9[2] Fundamentals of Mathematical Modeling, Simulation, and Process Control

If people do not believe that mathematics is simple, it is only because they do not realize how complicated life is.

John von Neumann

Reverend Thomas Bayes (was) a brilliant mathematician who devised a complex equation known as the Bayes theorem, which can be used to work out probability distributions. It had no practical application in his lifetime, but today, thanks to computers, is routinely used in the modeling of climate change, astrophysics and stock market analysis.

Bill Bryson

Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful.

George Edward Pelham Box

9.1 Chapter Purpose

Believe it or not, we have extensively, unconsciously, exposed you to, practiced, and developed mathematical models throughout this book. The first exposure to mathematical modeling in this book was perhaps in Chap. 2 (Sect. 2.4.1), where we introduced the ideal gas law. The ideal gas law is a mathematical representation that relates the pressure (P), volume (V), moles (n), and absolute temperature (T) of an ideal gas with a simple, but powerful, mathematical equation. Then, in the same chapter, we deduced and practiced the use of simple mathematical models like the one to convert temperatures from the Celsius scale to the Fahrenheit scale. In addition, in Sect. 2.7, you were exposed to several mathematical models that are common in chemical and bioprocess engineering. Then, in several of the following chapters, we utilized mathematical models. For example, in Chap. 6, we showed and employed different mathematical models that are frequently utilized in, for example, thermodynamics, heat transfer, and mass transfer. At this stage, a good exercise for you would be to identify throughout the book all mathematical models and to begin to understand their importance in chemical and bioprocess engineering.

The main purpose of this chapter is to understand and discover, through examples, the importance of mathematical modeling and to start constructing simple mathematical models. The second purpose is introduce you to process and bioprocess simulation. Again, in the case of simulation, you have already been exposed to and practiced simulation through some exercises in previous chapters of the

R. Simpson and S.K. Sastry, *Chemical and Bioprocess Engineering: Fundamental Concepts for First-Year Students*, DOI 10.1007/978-1-4614-9126-2_9,

book. For example, in Chap. 8 (Sect. 8.6, problem 3), it was proved that two continuous bioreactors in series (total volume V) were more effective than one continuous bioreactor of volume V. Then the question was to determine how many reactors in series were needed to reach a specific concentration of the substrate at the output stream. To answer the question, we first developed a general mathematical model that was capable of predicting the output substrate concentration (S) as a function of the number of bioreactors (n), and with this model and with the help of Excel, we constructed a table that *simulated* the output substrate concentration S for different values of n. Once more, we invite you to discover other examples and problems presented in the book that bear a direct relation to process and bioprocess simulation. Third, this chapter will introduce you to process and bioprocess control. Controlling a process means mastering it and keeping it running in peak condition, safe for people and equipment. How do I maintain a controlled process? How do I detect that a process is out of control? What is a smart way to take control? These are some of the questions that will be addressed in this chapter.

Finally, our main target is to continuously show you, through examples, the beauty and broad application of chemical and bioprocess engineering.

9.2 What Is Mathematical Modeling?

A mathematical model is an abstract representation of reality, in mathematical language, used to find solutions to different types of problems.

For example, we would like to determine the number of poles (Fig. 9.1) needed to separate two adjacent sites. According to experts, we should put the poles $\boldsymbol{d}$ meters apart (including poles at both extremes). Further, the distance between poles could be less than $\boldsymbol{d}$ meters but no greater. The experts also suggest that this fence utilize poles that are $\boldsymbol{e}$ meters in diameter ($\boldsymbol{e} \lll \boldsymbol{d}$). Then, if the fence has a total length of $\boldsymbol{a}$ meters ($\boldsymbol{a} \ggg \boldsymbol{d}$), how many poles are needed?

The variables in the problem are as follows:

a: Total length of fence in meters
n: Number of poles
d: Maximum distance between two poles in meters
e: Diameter of each pole in meters

Then, analyzing Fig. 9.1, we can write the following equation:

$$a = ne + (n - 1)d. \quad (9.1)$$

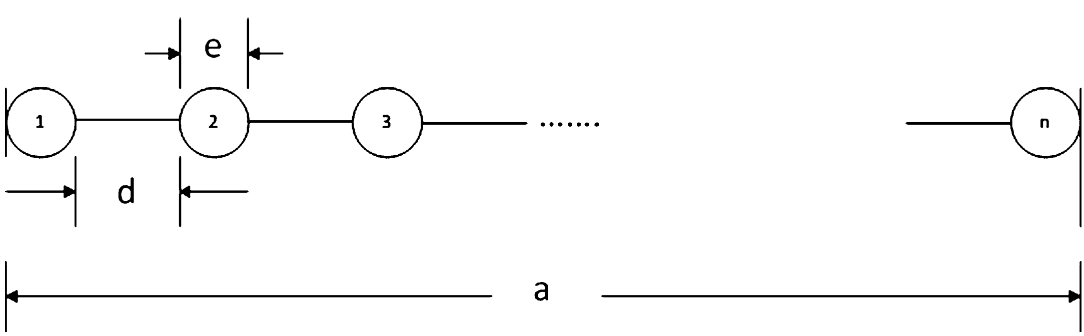


Fig. 9.1 Schematic representation of a fence

Solving for n we get

$$n = \frac{a + d}{d + e}. \tag{9.2}$$

If, for example, $a = 100$ m, $d = 4$ m, and $e = 0.2$ m, then $n = 24.76$ poles. Of course, we cannot employ 24.76 poles, but if we arrange (9.2) as follows:

$$d = \frac{a - ne}{n - 1}, \tag{9.3}$$

then, from (9.3), we can check that, by using 25 poles, the distance between poles will be $d = 3.96$ [m], which is in agreement with the expert recommendation ($d \leq 4$ m).

Equation (9.2) is a very simple but practical mathematical model that allows us to calculate the number of poles as a function of the fence length, the distance between poles, and the pole diameter. For example, if you decide that 25 poles is too many, and your budget will allow for just 20 poles, then, using (9.2), you can simulate different scenarios and determine the distance between poles if you are employing 20 poles or any other number of poles on this fence.

Mathematical models and simulation are powerful tools for engineers. In addition, with the help of computers, we can solve and simulate extremely complex mathematical models. Throughout your career, you will be learning, step by step, how to build interesting mathematical models for chemical and bioprocess engineering. In the next section, we will start building simple models, and in doing so, we will show you the potential and broad applications of this engineering tool.

9.3 Importance of Building Mathematical Models and Constructing Simple Models for Chemical and Bioprocess Engineering

9.3.1 What Have We learned?

One interesting lesson that we can learn from having solved problem 3 in Sect. 8.6 is that the larger the number of bioreactors (n) in series (for the same total volume V) was, the lower the output substrate concentration (S) was. But, possibly, of much greater interest was the discovery that the output substrate concentration was not very sensitive to an increasing number of bioreactors (Table 9.1).

From the table you will notice that the output substrate concentration decreases with the number of bioreactors, but this is barely noticeable. For example, we increased the number of reactors from 1 to

Table 9.1 Oulet concentration of substrate as a function to the number of bioreactors

Number of bioreactors	Output substrate concentration (g/L)
1	33.3
2	32.0
3	31.5
4	31.2
5	31.04
6	30.93
7	30.85
8	30.78

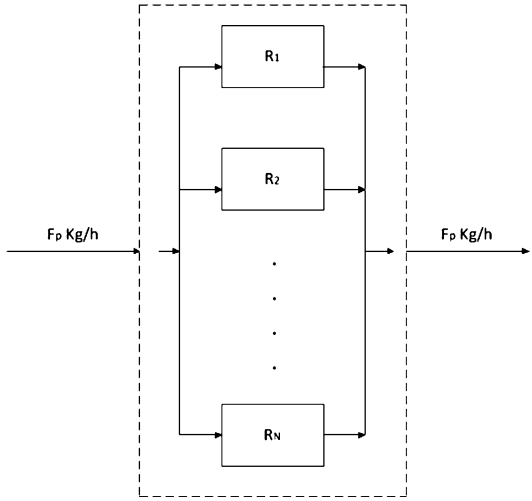


Fig. 9.2 *N* batch reactors operated in a continuous mode as a whole battery

8 (700 %), the substrate concentration just decreased from 33.3 to 30.78 g/L (7.6 %). In this case, intuitively, for several practical and operational reasons, we can infer that it is better to have just one bioreactor instead of several bioreactors in series.

Mathematical models will help us improve our decisions. In this example, we have developed a tool that allows us to further analyze the system and then find the optimum number of bioreactors. With a good model, we will be able to run simulations of different scenarios, improve our understanding and knowledge of the system, and design better control systems, as we will see in Sect. 9.4. Moreover, with an adequate mathematical model, we can drastically reduce the required number of experiments.

9.3.2 Building Simple Mathematical Models

In this section, we will attempt to develop mathematical models for different situations that you will face as a process or bioprocess engineer. Although these examples are limited and tailored to your mathematical background, it will be interesting and rewarding for you to discover that you can be involved with fascinating and ever-challenging examples.

Adapting a reactor batch-operation stage to a continuous processing line (can also be applied to, for example, bioreactors, autoclaves, and dryers).
In contrast to normal true batch processes, some processing plants are operated with just one stage functioning in a batch mode (e.g., winemaking, canned food production, dehydration processes) (Simpson et al. 2002). Moreover, most of the time it could be advantageous to achieve a fully continuous processing line, as shown in Fig. 9.2. As depicted in Fig. 9.2, although each reactor (R_1, R_2, …, R_N) is operated in a batch mode, the whole processing line operates in a continuous mode.

A Gantt chart showing the temporal programming schedule of a battery reactor system (Fig. 9.3) can be used as a first step in determining the number of reactors as a function of its effective volume (V_R) and volumetric flow rate (F_P) from the processing line. The continuous operation of the reactor

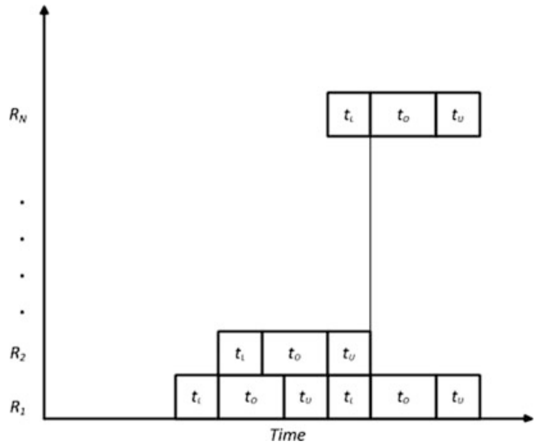


Fig. 9.3 Gantt chart of the reactor-operation against time

battery can be achieved if the loading step of the last reactor (R_N) finishes at the same time as the first reactor finishes its complete cycle and is ready for loading. As depicted in Fig. 9.3, this means that the loading time (t_L) multiplied by the number of reactors (R_N) must be equal to the total cycle time of one reactor ($t_L + t_O + t_U$). This relationship can be expressed mathematically as follows:

$$t_L R_N = t_L + t_O + t_U, \tag{9.4}$$

where R_N is the number of reactors and t_L, t_O, and t_U are the loading time, processing time, and unloading time, respectively. If we assume equal loading and unloading times ($t_L = t_U = t_X$), then substituting t_L and t_U by t_X in (9.4) and solving for N_R we get

$$R_N = 2 + \frac{t_O}{t_X}. \tag{9.5}$$

According to (9.5), the minimum number of reactors for a continuous processing line operation is three ($R_N \geq 3$). In addition, if we take into account that the effective volume of a reactor is the loading time (t_X) multiplied by the volumetric flow rate of the processing line (F_P), then

$$V_R = t_X F_P. \tag{9.6}$$

Then, solving (9.6) for t_X and replacing it in (9.5) we get

$$R_N = 2 + \frac{F_P t_O}{V_R}; \quad \text{therefore} \quad R_N = f(F_P, t_O, V_R). \tag{9.7}$$

Carrying out some calculations, assuming $F_P = 1{,}000$ L/h and $t_O = 10$ h, and then substituting F_p and t_O in (9.7), we can determine the number of reactors (R_N) according to its volume (V_R), as shown in Table 9.2.

This procedure, developed for chemical reactors, can be easily adapted and extended to other processes, like winemaking, canned food production, and batch dehydration.

Table 9.2 Reactors volume as a function of reactors number

Reactor volume, V_R (L)	Number of reactors, R_N
10,000	3
5,000	4
2,500	6
2,000	7
1,000	10

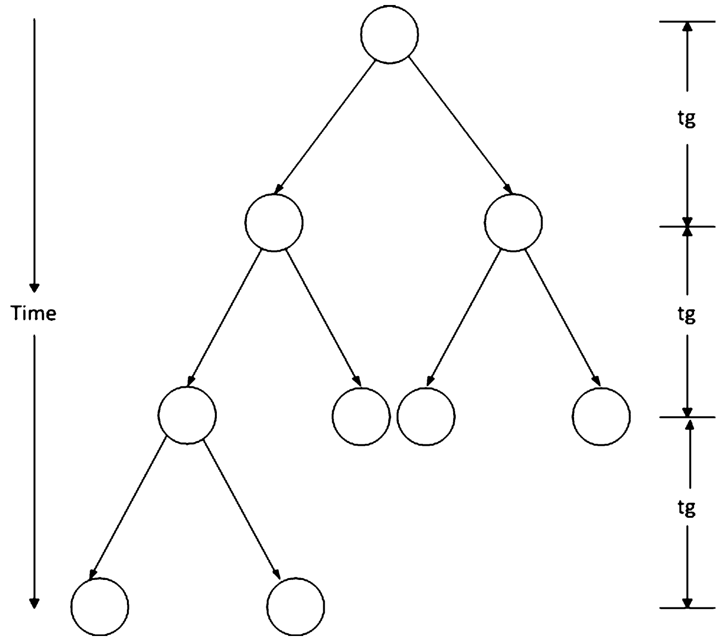


Fig. 9.4 Schematic representation of cellular division

Table 9.3 Bacteria population against time

Time	Bacteria population
0	$N_0 = 2^0 N_0$
$1t_g$	$2N_0 = 2^1 N_0$
$2t_g$	$4N_0 = 2^2 N_0$
$3t_g$	$8N_0 = 2^3 N_0$
...	...
...	...
nt_g	$N = 2^n N_0$

Modeling cell growth

Unicellular organisms (e.g., bacteria) duplicate in a process called cell division. Each cell divides into two new cells within a certain time, called the generation time (t_g). Schematically, we can represent this division process as depicted in Fig. 9.4.

Therefore, if we have N_0 bacteria at time = 0, then after one generation ($1t_g$) we will have $2N_0$ bacteria, and after two generations ($2t_g$) we will have $4N_0$ bacteria, and so on, implying that after each generation time, the bacterial population is doubling. Putting this information in tabular form, we get Table 9.3.

In addition, the number of generations (n) is related to time (t) and generation time (t_g) as follows:

$$n = \frac{t}{t_g}\left(\text{for } t = 0, \quad n = 0; \quad \text{for } t = 1t_g, \quad n = 1, \text{and so on}\right). \tag{9.8}$$

Then substituting n from (9.8) in the expression $N = 2^n N_0$, we get

$$N = 2^{\frac{t}{t_g}} N_0. \tag{9.9}$$

Now arranging (9.9) we obtain

$$\ln\left(\frac{N}{N_0}\right) = \frac{t}{t_g} \ln 2. \tag{9.10}$$

By definition, $ln2/t_g = \mu$ (specific growth rate); thus the number of bacteria after time t can be expressed by an exponential equation as follows:

$$N = N_0 \, e^{\mu t}. \tag{9.11}$$

According to (9.11), bacterial cell division obeys an exponential growth curve. As you will see in future courses, this simple mathematical model will be very useful when designing batch bioreactors and also in multiple practical applications in food science, environmental engineering, biological engineering, and biotechnology.

9.4 The Importance of Simulations in Chemical and Bioprocess Engineering

So far, we have provided examples of the importance of mathematical modeling, and although the examples were simple, we have been able, with rudimentary mathematical tools, to construct some mathematical models that are useful in chemical and bioprocess engineering. In addition, as mentioned and explained in Sect. 9.1, simulation can help us gain a better understanding of our system and determine which variables are most important within the mathematical model. Simulations also help us to analyze different scenarios and in this way get experience. Normally, it is thought that experience is only gained by practice. However, with a good mathematical model, through simulation we can learn a lot about our system and gain experience. And as you know, experience is the mother of the sciences.

As has been common throughout the book, we will illustrate the usefulness of simulation through examples.

Energy conservation

As a new engineer in a processing plant, you are assigned to investigate the benefits of adding insulation to a wall (stainless steel, 0.02 [m] thick, 8 m^2 of area) of a piece of equipment that is operating at 100 °C (ambient temperature is 20 °C). According to your boss, the company is wasting too much energy, and it might be profitable and environmentally friendly if the wall were insulated

Table 9.4 Heat losses against fiberglass thickness

Fiberglass thickness, L (m)	Heat losses, Q (W)
0	480,000
0.01	2,420
0.02	1,213
0.03	810
0.04	607
0.05	486
0.06	405

with some good insulator material (e.g., fiberglass). First, you take a look at your notes (Chap. 6, Table 6.2 and equations (6.16) and (6.17)) and decide to calculate the actual losses (without insulation) and then run a simulation to evaluate the heat losses under different fiberglass thicknesses. According to your notes, you estimate the actual heat losses as follows.

The heat losses (Q) for a wall under steady-state conditions can be estimated using the following equation:

$$Q = A\frac{k\Delta T}{L}, \tag{9.12}$$

where, in this case,
$A = 8\ \text{m}^2$, $k_{\text{STAINLESS STEEL}} = 15$ w/m °C, $\Delta T = 80$ °C, and $L = 0.02\ \text{m}^2$; then
$Q = 480{,}000$ W.

Now, from equation (6.17), we can write an expression for heat losses of a composite wall including fiberglass as

$$Q = A\frac{\Delta T}{\frac{L_1}{k_1} + \frac{L_2}{k_2}}. \tag{9.13}$$

$k_{\text{FIBERGLASS}} = 0.038$ W/m °C, then substituting ΔT, L_1, k_1, and k_2, we get

$$Q = 8\frac{80}{\frac{0.02}{15} + \frac{L}{0.038}}\ \text{W/m °C}.$$

Of course, if $L = 0$ (no fiberglass), then $Q = 480{,}000$ W. Table 9.4 shows the heat losses (Q) for different fiberglass thicknesses (L).

From Table 9.4 we can reach at least two important conclusions. First, the addition of an insulator is extremely effective in reducing heat loss. For example, the addition of 1 cm (0.01 m) of fiberglass reduced the heat losses almost 200 times (from 480,000 to 2,420 W). Second, although the addition of more fiberglass reduces heat loss, its effectiveness decreases as the thickness increases. From these statements we can infer that in similar processing situations, it is highly convenient to add an insulator, but the remaining question is: what is the optimum thickness? In Sect. 11.8, in problem 31, you will be challenged to find an optimum insulator thickness.

Simulation is the expression of mathematical modeling. As mentioned at the beginning of this section, simulation helps us to gain experience and allows us to optimize.

9.5 Why Do Automatic Process Control?

9.5.1 Management of Disturbances

Using the example of the shower from Chap. 3 (Sect. 3.2), we can ask ourselves what would happen if, after we got the water temperature to just the right setting, someone turned on cold water elsewhere in the house. The flow of cold water in the shower would probably decrease. Because the hot water comes through a different line, it would not decrease, and so the shower would get hotter. In this case, at home, the problem is not as critical because we can just step away from the hot water and adjust the temperature. However, in a process plant, emptying a pond might not be possible, or overheating could pose a fire hazard. Formally speaking, events that change features in materials entering a process are called perturbations. All processes are affected by them, whether the changes involve water flows, gases, vapors, fuel, coolant, temperatures, compositions, or what have you.

To take it to the industrial level, imagine a liquid that needs to be received and stored at 20 °C, but the actual temperature in the tank is 30 °C. We might think of passing the liquid through a radiator to cool down the temperature by 10 °C; this would solve the problem of the storage temperature. Something closer to reality is that the liquid would leave the tank at a temperature ranging between 25 and 32 °C, and because the temperature varies during the day, or because water is being added at a different temperature in winter than in summer, or because there are other water consumption needs at the plant, we would receive less water flow, for example. Then, when the water temperature is cooled by 10 °C, we store it at a temperature ranging between 15 and 22 °C. There might even be an extreme situation where the liquid leaves the tank at a temperature between 10 and 30 °C, when it sometimes needs to be cooled and sometimes requires heating. The treatment of disturbance is a major issue in the automatic control of processes. The control task is to ensure that, regardless of the inlet temperature of the liquid into the tank, it comes out at the desired temperature, i.e., 20 °C.

9.5.2 Maintaining Optimum Operating Conditions

Another critical aspect is to keep the process running under favorable conditions, which might mean maximizing production, minimizing energy consumption, or attaining some other desired outcome. Suppose there is a chemical reactor where a reagent A becomes a valuable product B. Furthermore, it is known that the higher the temperature of the reactor, the larger the amount of B will be produced. In the first instance, you could say that it is best to keep the temperature as high as possible. However, the more you want to heat, the greater will be the cost of heating. So there is a tradeoff; perhaps the most preferable situation would be to have a temperature that ensures a good supply of B, but without excessive consumption of heating oil.

Figure 9.5a shows that the higher the temperature, the greater will be the revenue generated by the increased production of B, but higher temperatures will bring higher heating costs. Figure 9.5b shows the difference between the revenue and the costs, i.e., the profits.

As depicted in Fig. 9.5b, at a temperature of 10 °C, there are no heating costs, but also not much production of B. At temperatures above 103 °C, the cost of heating exceeds the revenue received from the production of B and then it is no longer profitable to produce. As depicted in Fig. 9.5b, the optimum temperature is 70 °C. These three conditions are marked by an *X* in both graphs. Maintaining the temperature as close as possible to 70 °C will be the task of automatic control, i.e., any time the reactor temperature deviates from 70 °C, the system will be brought back to continuously operate at 70 °C.

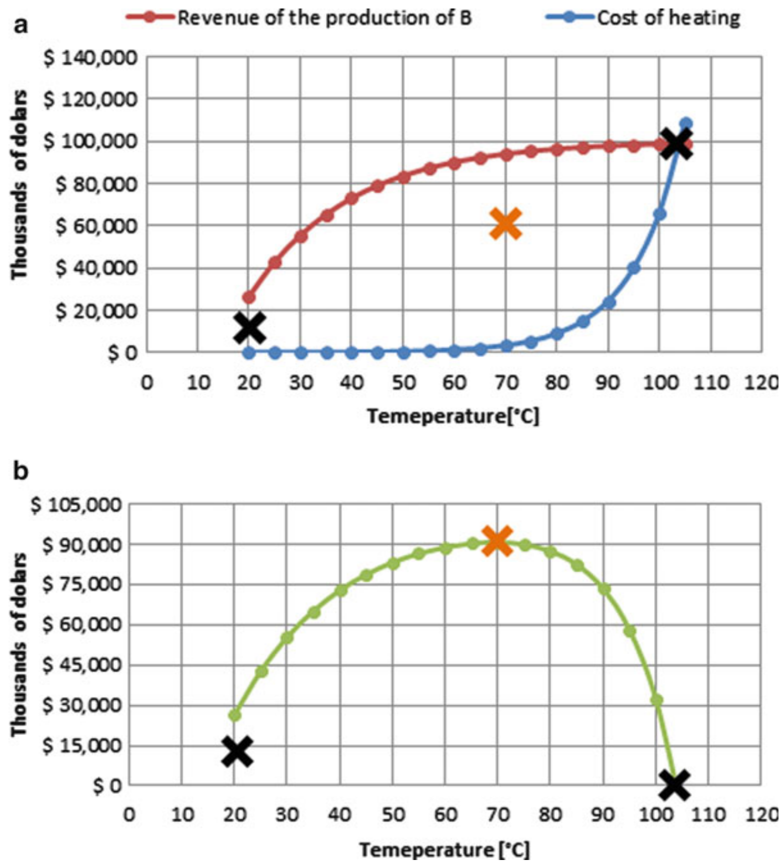


Fig. 9.5 (**a**) Revenues and costs of production of B. (**b**) Profits in production of B

9.5.3 Decreased Variability in Bottlenecks

There are cases where a suitable process control can even increase the overall performance of the process, especially in production processes working with bottlenecks. Such is the case of a factory that makes cereal bars where the product labels indicate a fiber content of 4 %. Given that the machines at the factory are not well controlled, the addition of fiber has a variability of ±2 %. In fact, the machines, programmed to add 4 % fiber, deliver a product that has between 2 and 6 % fiber. Therefore, to ensure that the products comply with the information on the label, 6 % fiber must be added and all bars are expected to have between 4 and 8 % fiber.

Suppose that, due to supplier constraints, the plant only has 100 kg of fiber a day and each cereal bar weight 100 g. Whereupon, under current conditions, the processing plant will be able to produce 16,667 cereal bars day. The situation would be very different if we could improve the control of the machines so that the error in the added amount of fiber were ±1 % instead of ±2 %, as shown in the center of Fig. 9.6. In this case, you could add 5 % fiber and expect the bars to have between 4 and 6 % fiber. It is easy to calculate that in this new scenario, the plant could produce 20,000 cereal bars daily. Although not conclusive, it seems attractive to invest in improving the control system.

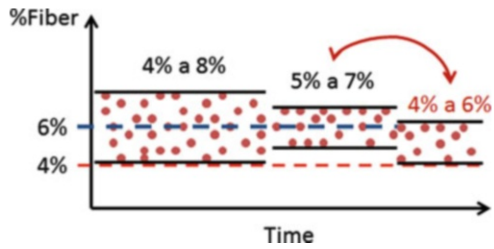


Fig. 9.6 Error in the amount of fiber against time

9.6 Control Strategies

9.6.1 PID Controller

The simplest control algorithm to calculate the compensating action of the variable is called proportional control. It is the first component of a more complex algorithm called a proportional integral derivative. As its name suggests, the command to the actuator is calculated in proportion to the error, as shown in the following equation:

$$\Delta c(t) = \mathrm{Kc} \times e(t), \tag{9.14}$$

where Kc is the proportional constant of the controller expressed as a %/bar and $e(t)$ is the negative feedback error (bar).

Thus, substituting (9.14) in (3.4) gives

$$c(t) = \mathrm{ce} + \mathrm{Kc} \times (\mathrm{PSP} - \mathrm{Pm}). \tag{9.15}$$

To have a better appreciation of the controller behavior, imagine that an operator that uses compressed air suddenly decreases its consumption. At steady state, the input mass flow rate of air equals the output mass flow rate of air, and there is no mass change in the storage tank. However, a decrease in the output mass flow rate of air will cause a rise in the tank pressure (input air > output air). To do some simple calculations, assume the following information: Kc = 0.5 %/bar, ce = 50 %, and a set point of 80 bar. Then, using (9.15), we can estimate the progress of the process as follows:

Time 0: the system is in steady state, and the measured pressure is equal to the desired state. Therefore,

$$c(0) = 50 + 0.5 \times (80 - 80) = 50 + 0 = 50. \tag{9.16}$$

Time 1: a perturbation is introduced raising the pressure to 85 bar, and the controller responds by closing the inlet valve 2.5 %, as shown by (9.17):

$$c(1) = 50 + 0.5 \times (80 - 85) = 50 - 2.5 = 47.5. \tag{9.17}$$

Time 2: the pressure is lowered to 82 bar but still exceeds the desired pressure. So the controller closes the valve in 1.0 % increments, as shown by (9.18):

$$c(2) = 47.5 + 0.5 \times (80 - 82) = 47.5 - 1.0 = 46.5. \tag{9.18}$$

Table 9.5 Summary of the data of the estimated progress of the process

t (s)	P_m (bar)	e (bar)	Δc (%)	c (%)
0	80	0.0	0.0	50.0
1	85	−5.0	−2.5	47.5
2	82	−2.0	−1.0	46.5
3	79	−1.0	+0.5	47.0
4	81	0.5	−0.5	46.5
5	80	−0.5	0.0	46.5
6	80	0.0	0.0	46.5
7	80	0.0	0.0	46.5

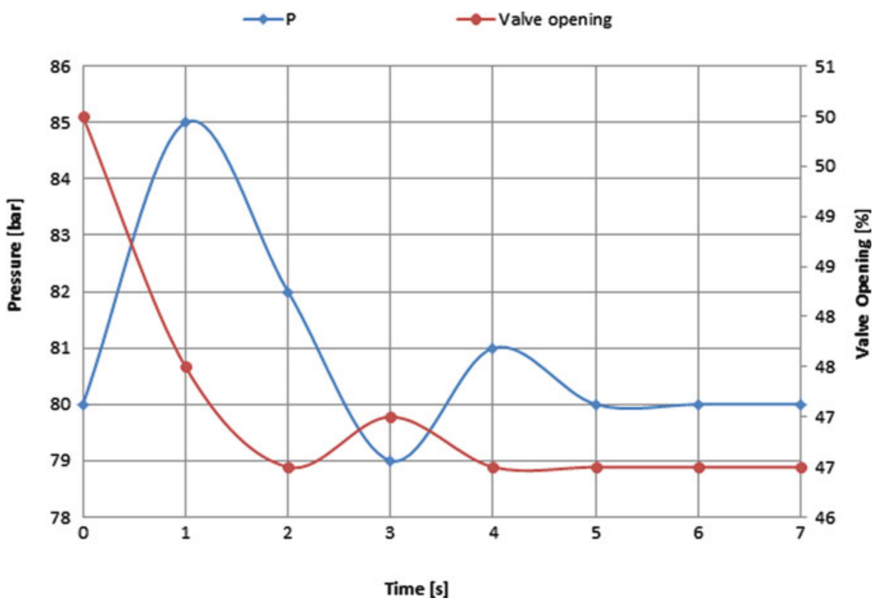


Fig. 9.7 Behavior of binary signal to control valve

Time 3: after closing the valve twice in quick succession, the pressure is now at 79 bar. As the pressure is now less than 80 bar, the controller responds by closing the outlet valve by 0.5 %, as shown by (9.19):

$$c(3) = 46.5 + 0.5 \times (80 - 79) = 46.5 + 0.5 = 47.0. \quad (9.19)$$

Time 4: with the outlet valve closed, the pressure has risen to 81 bar, again over the desired pressure, so the controller opens the valve 0.5 %:

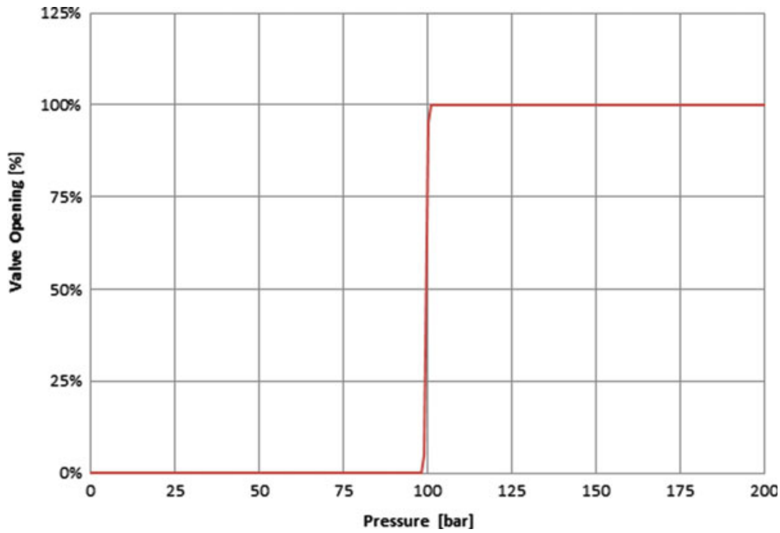
$$c(4) = 47.0 + 0.5 \times (80 - 81) = 47.0 - 0.5 = 46.5. \quad (9.20)$$

Time 5: since the last adjustment, the pressure is balanced at 80 bar, so the controller does not perform any more corrections:

$$c(5) = 46.5 + 0.5 \times (80 - 80) = 46.5 + 0.0 = 46.5. \quad (9.21)$$

Table 9.5 summarizes the data of the estimated progress of the process. The same data are depicted in Fig. 9.7.

Fig. 9.8



Unlike what is shown in Table 9.5, strictly speaking, we should mention that a pure proportional control cannot reach the set point with an accuracy of 100 %; it only reaches a value close to the set point, where the remaining difference is known as the offset.

In the search for greater efficiency in the ability of controllers to control processes, the proportional term is complemented by an integral expression and another, derivative, expression. In future courses, you will learn about this improvement and about controller tuning.

9.6.2 On/Off Controllers

The valve actuation PAHv-102 is governed by a binary control logic PAH programmed in controller-102. Binary means that there are only two possible states of the actuator, open or closed. As mentioned previously, the valve will open to 100 % if the pressure inside the tank E-102 becomes equal to or greater than 100 [bar]; otherwise, the valve will remain open 0 % (or 100 % closed). This can be represented as a piecewise function, composed as follows:

$$\text{if}\begin{cases}\text{Pressure} < 100\ \text{bar then valve is closed}\\ \text{Pressure} \geq 100\ \text{bar then valve is open}\end{cases}$$

In graphical terms, the behavior of the valve is depicted in Fig. 9.8.

9.7 Multivariable and Supervisory Control

In the examples of controlled processes that we have been discussing, we have worked with systems handling one resource and with one target variable, i.e., single-input/single-output (SISO) systems. However, in actual practice, the process is affected by multiple input variables and has multiple target variables, i.e., a multiple-input/multiple-output (MIMO) system.

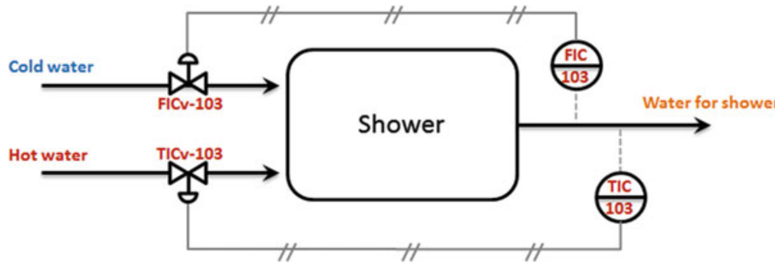


Fig. 9.9 Control loop for the shower system

9.7.1 Multivariable Control

Recall the example of the shower in Sect. 3.2. The action was the ability to change the cold water flow and the target the shower temperature (more specifically the pleasant feeling on the skin). But there may be situations in which, although the temperature is right, one cannot take a shower because the water flow is too low or too high. Implicitly there appears a second objective, which is adequate water flow. Intuitively, you can put together two control loops as indicated in Fig. 9.9.

Suppose that the temperature is fine, but the water flow is less than desired. If FIC-103 increases the cold water flow, it will increase the total water flow; however, the water temperature will go down. Consequently, TIC-103 will detect that the temperature has decreased and will try to compensate by increasing the flow of hot water. Of course, adding more hot water will lead to an increase in the total flow, but if both drivers (FIC-103 and TIC-103) are well tuned, the process will end with both converging to the desired values.

The problem that occurs when a control loop disturbs the stability of the other control loop is called coupling, and it can be a difficult problem to address.

Alternatively, one might try controlling the total flow by manipulating the hot water flow and the temperature by manipulating the cold water flow. Given multiple options for designing the control loops, the choice is usually based on specialized techniques. When variables cannot be linked, to avoid important couplings, uncouplers can be used. Uncouplers are elements that compensate actions on the loops in which no action has been taken.

9.7.2 Supervisory Control

Over time, new ways of managing more complex processes have been developed. Attempts have been made to go beyond the limitations of a PID controller, including staff experience in supervising process control systems. This does not necessarily involve a phenomenological model of processes because what is sought is a set of rules based on experience.

A supervisory control system could collect information on the flow and water temperature of the shower and, in concert, change the amount of cold water and hot water to meet both objectives simultaneously. The system is described in Fig. 9.10.

TT-106 and FT-106 transmitters report and record the state of target variables and instruct the system to define the desired flow of hot and cold water. Several variants of supervisory controls exist, but it is commonplace to look for a system that uses fuzzy logic to determine the changes in the set point of the process loops. An example of a fuzzy classification of the shower case is as follows:

In the case of temperature:

Less than 35 °C is a low temperature.

Between 35 and 45 °C is a pleasant temperature.

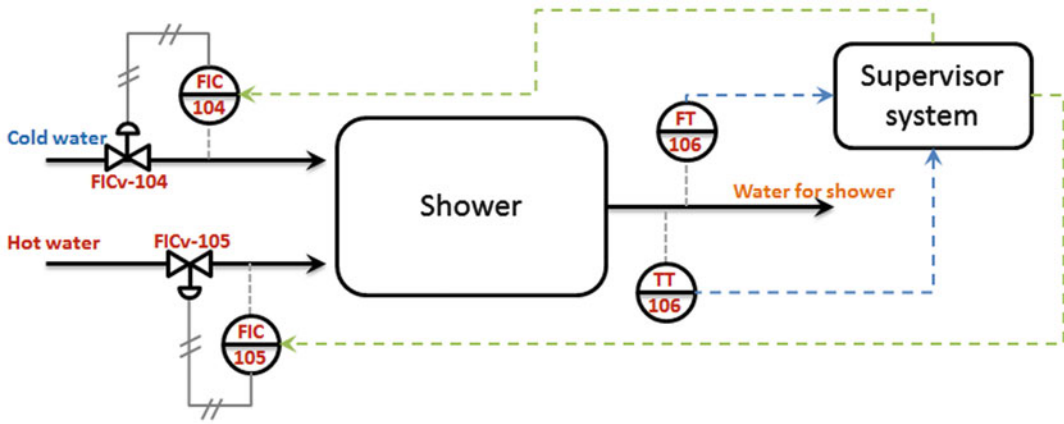


Fig. 9.10 P&ID system with supervisory control

Table 9.6 Rules for supervisory system

		Temperature		
		Low	Desired	High
Flow	Low	H: Increase C: Maintain	H: Increase C: Increase	H: Maintain C: Increase
	Desired	H: Increase C: Decrease	H: Maintain C: Maintain	H: Decrease C: Increase
	High	H: Maintain C: Decrease	H: Decrease C: Decrease	H: Decrease C: Maintain

H: action to be taken on hot water flow
C: action to be taken on cold water flow

Greater than 45 °C is a high temperature.
In the case of water flow:
Below 8 L/min indicates low flow.
Between 8 and 12 L/min indicates desired flow.
Greater than 12 L/min indicates high flow.

Once the status of the process performance is defined, the actuator may be defined as described in Table 9.6.

The supervisory system can achieve a better response in terms of speed and stability. As an example, if the temperature is acceptable but the flow rate is very low, the supervisory system simultaneously increases the flow of hot and cold water, achieving a greater flow but without changing the temperature. Another example is where the temperature is too high and the total flow too low. In that case, the system will maintain the hot water flow and increase the cold water flow; this would result in a lower temperature and a higher flow, favoring both goals at once.

9.8 Proposed Questions

1. Give one good reason why you should install an automatic control system in a process.

   A: The equipment is designed to operate effectively under certain specific conditions, such as at a certain temperature or concentration in the flows. However, a raw material might come to the equipment at a different temperature or a different concentration than those assumed in the design. Therefore, to meet the required specifications, it is essential to fit automatic controls that are capable of minimizing such disturbances and obtain a regular product, independent of the input variations.

2. Why is it important to include the integral term in a PID controller?

   A: Because each time the process deviates from the desired set point, this is the only way to effectively reach steady state with zero error between measurement and control reference values.

3. How poorly will a nontuned PID controller function?

   A: Tuning is key for determining how well and robustly (meaning the ability to operate under a wide variety of conditions and disturbances) a controller is performing. Tuning determines the controller response time, or how fast it can reach steady state when activated or following disturbances in the system, and the controller's ability to minimize steady-state error.

   Visit the following Web site for more information on different types of fedback control. https://newton.ex.ac.uk/teaching/resources/CDHW/Feedback/ControlTypes.html

4. What is the basic idea behind supervisory control and what kind of advantage does it have over traditional PID controllers?

   A: Supervisory controls seek to mimic the behavior of human supervisors who have had a lot of experience with the process, translating their knowledge into a set of logical rules to be performed each time the process requires it. The advantage of supervisory controls over traditional PIDs is that they allow for coordinated use of more than one resource at a time, bringing a process to a desired condition rapidly and efficiently.

5. What is an ON/OFF controller and what is its primary use?

   A: In a given scenario, a resource will be fully closed, but in all other scenarios the resource will be fully open (or vice versa). For example, in the case of a pressure relief valve on a pressurized tank, in normal conditions, the relief valve operates fully closed. But if for some unforeseen reason the pressure exceeds the safety limit, then the controller will open the valve completely, releasing the pressure inside the tank. One of the main uses of this type of control is in its security mechanisms due to its discrete nature.

References

Simpson, R., Almonacid, S., and Teixeira, A. 2002. Optimization criteria for batch retort battery design and operation in food canning-plants. J. Food Proc. Eng., 25, 515–538.

Additional Web References

Teacher package: Mathematical Modeling http://plus.maths.org/content/os/issue44/package/index
Introduction to Modeling Lesson https://www.youtube.com/watch?v=GnlgGmLNn5o
C Batch Process Control System http://www.youtube.com/watch?v=IlH-tSxlTRE
Introduction: PID Controller Design http://ctms.engin.umich.edu/CTMS/index.php?example=Introduction&section=ControlPID
PID Control - A brief introduction https://www.youtube.com/watch?v=UR0hOmjaHp0