Chapter 3. Batch Processing

What You Will Learn

- Batch processing is very different from continuous processing.
- The design equations are different—unsteady state.
- Scheduling of equipment is important.
- There are different types of scheduling patterns.

Some key reasons for choosing to manufacture a product using a batch process were discussed in Chapter 2. These include small production volume, seasonal variations in product demand, a need to document the production history of each batch, and so on. When designing a batch plant, there are many other factors an engineer must consider. The types of design calculations are very different for batch compared with continuous processes. Batch calculations involve transient balances, which are different from the steady-state design calculations taught in much of the traditional chemical engineering curriculum. Batch **sequencing**—the order and timing of the processing steps—is probably the most important factor to be considered. Determining the optimal batch sequence depends on a variety of factors. For example, will there be more than one product made using the same equipment? What is the optimal size of the equipment? How long must the equipment run to make each different product? What is the trade-off between economics and operability of the plant? In this chapter, these questions will be addressed, and an introduction to other problems that arise when considering the design and operation of batch processes will be provided.

3.1. Design Calculations for Batch Processes

Design calculations for batch processes are different from the steady-state design calculations taught in most unit operations classes. The batch nature of the process makes all design calculations unsteady state. This is best demonstrated by example; Example 3.1 illustrates the types of design calculations required for batch processing.

Example 3.1.

In the production of an API (active pharmaceutical ingredient), the following batch recipe is used.

Step 1: 500 kg of reactant A (MW = 100 kg/kmol) is added to 5000 kg of a mixture of organic solvent (MW = 200 kg/kmol) containing 60% excess of a second reactant B (MW = 125 kg/kmol) in a jacketed reaction vessel (R-301), the reactor is sealed, and the mixture is stirred and heated (using steam in the jacket) until the temperature has risen to 95°C. The density of the reacting mixture is 875 kg/m^3 (time taken = 1.5 h).

Step 2: Once the reaction mixture has reached 95°C, a solid catalyst is added, and reaction takes place while the batch of reactants is stirred. The required conversion is 94% (time taken = 2.0 h).

Step 3: The reaction mixture is drained from the reactor and passed through a filter screen (Sc-301) that removes the catalyst and stops any further reaction (time taken = 0.5 h).

Step 4: The reaction mixture (containing API, solvent, and unused reactants) is transferred to a distillation column, T-301, where it is distilled under vacuum. Virtually all of the unused reactants and approximately 50% of the solvent are removed as overhead product (time taken = 3.5 h). The end point for the distillation is when the solution remaining in the still contains less than 1 mol% of reactant B. This ensures that the crystallized API, produced in Step 5, meets specification.

Step 5: The material remaining in the still is pumped to a crystallizer, CR-301, where the mixture is cooled under vacuum and approximately 60% of the API from Step 2 crystallizes out (time taken = 2.0 h).

Step 6: The API is filtered from the crystallizer and placed in a tray dryer, TD-301, where any entrapped solvent is removed (time taken = 4 h).

Step 7: The dried API is sealed and packaged in a packing machine, PK-301, and sent to a warehouse for shipment to the customer (time taken = 1.0 h).

Perform a preliminary design on the required equipment items for this batch process.

Solution

The equipment items will be designed in sequence.

Step 1: Reaction Vessel—Preheat

The reaction vessel, which is used to preheat the reactants and subsequently run the reaction, is designed first. For the batch size specified, the volume of the liquid in the tank, V, and the volume required for the reaction vessel, V_{tank}, are given by Equations (E3.1a) and (E3.1b), in which it is assumed that the vessel is approximately 60% full during operation.

$$V = \frac{5500\ [\text{kg}]}{875\ [\text{kg/m}^3]} = 6.286\ \text{m}^3 \qquad \text{(E3.1a)}$$

$$V_{required} = \frac{5500\ [\text{kg}]}{875\ [\text{kg/m}^3]}\frac{1}{0.6} = 10.48\ \text{m}^3 = 2768\ \text{gal} \qquad \text{(E3.1b)}$$

Because reactors of this sort come in standard sizes, a 3000 gal (V_{tank}) reactor is selected.

The heat transfer characteristics of this vessel are then checked. For a jacketed vessel, the unsteady-state design equation is

$$\rho V C_p \frac{dT}{dt} = UA(T_s - T) \qquad \text{(E3.1c)}$$

where ρ is the liquid density, C_p is the liquid heat capacity, T is the temperature of the liquid in the tank (95°C is the desired value in 1.5 h), U is the overall heat transfer coefficient from the jacket to the liquid in the tank, A is the heat transfer area of the jacket (cylinder surface), and T_s is the temperature of the condensing steam. (Normally, there is also a jacketed bottom to such a vessel, but this added heat transfer area is ignored in this example for simplification.) Integration of this equation yields

$$\ln\frac{(T_s - T_{final})}{(T_s - T_o)} = -\frac{UA\Delta t}{\rho V C_p} \qquad \text{(E3.1d)}$$

where T_o is the initial temperature in the tank (assumed to be 25°C). The following “typical” values are assumed for this design:

C_p = 2000 J/kg°C

T_s = 120°C (200 kPa Saturated Steam)

U = 300 W/m^2°C

Tank Height to Diameter Ratio = 3/1 (so H = 3D)

Assuming the tank to be cylindrical and ignoring the volume of the bottom elliptical head, the tank volume is $V_{tank} = \pi D^2 H/4 = 3\pi D^3/4$. Thus, the tank diameter, D, is 1.689 m. The height of fill is $H_{fill} = 4V/(\pi D^2) = 2.806$ m. The area for heat transfer is $A = \pi D\boldsymbol{H}_{fill} = 14.89\ \text{m}^2$, because it was assumed there was negligible heat transfer to the vapor space. When these values are used in Equation (E3.1d), it is found that the time required for preheating the reactor, Δt, is 3288 s (55 min). Thus, the step time requirement of 1.5 h for this step is met. The additional time is required for filling, sealing, and inspecting the vessel prior to heating. It should be noted that there may be process issues that require a slower temperature ramp, which can be accomplished by controlling the steam pressure. Note also that it is assumed that the time requirement for cleaning the vessels in this example is included in the step times given in the problem statement.

Step 2: Reaction Vessel—Reaction

It is assumed that the reaction of one mole each of A and B to form one mole of the product is second order (first order in each reactant) and that the rate constant is $7.09 \times 10^{-4}\ \text{m}^3/\text{kmol s}$. The relationship for a batch reactor is

$$\frac{dC_A}{dt} = -kC_AC_B \tag{E3.1e}$$

where A and B are the two reactants, and A is the limiting reactant. The standard analysis for conversion in a reactor yields

$$C_A = C_{Ao}(1 - X) \tag{E3.1f}$$

$$C_B = C_{Ao}(\Theta - X) \tag{E3.1g}$$

$$\frac{dX}{dt} = kC_{Ao}(1 - X)(\Theta - X) \tag{E3.1h}$$

where $C_{Ao} = (500\ \text{kg}/100\ \text{kg/kmol})(875\ \text{kg/m}^3)/5500\ \text{kg} = 0.796\ \text{kmol/m}^3$. Because reactant B is present in 60% excess, $\Theta = 1.6$. The desired conversion, X_{final}, is 0.94. Integration of Equation (E3.1h) with an initial condition of zero conversion at time zero yields

$$\frac{1}{\Theta - 1}\left[ln\frac{\Theta - X_{final}}{1 - X_{final}}\right] = kC_{Ao}\Delta t \tag{E3.1i}$$

When all of the values are inserted into Equation (E3.1i), the time (Δt) is found to be 7082 s, or 118 min, which is just less than the desired 2 h allotted for the reaction. For simplicity, the additional reaction time that occurs after the mixture leaves the reactor until the catalyst is removed from the reacting mixture has been ignored.

Step 3: Draining Reaction Vessel and Catalyst Filtration

This step will be modeled as a draining tank, which may significantly underestimate the actual required time for draining and filtering. In reality, experimental data on the filter medium and inclusion of the exit pipe frictional resistance would have to be included to determine the actual time for a specific tank. Generally, the filter is the bottleneck in such a step. Here, a 2-in schedule-40 exit pipe, with a cross-sectional area of $0.00216\ \text{m}^2$, is assumed.

For a draining tank, the model is

$$\frac{dm}{dt} = \frac{d(\rho A_t H)}{dt} = -\dot{m} = -\rho A_p v_p \tag{E3.1j}$$

where ρ is the density of the liquid in the tank, A_t is the cross-sectional area of the tank, H is the height of liquid in the tank, A_p is the cross-sectional area of the exit pipe, and v_p is the velocity of liquid in the exit pipe, which, from Bernoulli's equation (turbulent flow), is $(2gH)^{1/2}$, where g is the gravitational acceleration. Therefore, Equation (E3.1j) becomes

$$\frac{dH}{dt} = -\frac{(2g)^{1/2}A_p}{A_t}H^{1/2} \qquad \text{(E3.1k)}$$

Integrating from H = 2.806 m at t = 0 to find the time when H = 0 yields

$$-2H^{0.5}\Big|_{2.806\ m}^{0} = \frac{2^{0.5}(9.81\ [\text{m/s}^2])^{0.5}(0.00216\ [\text{m}^2])}{\frac{\pi(1.689\ [\text{m}])^2}{4}}\Delta t \qquad \text{(E3.1l)}$$

which gives Δt = 785 s = 13 min, which is rounded up to 30 minutes for this step. Note that this time can be further reduced by pressurizing the vessel with an inert gas.

Step 4: Distillation of Reaction Products

A material balance on the reactor at the end of Step 2 yields the following:

Component, i	kmoles	x_i	MW	mass (kg)
Reactant A	= (1 – 0.94)(5.0) = 0.3	0.0106	100	30.0
Reactant B	= (1.6)(5) – (5.0 – 0.3) = 3.3	0.1166	125	412.5
Solvent S	20.0	0.7067	200	4000.0
Product P	= (0.94)(5.0) = 4.7	0.1661	225	1057.5
Total	**28.3**	**1.0000**		**5500.0**

Initially, the reaction mixture is heated to its boiling point of 115°C at the operating pressure. This is done by condensing steam in a heat exchanger located in the still of the column. The time to heat the mixture from 95°C (the temperature leaving the reactor, assuming no heat loss in the filter) to 115°C is given by Equation (E3.1d) with the following variable values:

T_s = 120°C

ρ= 875 kg/m^3

C_p = 2000 J/kg°C

U = 420 W/m^2°C

A = 10 m^2

Solving for the unknown time gives t = 4215 s = 70.3 min.

The distillation is performed using a still with three theoretical stages (N = 3), a boil-up rate, V = 30 kmol/h, and a reflux ratio, R = 4.5. The volatilities of each component relative to the product are given as follows:

α_{AP} = 3.375

α_{BP} = 2.700

α_{SP} = 1.350

α_{PP} = 1.000

The solution methodology involves a numerical integration using the method of Sundaram and Evans [1]. The overall material and component balances are given by

$$-\frac{dW}{dt} = D = \frac{V}{1+R}$$

or in finite difference form,

$$W^{(k+1)} = W^{(k)} - \left(\frac{V}{1+R}\right)\Delta t \tag{E3.1m}$$

$$\frac{d(Wx_{W_i})}{dt} = x_{D_i}\frac{dW}{dt}$$

or in finite difference form,

$$x_{W_i}^{(k+1)} = x_{W_i}^{(k)} + (x_{D_i}^{(k)} - x_{W_i}^{(k)})\frac{W^{(k+1)} - W^{(k)}}{W^{(k)}} \tag{E3.1n}$$

where W is the total moles in the still; x_{Di} and x_{Wi} are the mole fractions of component i, at any time t, in the overhead product and in the still, respectively; k is the index for time in the finite difference representation; and Δt is the time step. These equations are solved in conjunction with the sum of the gas-phase mole fraction equaling unity and the Fenske-Underwood-Gilliland method for multicomponent distillation. This leads to the following additional equations:

$$x_{D_r} = \frac{x_{W_r}}{\sum_{i=1}^{C} x_{W_i}\alpha_{1,C}^{N_{min}}} \text{ and } x_{D_i} = x_{W_i}\left(\frac{x_{D_i}}{x_{w_i}}\right)\alpha_{i,r}^{N_{min}} \tag{E3.1o}$$

$$R_{min} = \frac{\alpha_{1,C}^{N_{min}} - \alpha_{1,c}}{(\alpha_{1,C} - 1)\sum_{i=1}^{C} x_{w_i}\alpha_{1,C}^{N_{min}}} \text{ and } \frac{N - N_{min}}{N+1} = 0.75\left[1 - \left(\frac{R - R_{min}}{R+1}\right)^{0.5668}\right] \tag{E3.1p}$$

where R_{min} and N_{min} are the minimum values for the reflux ratio and the number of theoretical stages, respectively. The solution of these equations is explained in detail by Seader and Henley [2], and the results for this example are shown in Figures E3.1(a) and E.3.1(b).

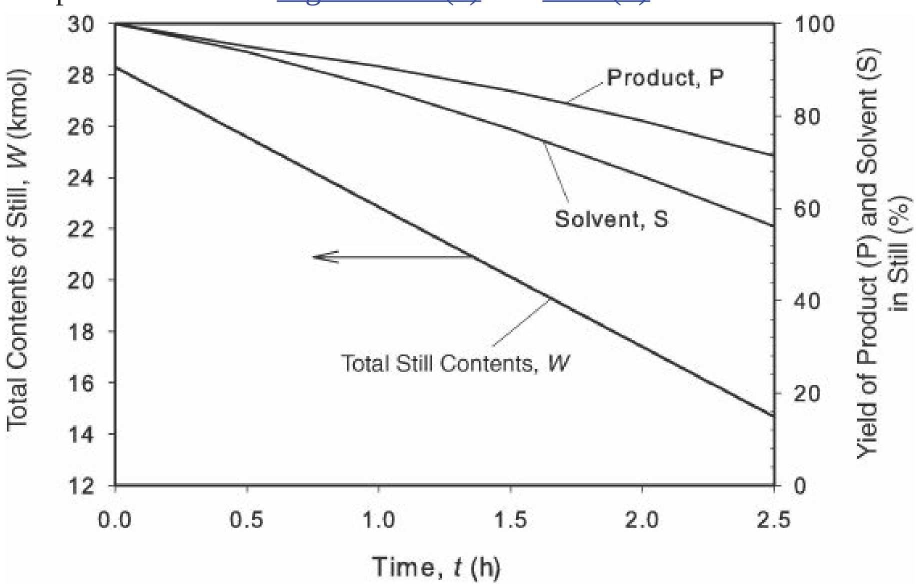

Figure E3.1(a). Change of Still Contents and Yields of P and S with Time

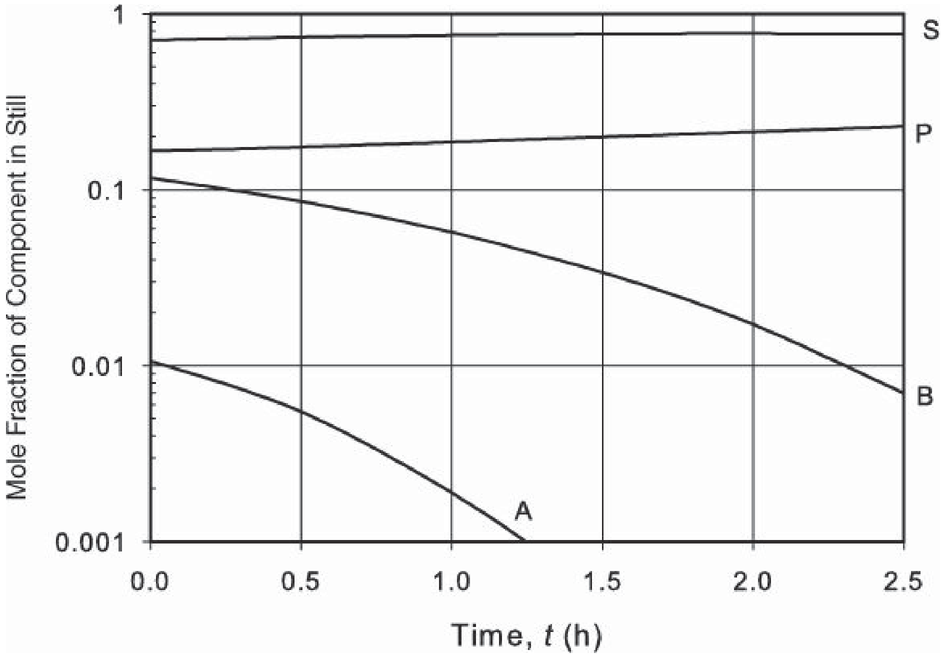

Figure E3.1(b). Change in Composition of Still Material with Time

From Figures E3.1(a) and (b), the mole fraction of reactant B is seen to drop to less than the specification of 0.01 (1 mol%) at a time of approximately 2.3 h. This time, coupled with the heating time of 70.2 min, gives a total of 3.5 h. However, note that only about 75% of the product remains in the still to be recovered in the next step.

Step 5: Cooling and Crystallization of Product

The analysis of the crystallization, filtration, drying, and packaging steps is beyond the scope of this analysis. Therefore, it is assumed that the times for each of these steps have been determined through laboratory-scale experiments, and those times are simply stated here. The amount of product crystallized is 80% of the product recovered from the still, or 60% of the 1057.5 kg produced in the reactor (634.5 kg). The time required to cool and crystallize is 2 h.

Step 6: Filtration and Drying

The time required for filtration and drying is 4 h.

Step 7: Packaging

The time required for packaging is 1 h.

There are several unique features of batch operations observed in Example 3.1. First, the heating, reaction, and separations steps are unsteady state, which is different from the typical steady-state analysis with which most undergraduate chemical engineers are familiar. Secondly, it is observed that no provision was made to recycle the unreacted raw materials. In Chapter 2, recycle was shown to be a key element of a steady-state chemical process. Raw materials are almost always the largest item in the cost of manufacturing; therefore, recycling unreacted raw materials is essential to ensure profitability. So, how is this done in a batch process? In Example 3.1, the overhead product from the batch distillation contains unreacted raw material and product in the solvent. This could be sent to a holding tank and periodically mixed with a stream containing pure solvent and just enough reactants A and/or B to make up a single charge to the process in Step 1. However, the recycling of product to the reactor would have to be investigated carefully to determine whether unwanted side reactions take place at higher product concentrations. Even though an additional tank would need to be purchased, it is almost certain that the cost benefit of recycling the raw materials would far outweigh the cost of the additional tank. Third, it is observed that, overall, only 60% of the product made in the reactor is crystallized out in Step 5. This means that the **mother liquor** (solution containing product to be crystallized after some has crystallized out) contains significant amounts of valuable product. Additional crystallization steps could recover some, if not most, of the valuable product. The strategy for accomplishing this could be as simple as scheduling a second or third cooling or crystallization step, or it could involve storing the mother liquor from several batch processes until a sufficient volume is available for another cooling or crystallization step. These additional crystallization steps are tantamount to adding additional separation stages.

3.2. Gantt Charts and Scheduling

Gantt charts (see, for example, Dewar [3]) are tabular representations used to illustrate a series of tasks (rows) that occur over a period of time (columns). These charts graphically represent completion dates, milestone achievements, current progress, and so on [3] and are discussed further in Chapter 28 as a planning tool for completing large design projects. In this chapter, a simplified Gantt chart is used to represent the scheduling of equipment needed to produce a given batch product. Example 3.2 illustrates the use of Gantt charts to show the movement of material as it passes through several pieces of equipment during a batch operation.

Example 3.2.

Draw a Gantt chart that illustrates the sequence of events in the production of the API in Example 3.1.

Solution

Gantt charts for this process are shown in Figure E3.2. Note that in both charts, Steps 1 and 2 have been consolidated into one operation because they occur sequentially in the same piece of equipment. The top chart shows the row names as tasks, and the bottom figure simply identifies each row with the equipment number. In general, the notation used in the bottom figure will be adopted.

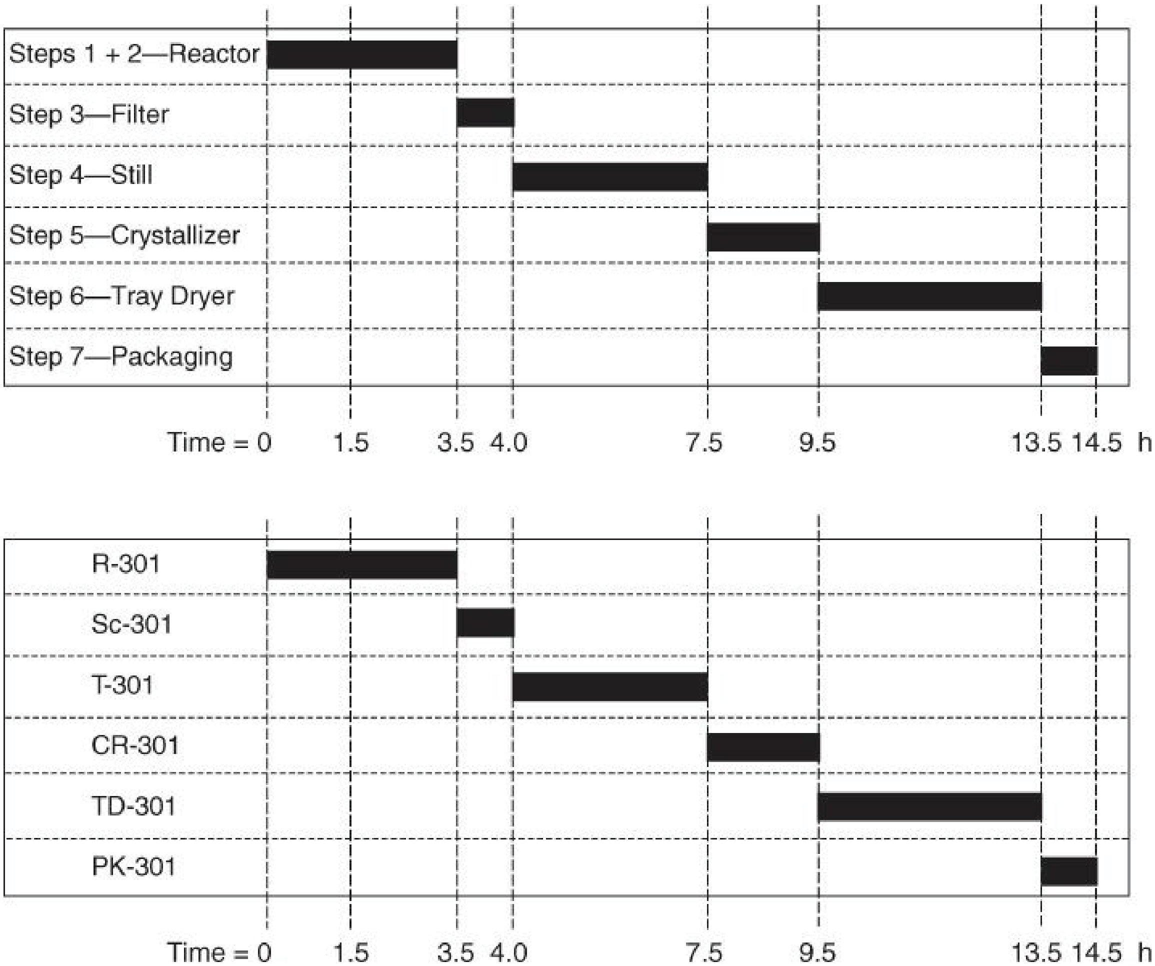

Figure E3.2. Gantt Chart Showing Sequence of Events for the Manufacture of API in Example 3.1

3.3. Nonoverlapping Operations, Overlapping Operations, and Cycle Times

In general, product is produced throughout an extended period of time by using a repeating sequence of operations. For example, the batch process described in Example 3.1 produces a certain amount of crystallized API, namely, 634.5 kg. If it is desired to produce 5000 kg, then the sequence of steps must be repeated 5000/634.5 ≅ 8 times. There are several ways to repeat the sequence of tasks needed to make one batch, in order to make the desired total amount of product (5000 kg). An example of one such **nonoverlapping** scheme is shown in Figure 3.1.

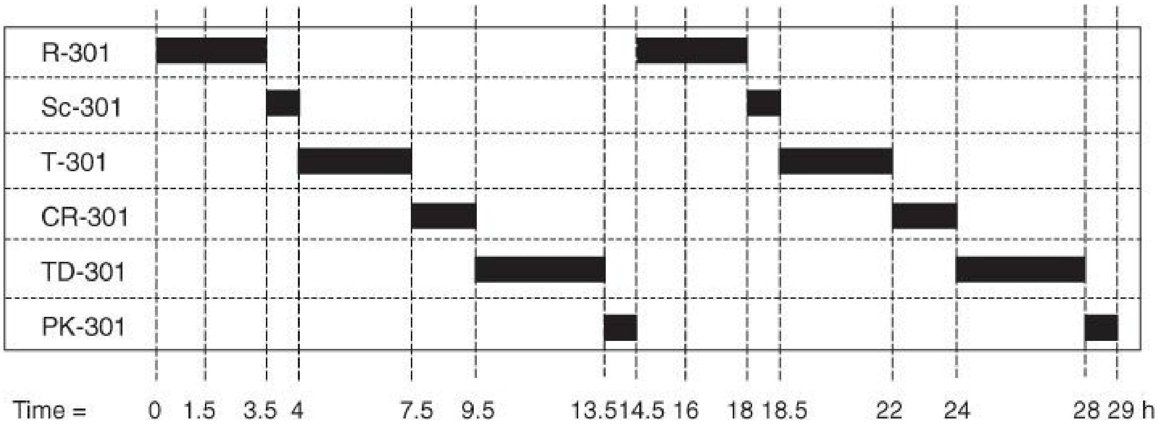

Figure 3.1. Example of a Nonoverlapping Sequence of Batch Operations

For the nonoverlapping (designated by the subscript *NO*) scheme, the total processing time is the number of batches multiplied by the time to process a single batch.

$$T_{NO} = n\sum_{i=1}^{m} t_i \qquad (3.1)$$

where T_{NO} is the total time to process *n* batches without overlapping, each batch having *m* steps of duration $t_1, t_2, \ldots, t_m$. For this example, the total time is equal to (8)(3.5 + 0.5 + 3.5 + 2 + 4.0 + 1.0) = (8)(14.5) = 116.0 h.

For the process described in Figure 3.1, using the nonoverlapping scheme, the equipment is used infrequently, and the total processing time is unduly long. However, such a scheme might be employed in plants that operate only a single shift per day. In such cases, the production of a single batch might be tailored to fit an 8 or 10 h shift (for this example, the shift would have to be 14.5 h), with the limitation that only one batch would be produced per day. Although such a scheme does not appear to be very efficient, it eliminates prolonged storage of intermediate product and certainly makes the scheduling problem easy.

The total time to process all the batches can be reduced by starting a batch before the preceding batch has finished. This is equivalent to shifting backward the time blocks representing the steps in the batch process, as shown in Figure 3.2.

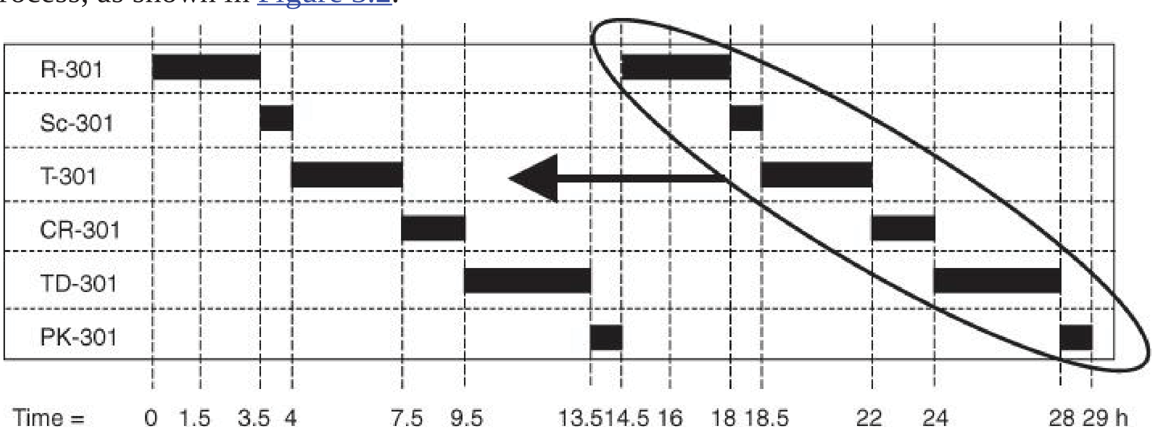

Figure 3.2. Backward Shifting of Batches, Giving Rise to Overlapping Sequencing

This shifting of batches backward in time leads to the concept of **overlapping** sequencing of batches. The limit of this shifting or overlapping process occurs when two time blocks in consecutive batches just touch each other (assuming that cleaning, inspection, and charging times are included). This situation is shown in Figure 3.3.

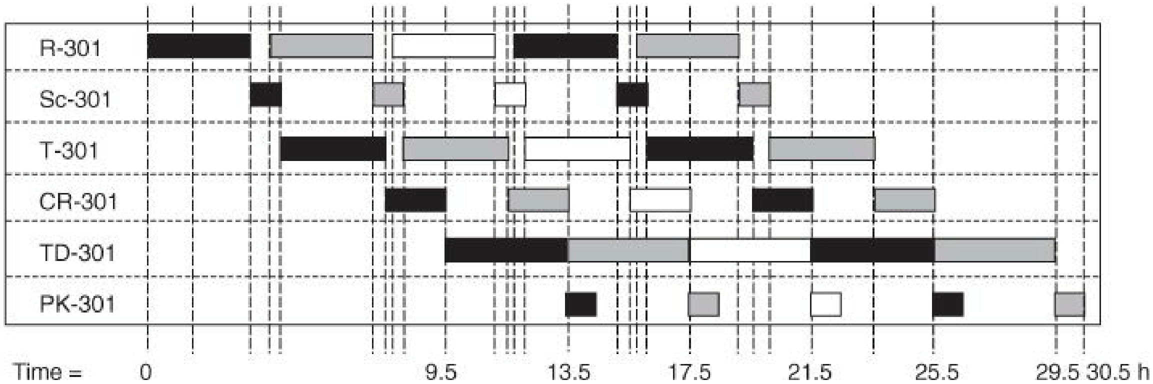

Figure 3.3. The Limiting Case for Overlapping Batch Sequencing

From Figure 3.3, it can be seen that the limiting case for overlapping occurs when the step taking the longest time (here, the tray drying step in TD-301, which takes 4 h to complete) repeats itself without a waiting time between batches. The time to complete *n* batches using this limiting overlapping scheme is given by

$$T_O = T = (n-1) \max_{i=1,\ldots,m} (t_i) + \sum_{i=1}^{m} t_i \qquad (3.2)$$

where T_O is the minimum total (overlapping) time, and [max (t_i)] is the maximum individual time step for the batch process. The subscript O denoting overlapping will be dropped, and T will be used as the total processing time from this point on. For the example, T = (8–1)(4.0) + (14.5) = 42.5 h.

Comparing Figures 3.1 and 3.3, the use of overlapping sequencing reduces the processing time significantly (from 116 to 42.5 h) and makes much better use of the equipment; specifically, the equipment is operated for a higher fraction of time in the overlapping scheme compared with the nonoverlapping scheme.

In batch operations, the concept of **cycle time** is used to refer to the average time required to cycle through all necessary steps to produce a batch. The formal definition is found by dividing the total time to produce a number of batches by the number of batches. Thus, from Equations (3.1) and (3.2),

$$t_{cycle,NO} = \frac{T_{NO}}{n} = \frac{n\sum_{i=1}^{m} t_i}{n} = \sum_{i=1}^{m} t_i \qquad (3.3)$$

$$t_{cycle,O} = t_{cycle} = \frac{T}{n} = \frac{(n-1) \max_{i=1,\ldots,m} (t_i) + \sum_{i=1}^{m} t_i}{n} \qquad (3.4)$$

For the overlapping scheme, when the number of batches (*n*) to be produced is large, the cycle time is approximated by

$$t_{cycle} \cong \max_{i=1,\ldots,m} \{t_i\} \qquad (3.5)$$

Therefore, for Example 3.1, the nonoverlapping and overlapping cycle times are 14.5 h and 4 h, respectively.

3.4. Flowshop and Jobshop Plants

Thus far, the discussion has focused on the production of only a single product. However, most batch plants produce multiple products. All these products may require the same processing steps, or more often will require only a subset of all possible steps. Moreover, the order in which a batch process uses different equipment might also differ from product to product.

3.4.1. Flowshop Plants

Consider a plant that must make three products: A, B, and C. Figure 3.4 shows an example of the sequence of equipment used to produce these three products. In Figure 3.4, all the products use the same equipment in the same order or sequence, but not necessarily for the same lengths of time. This type of plant is sometimes referred to as a **flowshop** plant [4]. The total time for operation of overlapping schedules depends on the number of runs of each product and how these runs are scheduled. One approach to scheduling multiple products is to run each product in a campaign during which only that product is made. Then the plant is set up to run the next product in a campaign, and so on. The case when multiple products, using the same equipment in the same order, are to be produced in separate campaigns is considered first. If the corresponding numbers of batches for products A, B, C in a campaign are n_A, n_B, and n_C, respectively, then the total processing time, or production cycle time, can be found by adding the operation times for each product. If the number of batches per campaign is large (for example, >10), then the production cycle time can be approximated by

$$T = \sum_{j=A}^{C} n_j \{t_{cycle}\}_j \cong \sum_{j=A}^{C} n_j \left\{ \max_{i=1,\ldots,m} \{t_i\} \right\}_j \quad (3.6)$$

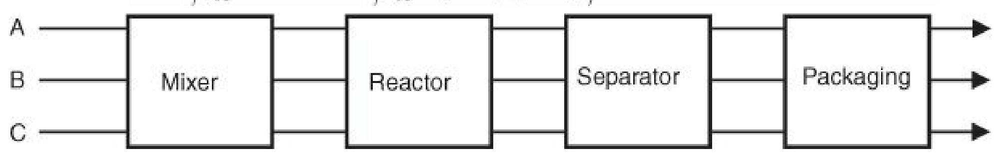

Figure 3.4. An Example of a Flowshop Plant for Three Products A, B, and C

An illustration of a multiple-product process is given in Example 3.3.

Example 3.3.

Consider three batch processes, producing products A, B, and C, as illustrated in Table E3.3. Each process uses the four pieces of equipment in the same sequencing order but for different times.

Table E3.3. Equipment Times (in Hours) Needed to Produce A, B, and C

Product	Time in Mixer	Time in Reactor	Time in Separator	Time in Packaging	Total Time
A	1.5	1.5	2.5	2.5	8.0
B	1.0	2.5	4.5	1.5	9.5
C	1.0	4.5	3.5	2.0	11.0

Market demand dictates that equal numbers of batches of the three products be produced over a prolonged period of time.

Determine the total number of batches that can be produced in a production cycle equal to one month of operation of the plant using separate campaigns for each product, assuming that a month of operation is equivalent to 500 h (based on 1/12 of a 6000 h year for a three-shift plant operating five days per week).

Solution

The time to produce each product is given by Equation (3.2). Assume that each product is run x times during the month:

$$T = 500 = \sum_{j=A}^{C} \left\{ (n-1) \max_{i=1,\ldots,m} \{t_i\} + \sum_{i=1}^{m} t_i \right\}_j$$

$$500 = [(x-1)(2.5) + 8] + [(x-1)(4.5) + 9.5] + [(x-1)(4.5) + 11]$$

$$500 = (x-1)(11.5) + 28.5 \Rightarrow x = \frac{(500-28.5)}{11.5} + 1 = 42$$

Thus, 42 batches each of A, B, and C can be run as campaigns in a 500 h period. The cycle times are $t_{cycle,A}$ = [(41)(2.5) + 8/(42)] = 2.631 h, $t_{cycle,B}$ = 4.619 h, and $t_{cycle,C}$ = 4.655 h.

Using Equation (3.6) with the approximations $t_{cycle,A}$ = 2.5, $t_{cycle,B}$ = 4.5, and $t_{cycle,C}$ = 4.5,

$$T = 500 = x(2.5 + 4.5 + 4.5) \Rightarrow x = \frac{500}{11.5} = 43$$

Equation (3.6) slightly overestimates the number of batches that can be run in the 500 h period but is a very good approximation. In general, Equation (3.6) will be used to estimate cycle times and other calculations for single-product campaigns for multiproduct plants.

Running campaigns for the production of the same product is efficient and makes scheduling relatively easy. However, this strategy suffers from a drawback: The longer the production cycle, the greater the amount of product that must be stored. The concept of product storage is addressed in the following section. However, the bottom line is that storage requires additional equipment or warehouse floor space that must be purchased or rented. On the other hand, a strategy of single-product campaigns may decrease cleaning times and costs, which generally are greater when switching from one process to another. Therefore, the implementation of a batch sequencing strategy that uses sequences of single-product campaigns involves additional costs that should be included in any design and optimization. The extreme case for single-product batch campaigning occurs for seasonal produce (a certain vegetable oil, for example), where the feed material is available only for a short period of time and must be processed quickly, but the demand for the product lasts the whole year.

An alternative to running single-product campaigns (AAA…, BBB…, CCC…) over the production cycle is to run multiproduct campaigns—for example, ABCABCABC, ACBACBACB, AACBAACBAACB, and so on. In this strategy, products are run in a set sequence and the sequence is repeated. This approach is illustrated in Example 3.4.

Example 3.4.

Consider the same processes given in Example 3.3. Determine the number of batches that can be produced in a month (500 h) using a multiproduct campaign strategy with the sequence ABCABCABC.. …

The Gantt chart for this sequence is shown in Figure E3.4.

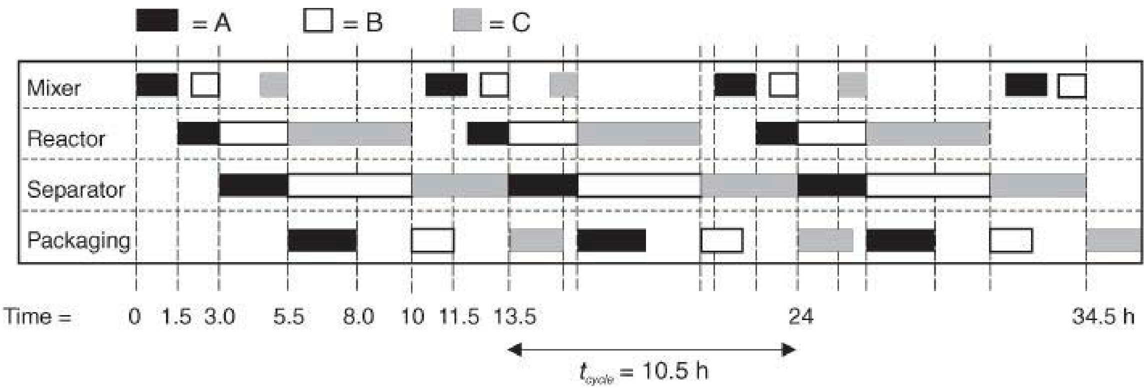

Figure E3.4. Gantt Chart Showing the Multiproduct Sequence ABCABCABC. …

From Figure E3.4, it can be seen that the limiting equipment for this sequence is the separator. This means that the separator is used without downtime for the duration of the 500 h. If *x* batches are produced during the 500 h period, then

$$T = 500 = (3 + x(2.5 + 4.5 + 3.5) + 2) \Rightarrow x = \frac{(500-5)}{10.5} = 47$$

Therefore, an additional five batches of each product can be produced using this sequence compared with the single-product campaign discussed in Example 3.3, assuming no additional cleaning time. It should be noted that other sequences, such as BACBACBAC, could be used, and these may give more or fewer batches than the sequence used here.

3.4.2. Jobshop Plants

The flowshop plant discussed previously is one example of a batch plant that processes multiple products. When not all products use the same equipment or the sequence of using the equipment is different for different products, then the plant is referred to as a **jobshop** plant [4]. Figure 3.5 gives two examples of such plants. In Figure 3.5(a), all the products move from the left to the right—that is, they move in the same direction through the plant, but not all of them use the same equipment. In Figure 3.5(b), products A and B move from left to right, but product C uses the equipment in a different order from the other two products. The sequencing of multiproduct campaigns for this type of plant is more complex and is illustrated in Example 3.5. The relative efficiencies of different processing schemes for the plant shown in Figure 3.5(b) are calculated in Example 3.6.

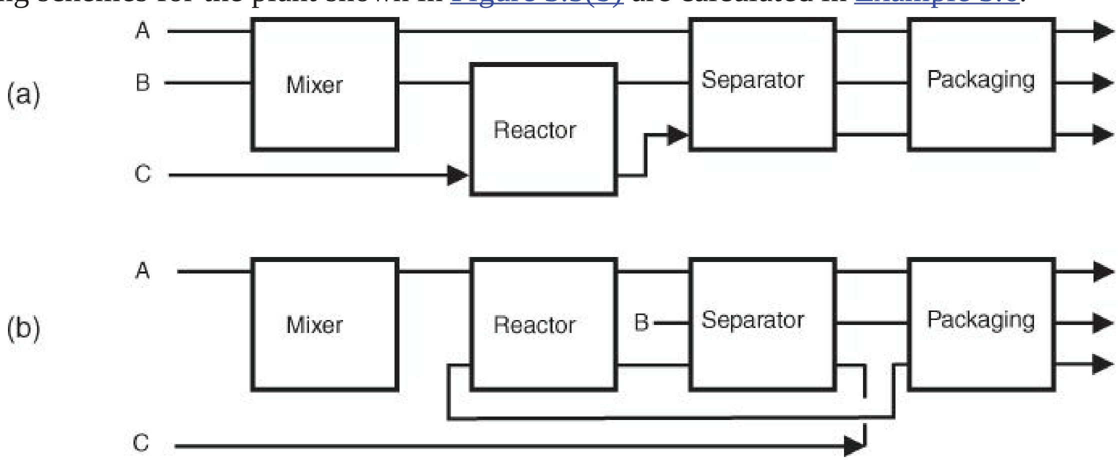

Figure 3.5. Two Examples of Jobshop Plants for Three Products A, B, and C

Example 3.5.

Consider the jobshop plant following the sequence shown in Figure 3.5(b) and described in Table E3.5. Construct the Gantt charts for overlapping single-product campaigns for products A, B, and C and for the multiproduct campaign with sequence ABCABCABC. …

Table E3.5. Equipment Processing Times (in Hours) for Processes A, B, and C

Process	Mixer	Reactor	Separator	Packaging
A	1.0	5.0	4.0	1.5
B	—	—	4.5	1.0
C	—	3.0	5.0	1.5

Solution

The Gantt charts for the three processes are shown in Figure E3.5. The top chart shows the timing sequences for each batch, and the next three charts show overlapping campaigns for products A, B, and C, respectively. It can be seen that the rules and equations for overlapping campaigns given previously still apply. The bottom chart shows the overlapping multiproduct campaign using the sequence ABCABCABC… Note that there are many time gaps separating the use of the different pieces of equipment, and no one piece of equipment is used all the time. This situation is common in jobshop plants, and strategies to increase equipment usage become increasingly important and complicated as the number of products increases.

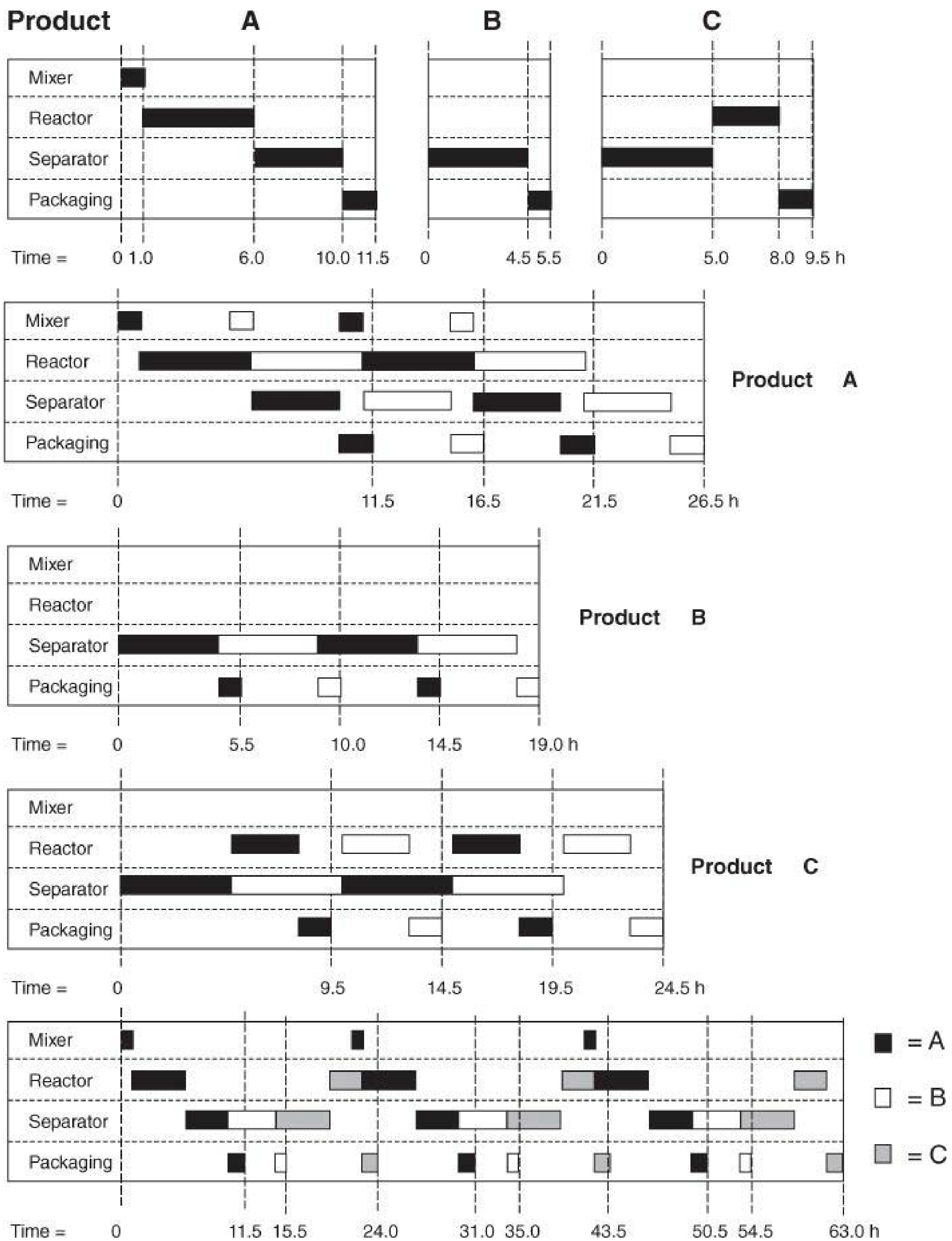

Figure E3.5. Gantt Charts for Single-Product and Multiproduct Campaigns

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Example 3.6.

It is desired to produce the same number of batches of A, B, and C. Using information from Example 3.5, determine the total number of batches of each product that can be produced in an operating period of 1 month = 500 h, using single-product campaigns and a multiproduct campaign following the sequence ABCABCABCABC. …

Solution

For the single-product campaigns, the number of batches of each product, *x*, can be estimated using Equation (3.6). Thus

$$500 = x(5 + 4.5 + 5) \Rightarrow x = \frac{500}{14.5} = 34$$

Therefore, 34 batches of each product can be made in a 500 h period using single-product campaigns.

For the multiproduct campaign, referring to Figure E3.5, the cycle time for the sequence ABC is 19.5 h. This is found by determining the time between successive completions of product C: 43.5 – 24 = 19.5 h, and 63 – 43.5 = 19.5 h. Therefore, the number of batches of A, B, and C that can be produced is given by

$$500 = x(19.5) \Rightarrow x = \frac{500}{19.5} = 25$$

This multiproduct sequence is clearly less efficient than the single-product campaign approach, but it does eliminate intermediate storage. It should be noted that different multiproduct sequences give rise to different results, and the ABCABC sequence may not be the most efficient sequence for the production of these products.

3.5. Product and Intermediate Storage and Parallel Process Units

In this section, the effect of intermediate and product storage on the scheduling of batch processes and the use of parallel process units or equipment are investigated. Both of these concepts will, in general, increase the productivity of batch plants.

3.5.1. Product Storage for Single-Product Campaigns

When using combinations of single-product campaigns in a multiproduct plant, it is necessary to store product during the campaign. For example, considering the products produced in Example 3.3, the plant will produce 43 batches each of products A, B, and C in a 500 h period. If the required production rates for these three products are 10,000, 15,000, and 12,000 kg/month, respectively, then what is the amount of storage required? In practice, it is the volume, and not the weight, of each product that determines the required storage capacity. For this example, it is assumed that the densities of each product are the same and equal to 1000 kg/m^3. Considering product A first and assuming that demand is steady, the demand rate (r_d) is equal to 10,000/500 = 20 kg/h = 0.020 m^3/h. Note that the demand rate is calculated on the basis of plant operating hours, and not on the basis of a 24-hour day. During the campaign, 10,000 kg of A must be made in 43 batch runs, with each run taking $t_{cycle, A}$ = 2.5 h. Thus, during production, the production rate (r_p) of A is equal to 10,000/(43)(2.5) = 93.0 kg/h = 0.0930 m^3/h. Results for all the products are given in Table 3.1.

Table 3.1. Production and Demand Rates for Products A, B, and C in Example 3.3

Rate	Product A	Product B	Product C
Volume (m^3) of product required per month	10.0	15.0	12.0
Cycle time (h)	2.5*	4.5*	4.5*
Production rate, r_p (m^3/h)	$(10)/[(43)(2.5)] = 0.0930$	0.07752	0.06202
Demand rate, r_d (m^3/h)	$(10)/(500) = 0.020$	0.030	0.024

*These are approximate cycle times based on Equation (3.5).

When a campaign for a product is running, the rate of production is greater than the demand rate. When the campaign has stopped, the demand rate is greater than the production rate of zero. Therefore, the accumulation and depletion of product over the monthly period are similar to those shown in Figure 3.6. The changing inventory of material is represented on this figure by the bottom diagram. The maximum inventory, V_s, is the minimum storage capacity that is required for the product using this single-product campaign strategy. The expression for calculating V_s is

$$V_s = (r_p - r_d)t_{camp} \quad (3.7)$$

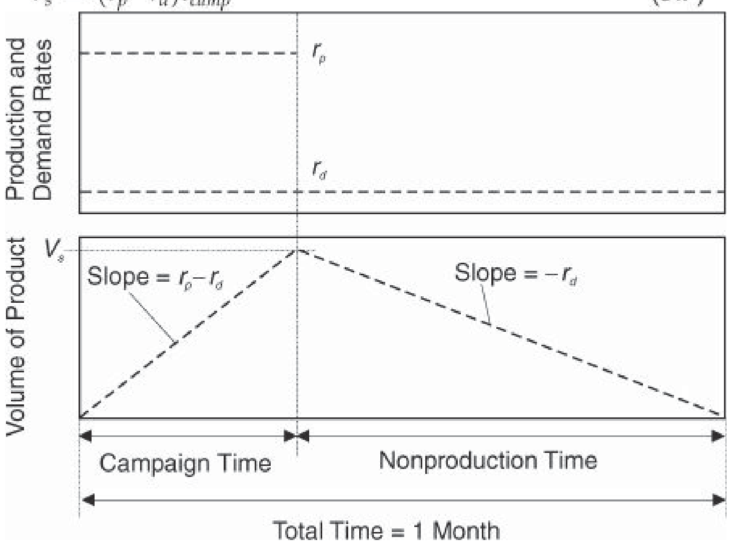

Figure 3.6. Changing Inventory of Product during Single-Product Campaign Run within a Multiproduct Process

where t_{camp} is the campaign time. This assumes that the shipping rate of product from the plant is constant during plant operating hours. Because shipping is usually itself a batch process, the actual minimum storage capacity could be more or less than that calculated in Equation (3.7). The strategies for matching shipping schedules to minimize cost (including storage costs and missed-delivery risks) are known as logistics and are not covered here.

Determination of the minimum storage capacities for all products in Example 3.3 is given in Example 3.7.

Example 3.7.

For the products A, B, and C in Example 3.3, determine the minimum storage capacities for the single-product campaign strategy outlined in Example 3.3.

Solution

Table E3.7 shows the results using data given in Example 3.3 and Table 3.1.

Table E3.7. Results for the Estimation of Minimum Storage Volume from Equation (3.7)

Product	Campaign Time, t_{camp} (h)	$r_p - r_d$ (m^3/h)	V_s (m^3)
A	(43)(2.5) = 107.5	0.09302 – 0.020 = 0.07302	(0.07302)(107.5) = 7.85
B	(43)(4.5) = 193.5	0.07752 – 0.030 = 0.04752	(0.04752)(193.5) = 9.20
C	(43)(4.5) = 193.5	0.06202 – 0.024 = 0.03802	(0.03802)(193.5) = 7.36

It should be noted that the production cycle time is equal to the sum of the campaign times, or (107.5 + 193.5 + 193.5) = 494.5 h, which is slightly less than 500 h. This discrepancy reflects the approximation of cycle times given by Equation (3.6). The actual cycle times for A, B, and C are found from Example 3.3 and are equal to 2.63, 4.62, and 4.65 h, respectively. The corresponding values of V_s are 7.79, 9.18, and 7.31 m^3. Clearly, these differences are small, and the approach using Equation (3.6) is acceptable when the number of production runs per campaign is 10 or more.

3.5.2. Intermediate Storage

Up to this point, it has been assumed that there is no intermediate product storage available. This type of process is also known as a **zero wait,** or a **zw process** [4]. Specifically, as soon as a unit operation is completed, the products are transferred to the next unit operation in the sequence, or they go to final product storage. The concept of storing the final product to match the supply with the demand was demonstrated in Example 3.7. However, it may also be beneficial to store the output from a given piece of equipment for a period of time to increase the overall efficiency of a process. It may be possible to store product in the equipment that has just been used. For example, if two feed streams are mixed in a vessel, the mixture could be stored until the next process unit in the production sequence becomes available. In this case, the storage time is limited based on the scheduling of equipment. This **holding-in-place** method may not work for some unit operations. For example, in a reactor, a side reaction may take place, and unless the reaction can be quenched, the product yield and selectivity will suffer. The upper limit of the intermediate storage concept occurs when there is **unlimited intermediate storage (uis)** available, and this is referred to as a **uis process** [4]. In general, cycle times can be shortened when intermediate product storage is available. This concept is illustrated in Figure 3.7, which is based on the information given in Table 3.2.

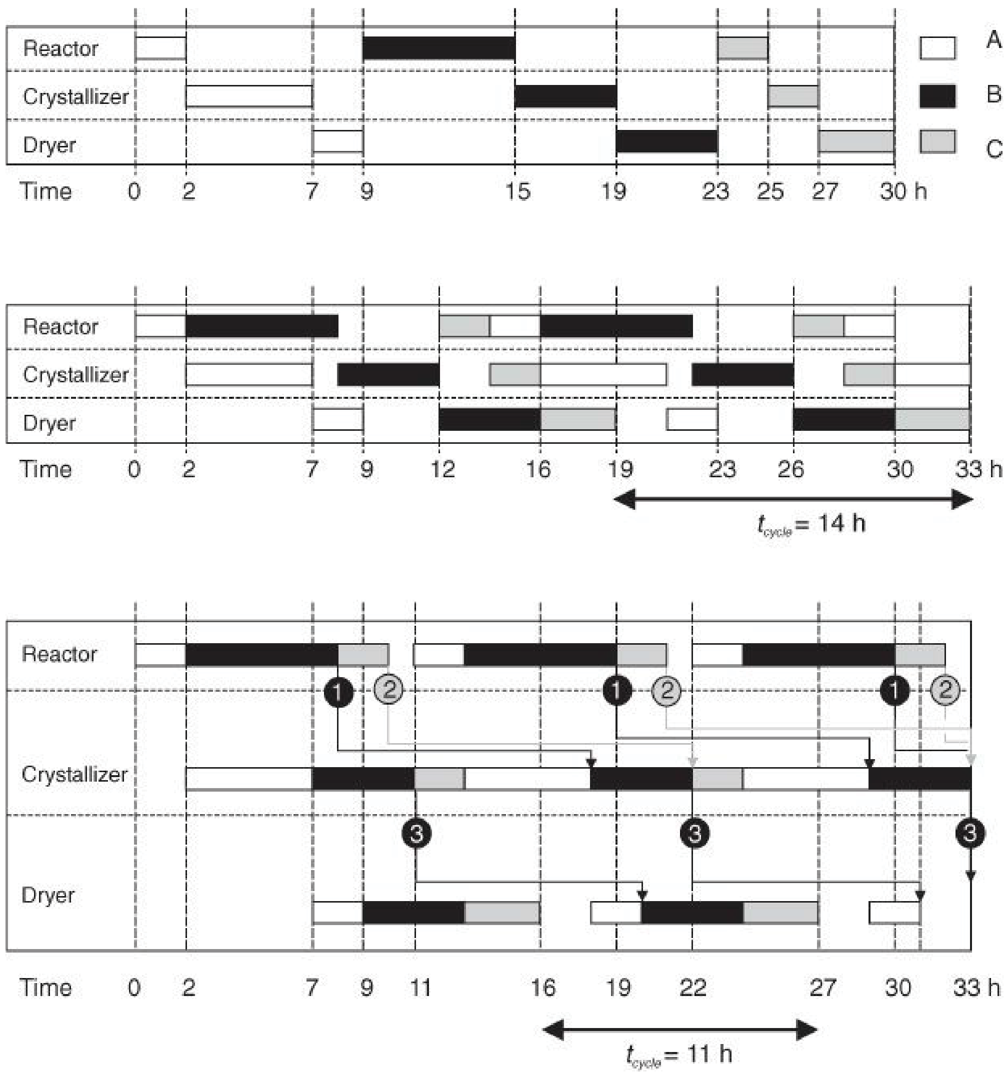

Figure 3.7. Multiproduct Sequence (ABC) for Products Given in Table 3.2 Showing Effect of Intermediate Storage (Storage Shown as Circles; Number Identifies Individual Tanks for Each Intermediate Product)

Table 3.2. Equipment Times (in Hours) Required for Products A, B, and C

Product	Reactor	Crystallizer	Dryer	Total
A	2.0	5.0	2.0	9.0
B	6.0	4.0	4.0	14.0
C	2.0	2.0	3.0	7.0
Total Time per Equipment	10.0	11.0	9.0	

Without intermediate product storage, the shortest multiproduct campaign, as given by Equation (3.6), is 14 h, as shown in Figure 3.7. However, if the materials leaving the reactor and crystallizer are placed in storage prior to transfer to the crystallizer and dryer, respectively, then this time is reduced to 11 h. The limiting cycle time for a uis process is given by

$$t_{cycle,uis} = \max_{j=1,m} \sum_{i=1}^{N} nc_i t_{i,j} \qquad (3.8)$$

where m is the number of unit operations, N is the number of products, and nc_i is the number of campaigns of product i produced in a single multiproduct sequence. For the case shown in Table 3.2 and Figure 3.7, $n = 1$ (because only one campaign for each product (A, B, and C) is used in the multiproduct sequence), and Equation (3.8) is the maximum value given in the last row of Table 3.2, or 11.0 h.

The total amount of storage required for this example is fairly small, because only three storage vessels are required, each dedicated to one intermediate product. The downside of this approach is that there are many more material transfers required, and the potential for product contamination and operator error increases significantly.

3.5.3. Parallel Process Units

Another strategy that can be employed to increase production is to use duplicate equipment. This strategy is most beneficial when there is a bottleneck involving a single piece of equipment that can be relieved by adding a second (or more) units in parallel. This strategy can be extended to a limiting case in which parallel trains of equipment are used for each product. This strategy eliminates the dependence of scheduling between the different products but is more expensive, because the number of pieces of equipment increases m-fold, where m is the number of products. An example of using parallel equipment is shown in Figure 3.8 based on the data in Table 3.3.

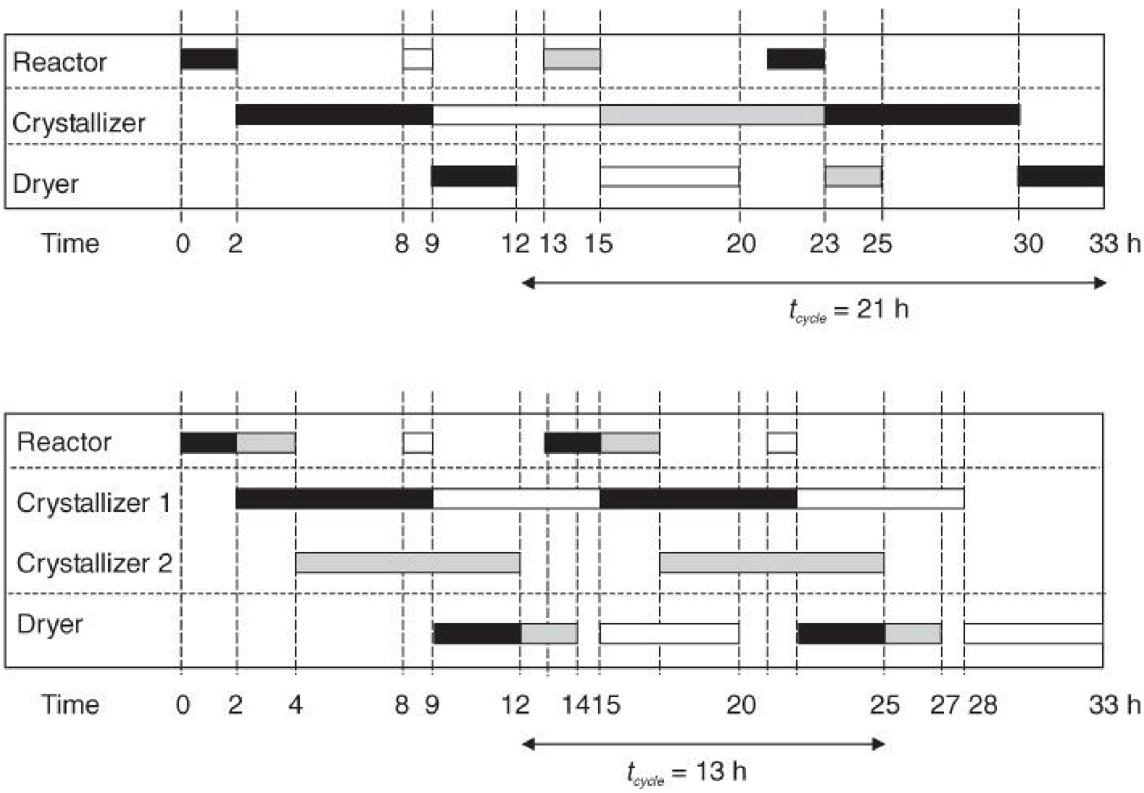

Figure 3.8. The Effect of Adding an Additional Crystallizer to the Process Given in Table 3.2

Table 3.3. Data (Times in Hours) for Multiproduct Batch Process Shown in Figure 3.8

Process	Reactor	Crystallizer	Dryer
A	2.0	7.0	3.0
B	1.0	6.0	5.0
C	2.0	8.0	2.0

From the top chart in Figure 3.8, the limiting piece of equipment is seen to be the crystallizer. The bottom chart shows the effect of adding a second crystallizer that processes product C. The effect is to reduce the cycle time from 21 h to 13 h, a considerable improvement in throughput. The determination of whether to make this change must be made using an appropriate economic criterion, such as net present value (NPV) or equivalent annual operating cost (EAOC), which are discussed in Chapter 10. The resulting tradeoff is between increased product revenues and the cost of purchasing a second crystallizer plus additional operators to run the extra equipment.

3.6. Design of Equipment for Multiproduct Batch Processes

The design of equipment sizes for multiproduct batch processes depends on the production cycle time, whether single- or multiproduct campaigns are used, the sequence of products for multiproduct campaigns, and the use of parallel equipment. As an example, the multiproduct process described in Table 3.4 will be analyzed. It is assumed that each product will be produced using a single-product campaign. The production cycle will be 500 h (equivalent to one month in a 6000 h year). The production cycle will be repeated 12 times in a year. The required amount of each product is given in Table 3.4 along with the processing times.

Table 3.4. Data for a Multiproduct Batch Process

Process	Reactor and Mixer	Filtration	Distillation	Yearly Production	Production in 500 h
A	7.0 h	1.0 h	2.0 h	120,000 kg	10,000 kg
B	9.0 h	1.0 h	1.5 h	180,000 kg	15,000 kg
C	10.0 h	1.0 h	3.0 h	420,000 kg	35,000 kg

By studying Table 3.4, it is apparent that the limiting piece of equipment is the mixing and reaction vessel, and the cycle times can be found from this piece of equipment. To estimate equipment volume, it is necessary to determine the volume of each piece of equipment per unit of product produced. To determine these quantities, descriptions of the method (recipe) for using each piece of equipment for each product must be known. The procedure to estimate the specific volume of the reactor for process A in Table 3.4 is given in Example 3.8.

Example 3.8.

The following is a description of the reaction in process A, based on a laboratory-scale experiment. First, 10 kg of liquid reactant (density = 980 kg/m^3) is added to 50 kg of a liquid mixture of organic solvent containing excess of a second reactant (density of mixture = 1050 kg/m^3) in a jacketed reaction vessel, the reactor is sealed, and the mixture is stirred and heated. Once the reaction mixture has reached 95°C, a solid catalyst (negligible volume) is added, and reaction takes place while the batch of reactants continues to be stirred. The required conversion is 94%, 17.5 kg of product is produced, and the time taken is 7.0 h. The reactor is filled to 60% of maximum capacity to allow for expansion and to provide appropriate vapor space above the liquid surface. Determine the volume of reaction vessel required to produce 1 kg of product.

Solution

$$\text{volume of reactor} = \left(\frac{10\,[\text{kg}]}{980\,[\text{kg/m}^3]} + \frac{50\,[\text{kg}]}{1050\,[\text{kg/m}^3]}\right)\frac{100}{60} = 0.09637\ \text{m}^3$$

$$v_{react} = \frac{\text{volume of reactor}}{\text{mass of product}} = \frac{0.09637}{17.5} = 0.005507\ \text{m}^3/\text{kg-product}$$

Similar calculations can be made for the reactor/mixer for processes B and C in Table 3.4, and these results are given in Table 3.5 along with the cycle times for each process. It should be noted that even for a preliminary design and cost estimate, other attributes of the equipment should also be considered. For example, in order to specify fully the reactor and estimate its cost, the heating duty and the size of the motor for the mixer impeller must be calculated. To simplify the current example, only the volumes of the reactor are considered, but it should be understood that other relevant equipment properties must also be considered before a final design can be completed. This procedure should be applied to all the equipment in the process.

Table 3.5. Specific Reactor/Mixer Volumes for Processes A, B, and C

Process	A	B	C
v_{react} (m^3/kg-product)	0.005507	0.007860	0.006103
t_{cycle} (h)	7.0	9.0	10.0

Let the single-product campaign times for the three products be t_A, t_B, and t_C, respectively. Applying Equation (3.6), the following relationship is obtained:

$$t_A + t_B + t_C = 500 \tag{3.9}$$

The number of batches per campaign for each product is then given by $t_x/t_{cycle,x}$ and

$$\text{Batch size (kg/batch)} = \frac{\text{production of } x}{t_x/t_{cycle,x}} \tag{3.10}$$

Furthermore, the volume of a batch is found by multiplying Equation (3.10) by $\upsilon_{reac,x}$, and equating batch volumes for the different products yields

$$\text{Volume of batch} = \frac{(\text{production of } x)(v_{react,x})}{t_x/t_{cycle,x}} \tag{3.11}$$

$$\frac{(10{,}000)(0.005507)}{t_A/7.0} = \frac{(15{,}000)(0.007860)}{t_B/9.0} = \frac{(35{,}000)(0.006103)}{t_B/10.0} \tag{3.12}$$

Solving Equations (3.9) and (3.12) yields

$$t_A = 53.8\ \text{h}$$

$$t_B = 148.1\ \text{h}$$

$$t_C = 298.1\ \text{h}$$

$$\upsilon_{react,A} = \upsilon_{react,B} = \upsilon_{react,C} = 7.17\ \text{m}^3$$

Number of batches per campaign for product A = 7.7

Number of batches per campaign for product B = 16.5

Number of batches per campaign for product C = 29.8

Clearly the number of batches should be an integer value. Rounding these numbers yields

For product A

Number of batches = 8

$t_A = (8)(7) = 56$ h

$V_A = (10{,}000)(0.005507)(7)/(56) = 6.88\ m^3$

For product B

Number of batches = 16

$t_B = (16)(9) = 144$ h

$V_B = (15{,}000)(0.007860)(9)/(144) = 7.37\ m^3$

For product C

Number of batches = 30

$t_C = (30)(10) = 300$ h

$V_C = (35{,}000)(0.006103)(10)/(300) = 7.12\ m^3$

Total time for production cycle = 500 h

Volume of reactor = 7.37 m^3 (limiting condition for product B)

= (7.37)(264.2) =1947 gallons

The closest standard size, 2000 gallons, is chosen.

3.7. Summary

In this chapter, concepts important to the design of batch processes were introduced. Gantt charts were used to illustrate the timing and movement of product streams through batch processes. The concepts of nonoverlapping and overlapping sequences were discussed for single-product and multiproduct processes. The differences between flowshop and jobshop plants were introduced, and the strategies for developing single-product and multiproduct campaigns for each type of process were discussed. The role of intermediate and final product storage and the methods to estimate the minimum product storage for single-product campaigns were illustrated. The addition of parallel equipment was shown to reduce product cycle time. Finally, an example of estimating the size of vessels required in a multiproduct process was given.

What You Should Have Learned

- The difference between design considerations for batch versus continuous processes
- Batch scheduling patterns
  - Flowshop versus jobshop plants
  - Impact of storage requirements
  - Single- versus multiproduct plants

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3. Dewar, J. D., “If You Don’t Know Where You’re Going, How Will You Know When You Get There?” *CHEMTECH* 19, no. 4 (1989): 214–217.

4. Biegler, L. T., I. E. Grossman, and A. W. Westerberg, *Systematic Methods of Chemical Process Design* (Upper Saddle River, NJ: Prentice Hall, 1997).

Short Answer Questions

1. What is a flowshop plant?
2. What is a jobshop plant?
3. What are the two main methods for sequencing multiproduct processes?
4. Give one advantage and one disadvantage of using single-product campaigns in a multiproduct plant.
5. What is the difference between a zero-wait and a uis process?

Problems

6. Consider the processes given in Example 3.3. Determine the number of batches that can be produced in a month (500 h) using a series of single-product campaigns when the required number of batches for product A is twice that of either product B or product C.
7. Consider the processes given in Examples 3.3 and 3.4. Determine the number of batches that can be produced in a month (500 h) using a multiproduct campaign strategy with the sequence ACBACBACB. Are there any other sequences for this problem other than the one used in Example 3.4 and the one used here?
8. Consider the multiproduct batch plant described in Table P3.8.

Table P3.8. Equipment Processing Times for Processes A, B, and C

Process	Mixer	Reactor	Separator
A	2.0 h	5.0 h	4.0 h
B	3.0 h	4.0 h	3.5 h
C	1.0 h	3.0 h	4.5 h

It is required to produce the same number of batches of each product. Determine the number of batches that can be produced in a 500 h operating period using the following strategies:

a. Single-product campaigns for each product

b. A multiproduct campaign using the sequence ABCABCABC. …

c. A multiproduct campaign using the sequence CBACBACBA. …

9. Consider the process given in Problem 3.8. Assuming that a single-product campaign strategy is used over a 500 h operating period and further assuming that the production rates (for a year = 6000 h) for products A, B, C are 18,000 kg/y, 24,000 kg/y, and 30,000 kg/y, respectively, determine the minimum volume of product storage required. Assume that the product densities of A, B, and C are 1100, 1200, and 1000 kg/m^3, respectively.
10. Using the data from Tables P3.10(a) and (b), and following the methodology given in Section 3.6, determine the number of batches and limiting reactor size for each product.

Table P3.10(a). Production Rates for A, B, and C

Product	Yearly Production	Production in 500 h
A	150,000 kg	12,500 kg
B	210,000 kg	17,500 kg
C	360,000 kg	30,000 kg

Table P3.10(b). Specific Reactor/Mixer Volumes for Processes A, B, and C

Process	A	B	C
v_{react} (m^3/kg-product)	0.0073	0.0095	0.0047
t_{cycle} (h)	6.0	9.5	18.5

11. Referring to the batch production of amino acids described in Project 8 in Appendix B, the batch reaction times and product filtration times are given in Table P3.11.

Table P3.11. Batch Step Times (in Hours) for Reactor and Bacteria Filter for Project 8 in Appendix B

Product	Reactor*	Precoating of Bacteria Filter	Filtration of Bacteria
L-aspartic acid	35	25	5
L-phenylalanine	65	25	5

*Includes 5 h for filling, cleaning, and heating.

The capacity of the reactors chosen for both products is 10,000 gallons each. The precoating of the filters may occur while the batch reactions are taking place, and hence the critical time for the filtration is 5 h. It should be noted that intermediate storage is not used between the reactor and filter, and hence the batch times for the reactors must be extended an additional 5 h while the contents are fed through the filter to storage tank V-901. It is desired to produce L-aspartic acid and L-phenylalanine in the ratio of 1 to 1.25 by mass. Using a campaign period of 1 year = 8000 h and assuming that there is a single reactor and filter available, determine the following:

a. The number of batches of each product that can be produced in a year, maintaining the desired ratio of the two products, if one single-product campaign is used for each amino acid per year.

b. The amount of final product storage for each product assuming a constant demand of each product over the year. Express this amount of storage as a volume of final solid crystal product (bulk density of each amino acid is 1200 kg/m^3). You may assume that the recovery of each amino acid is 90% of that produced in the reactor.

c. By how much would the answer to Part (b) change if the single-product campaigns for each amino acid were repeated every month rather than every year?

12. Referring to Problem 3.11, by how much would yearly production change if the following applied?

a. The reaction times for L-aspartic acid and L-phenylalanine were reduced by 5 h each. Use the same scenario as described in Problem 3.11, Part (a).

b. The reaction times for L-aspartic acid and L-phenylalanine were increased by 5 h each. Use the same scenario as described in Problem 3.11, Part (a).

13. It is desired to produce three different products, A, B, and C, using the same equipment in a batch processing plant. Each production method uses the same equipment in the same order for the times given in Table P3.13.

Table P3.13. Equipment Processing Times for Problem 3.13

Equipment Process	Mixer\Reactor	Filter	Crystallizer	Dryer	Density
A	2.5 h	1.5 h	4.5 h	5.0 h	900 kg/m^3
B	3.5 h	3.5 h	5.5 h	4.0 h	1000 kg/m^3
C	2.0 h	3.5 h	5.0 h	4.0 h	850 kg/m^3

It has been determined that market forces dictate that the rate of production of product B should be twice that of A and for C should be three times that of A. For a one-month campaign, equivalent to 600 h, answer the following questions:

a. Assume that each product will be produced in separate campaigns; for example, first make all A, then B, then C. Determine the number of batches for each product.

b. If the yearly demand for product C is 180,000 kg/y (180 tonne/y), determine the storage capacity (volume) for this product assuming constant demand for C throughout the campaign period.

c. Determine the number of batches that could be produced during a 600 h period if the multibatch sequence ABBCCCABBCCC . . . is used.

14. A batch chemical plant is to be used to produce three chemical products (A, B, and C) using a flowshop plant. The times for each product in each piece of equipment (in hours) are shown in Table P3.14.

Table P3.14. Equipment Processing Times for Problem 3.14

Unit Op/ Product	Heating	Reaction/ Mixing	Filtration	Distillation	Crystallization
A	1.0	3.0	1.0	2.5	3.5
B	1.5	3.5	1.0	1.5	4.0
C	2.5	2.0	0.5	2.5	3.0

Market demands for these products require that the ratio of A to B to C be 1/2/2. Therefore, $n_B = n_C = 2n_A$. For this batch plant, answer the following questions:

a. In an operating period of 600 h, how many batches of A, B, and C can be made using three single-product campaigns (AAA…, BBBBBB…, CCCCCC…)?

b. Using multiple batch campaigns in the order ABBCCABBCC …, how many batches of A, B, and C can be made?

c. How would the answer to Part (a) change if the number of batches of A were twice those of B and C (instead of half)?

d. For Part (a), if the required production over the 600 h of operation for product B was 20,000 kg or 17.5 m^3 of product, what volume of intermediate storage would be required to ensure that a constant supply of B could be maintained over the 600 h operation?