours and six days. Suppose the dull Tuesday of case 2 ends 0.43 K short of the recipe. What would a six-day window allow the grower to do about it, and what must the grower still check?

13.11 Application area · 4 min

In case 8 the gas price triples for a whole day. Re-planning wins back $68 of the $1217 the spike adds, while lowering the recipe to 18.5 °C would save $125. Explain to a grower why re-planning wins back so little, and name two pieces of equipment that real houses use to move gas in time.

13.12 Review the agent · 5 min

An AI assistant reviews the graded week and writes: “Each point of humidity limit is worth $76 to $113 a week. Raise the limit from 83 to 90 %: the week will cost about $4961 instead of $5594, and since the override still holds the house at its limit, the humidity target stays met.” Find the flaw in the claim and say how you would check it in the app.