Chemical Process Design / Diseño de Procesos Químicos

Topic 9. Design and scheduling of batch processes

Javier R. Viguri Fuente
Eva Cifrian Bemplosta

Department of Chemistry and Process & Resource Engineering
GER Green Engineering and Resources Research Group

This work is published under a License:
Creative Commons BY-NC-SA 4.0
INDEX

1.- Batch Processes: Introduction
2.- Single Product Batch Plants: Example, Scheduling by Gantt chart
3.- Multiple Product Batch Plants: Campaigns
4.- Transfer Policies
5.- Parallel units and Intermediate storage
6.- Synthesis of flowshop plants
7.- Sizing of vessels in batch plants
8.- Inventories
9.- Further Reading and References

PRACTICAL CHAPTER

RELEVANT TO LEARNING
1.- Batch Processes: Introduction

- **Continuous processes**: manufacture of commodities.

- **Batch processes**: specialty chemicals, pharmaceuticals.

- **Semicontinuous processes**: hybrids of batch and continuous.

**BATCH or SEMICONTINUOUS**
- SMALL production rates.
- LARGE residence times.
- INTERMITENT product demand.
- SAFETY aspects are of great concern.
- MULTIPRODUCT facilities.
- Mostly RECIPE Based.
1.- Batch Processes: Introduction

Batch reactors used in the dairy industry. © DCI Inc. St. Cloud, MN.

Fermentation plant producing enzymes at industrial scale. © Fraunhofer.


1.- Batch Processes: Introduction

When a batch process is used to manufacture two or more products (*Multiple Product Batch Plants*), two major limiting types of plants can arise:

- **FLOWSHOP (or multiproduct) plants** in which all products require all stages following the same sequence of operations.

- **JOBSHOP (or multipurpose) plants** where not all products require all stages and/or follow the same sequence.

The greater the similarity in the products being produced, the closer a real plant will approach a flowshop, and vice versa—the more dissimilar, the more it will approach a jobshop.
Processing Steps (RECIPE):
1. Mix A + B, heat to 80°C, react to form C. Total 4 hours.
2. Mix with solvent D for 1 hr. at 20°C.
3. Centrifuge to separate the product C for 2 hrs.
4. Dry in a tray for 1 hour at 60°C.

• Amounts are also specified.
• Assume processing times independent of batch sizes.
• Neglect transfer times.
2.- Single Product Batch Plants: Example, Scheduling by Gantt chart

Scheduling → Gantt chart (time activity chart)

RECIPE
1. Mix 4 hrs.
2. Mix 1 hr.
3. Centrifuge 2 hrs.
4. Dry 1 hr.

Cycle time (CT) = time between the completions of batches.

Non-overlapping:
\[
CT = \sum_{j=1}^{M} \tau_j
\]

Overlapping:
\[
CT = \max_{j=1,M} \{\tau_j\}
\]

Makespan = total time required to produce a given number of batches.

Bottleneck unit = unit having the longest batch unit.

- Cycle time (CT) = 4 + 1 + 2 + 1 = 8 hrs.
- Makespan (2 batches) = 16 hrs. Poor equipment use.

- Cycle time (CT) = max \{4, 1, 2, 1\} = 4 hrs.
- Makespan (2 batches) = 12 hrs.

- Examples with Zero-Wait (ZW) policy: transfer to units as soon as processing finished.
3.- Multiple Product Batch Plants

If Multiple products are produced, more alternatives for scheduling (Campaigns).

**Example:** production of 2 batches of A and 2 batches of B.

### a) Single Product Campaigns (SPC)

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

- Cycle time A = 5 hrs.
- Cycle time B = 4 hrs.
  \[ \text{CT}_{A+B} = 9 \text{ hrs.} \] 
  (To repeat AABB).
- Makespan (2 batches) = 20 hrs.

### b) Mixed Product Campaigns (MPC)

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
</tr>
</tbody>
</table>

- \[ \text{CT}_{A+B} = 7 \text{ hrs.} \] 
  (To repeat ABAB).
- Makespan (2 batches) = 18 hrs.
3.- Multiple Product Batch Plants

With clean-up (changeover) times (e.g. 1 hr.) the results will be:

- $CT_{A+B} = 9 \text{ hrs.} \text{ (To repeat ABAB).}$
- Makespan (2 batches) = 21 hrs.
4.- Transfer policies

**ZW:** zero-wait, transfer immediately.

**NIS:** no intermediate storage. Need not transfer immediately, can store in unit.

**UIS:** unlimited intermediate storage, between stages in storage vessels.

In practice, plants will normally have a mixture of the three transfer policies.

**Example:** production of the same number of batches of each product using a sequence ABAB.

<table>
<thead>
<tr>
<th>Product</th>
<th>Processing Time (hrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>j_1 j_2 j_3</td>
</tr>
<tr>
<td>i_1</td>
<td>t_{11} t_{12} t_{13}</td>
</tr>
<tr>
<td>i_2</td>
<td>t_{21} t_{22} t_{23}</td>
</tr>
</tbody>
</table>

\[
CT_{UIS} = \max_{j=1 \ldots M} \left\{ \sum_{i=1}^{N} n_i \tau_{ij} \right\}
\]

Is the absolute minimum (UIS) with:

- \( \tau_{ij} \): processing time of product \( i \) for stage \( j \).
- \( n_i \): number of batches for product \( i \).
- \( M \): number of stages.
- \( N \): number of products.
4.- Transfer policies

**ZW transfer**
- \(CT_{A+B} = 6 + 3 + 2 \text{ (slack)} = 11 \text{ hrs.} \) (To repeat ABAB).
- Makespan (2 batches) = 26 hrs.

**NIS transfer**
- \(CT_{A+B} = 6 + 3 + 1 \text{ (slack)} = 10 \text{ hrs.} \) (To repeat ABAB).
- Makespan (2 batches) = 25 hrs.

**UIS transfer**
- \(CT_{A+B} = 6 + 3 = 9 \text{ hrs.} \) (To repeat ABAB).
- Makespan (2 batches) = 24 hrs.
5. - Parallel units and Intermediate storage

Intermediate storage tanks between stages \( \rightarrow \) can increase the efficiency or equipment utilization. Parallel units operating out of cycle.

**Example:** fermentation plant. **Stage 1** (fermenter) takes 12 hrs. **Stage 2** (separation) only 3 hrs. Assume zero-wait transfer and the size of the batch in each stage is the same (1000 kg).

![Diagram showing parallel units and intermediate storage]

**Alternatives to decrease CT:**

a) Intermediate storage between stages.

b) Two parallel units in **Stage 1** (Bottleneck unit).
5.- Parallel units and Intermediate storage

a) Intermediate storage between stages: change batch size. Decoupling the two stages so that each stage can operate with different cycle times and batch sizes.

- The cycle time has been halved → can reduce the batch size to 500 kg.
- 4 fermenters eliminate all idle times.

b) Two parallel units in stage 1 (Bottleneck unit).

\[ CT = \max_{j=1 \ldots M} \left\{ \frac{\tau_{ij}}{NP_j} \right\} \]

- \(\tau_{ij}\): processing time of product \(i\) for stage \(j\).
- \(NP_j\): number of parallel units.
- \(M\): number of stages.

\[ CT = \max \{12 / 2, 3\} = 6 \text{ hrs.} \]
6.- Synthesis of Multiproduct Batch Plants (p. 196 Biegler (et al.) 1997)

- **STRUCTURAL DECISIONS:**
  a) Assignment of tasks to equipment.
  b) Number of parallel units or intermediate storage.

- **SIZING DECISIONS:**
  a) Equipment sizing.

- **SCHEDULING DECISIONS:**
  a) Campaigns and transfer policies.
  b) Length of production cycles.
  c) Sequencing at products.

**Assignment of tasks to equipment:**

Recipe → Successive tasks.

Ex. Single product batch process with four processing tasks.

<table>
<thead>
<tr>
<th>Task N°</th>
<th>Task 1</th>
<th>Task 2</th>
<th>Task 3</th>
<th>Task 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation (t)</td>
<td>Mix (2 hrs.)</td>
<td>React (4 hrs.)</td>
<td>Mix (1 hrs.)</td>
<td>React (2 hrs.)</td>
</tr>
<tr>
<td>Material</td>
<td>C/S</td>
<td>C/S</td>
<td>C/S</td>
<td>S/S</td>
</tr>
</tbody>
</table>

1. The simplest alternative is to assign each task to one processing device:

- Cycle time = 4 hrs.  
- 4 pieces of equipment.
2. The **Second alternative** is to assign Tasks 3 and 4 to one single piece of equipment, namely to the stainless steel (S/S) reactor. In this alternative, the cycle time remains unchanged in 4 hours despite the fact that we have eliminated one piece of equipment. This alternative is clearly superior to the previous one. Thus, a simple design guideline that we can postulate is: "Merge adjacent tasks whose sum of processing times does not exceed the cycle time".

   ![Diagram of three tanks connected in series]

   - Cycle time = 4 hrs.
   - 3 pieces of equipment.

3. A **Third alternative** is all tasks merged in one piece of equipment → the jacketed stainless steel vessel that can perform the four tasks.

   ![Diagram of a single tank]

   - Cycle time = 9 hrs.
   - 1 piece of equipment.

---

**Economic evaluation** → The best Alternative
7.- Sizing Batch Processes: Single Product Plants

**Example:** demand of 500,000 lb/yr. of product C. The plant is assumed to operate 6000 hours per year. The recipe for producing product C is as follows:

**Recipe in weight:**

1. Mix 1 lb. A, 1 lb B, and react for 4 hours to form C. The yield is 40% and the density of the mixture, \( r_m \) is 60 lb/ft\(^3\).
2. Add 1 lb solvent and separate by centrifuge during 1 hour to recover 95% of product C. The density of the mixture is \( r_m \) 65 lb/ft\(^3\).

**Mass Balance**

![Mass Balance Diagram]

Define **Size Factors**, \( S_j \), for each stage \( j \):

\[ S_j = \text{volume vessel } j \text{ required to produce 1 lb of final product.} \]
7.- Sizing Batch Processes: Single Product Plants

• **STAGE 1**: specific volume \( v = \frac{1}{r_m} = \frac{1}{60} = 0.0166 \text{ ft}^3/\text{lb mix} \).
  
  Size Factor: \( S_1 = 0.0166 \text{ ft}^3/\text{lb mix} \cdot [2 \text{ lb mix} / 0.76 \text{ lb prod.}] = 0.0438 \text{ ft}^3/\text{lb prod.} \)

• **STAGE 2**: specific volume \( v = \frac{1}{r_m} = \frac{1}{62.5} = 0.0153 \text{ ft}^3/\text{lb mix} \).
  
  Size factor: \( S_2 = 0.0153 \text{ ft}^3/\text{lb mix} \cdot [3 \text{ lb mix} / 0.76 \text{ lb prod.}] = 0.0607 \text{ ft}^3/\text{lb prod.} \)

- **If One Unit per Stage, ZW policy transfer:**
  
  - Cycle time = Max \{4, 1\} = 4 hrs. → N° Batches = 6000 h / [4 hrs / batch] = 1500 batches.
  
  - Batch Size Product i (Bi): \( B = \frac{500,000 \text{ lb prod.}}{1500} = 333 \text{ lb prod.} \)
  
  - Size Vessel 1: \( V_1 = S_1 \cdot B = 0.0438 \text{ ft}^3/\text{lb prod.} \cdot 333 \text{ lb prod.} = 14.6 \text{ ft}^3 \)
  
  - Size Vessel 2: \( V_2 = S_2 \cdot B = 0.0607 \text{ ft}^3/\text{lb prod.} \cdot 333 \text{ lb prod.} = 20.2 \text{ ft}^3 \)

- **Bottleneck Stage 1 → 2 Parallel Units in Stage 1:**
  
  - Cycle time = \( \max \{4 / 2, 1\} = 2 \) hrs. → N° Batches = 6000 / 2 = 3000 batches.
  
  - Batch Size = 166 lb.
  
  - Stage 1: 2 vessels, \( V_1 = 7.3 \text{ ft}^3 \).
  
  - Stage 2: 1 vessel, \( V_2 = 10 \text{ ft}^3 \).

\[ VT = 24.6 \text{ ft}^3, \text{ 3 vessels} < VT = 34.8 \text{ ft}^3, \text{ 2 vessels.} \]

Reduction in the investment cost depending on the cost correlation.
7.- Sizing Batch Processes: Single Product Plants

- Sizing depends on how the plant is scheduled.
- Simplest Alternative: Single Product Campaigns with fixed production cycle.

**Example:** demand 500,000 lb/yr of A, and 300,000 lb/yr of B. The plant is assumed to operate 6000 hours per year. We will select arbitrarily a production cycle of 1000 hours (42 days), which implies \[6000 / 1000 = 6 \text{ campaigns}\] over one year.

<table>
<thead>
<tr>
<th>Product</th>
<th>Processing Time (hrs.)</th>
<th>Side Factors (ft³/lb prod.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stage 1</td>
<td>Stage 2</td>
</tr>
<tr>
<td>A</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

Cleanup times: 4 hrs. A to B, B to A.

Cycle time \(A = CT_A = 8 \text{ hrs.}\), Cycle time \(B = CT_B = 6 \text{ hrs.}\);

**Effective time for production** in each cycle = \(t_A, t_B\); \(t_A + t_B = 992 \text{ hrs.}\).

How to allocate the production of A and B (i.e. selecting \(t_A, t_B\)) during this time horizon?
7.- Sizing Batch Processes: Single Product Plants

A simple solution is to use as a heuristic the same batch size for all products. The batch size $B_i$ for product $i$ is given by:

$$B_i = \frac{\text{Production per campaign} (P_i)}{\text{n° batches } i} = \frac{P_i}{\text{production time } t_i / CT_i}$$

Production per campaign ($P_i$) → $P_A$: 500,000 / 6 = 83,333 lb ; $P_B$: 300,000 / 6 = 50,000 lb.

Applying the heuristic of equating the batch sizes and constraining the production times to 992 hours yields the two equations:

- **Linear Equations**: $\frac{83,333}{t_A / 8} = \frac{50,000}{t_B / 6}$ ; $t_A + t_B = 992$.
- **Solutions**: $t_A = 684$ hrs. ; $t_B = 308$ hrs. ; $B_A = B_B = 974$ lb.

The required volumes for each product in the two stages ($V_{ij} = S_{ij} B_i$):

<table>
<thead>
<tr>
<th>Product</th>
<th>Volumes $V_{ij}$ ($\text{ft}^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stage 1</td>
</tr>
<tr>
<td>A</td>
<td>77.9</td>
</tr>
<tr>
<td>B</td>
<td>87.7</td>
</tr>
</tbody>
</table>

The largest volumes to be selected in each stage are given by: $V_j = \max\{V_{ij}\}$

$\Rightarrow V_1 = 87.7$ ft$^3$ ; $V_2 = 48.7$ ft$^3$. 
8.- Inventories

Selection of the Production Cycle (PC): Trade-off.

Fraction of transition or cleanup times vs. Inventories.

PC ↓ → ↓ Inventory (products available frequently) + ↑ fraction of the transitions.
PC ↑ → ↑ Inventory (production less frequently) + ↓ fraction of the transitions.

Example: demand 500,000 kg/yr of A, and 1,000,000 kg/yr of B. 8000 hrs. horizon time.

<table>
<thead>
<tr>
<th>Product</th>
<th>Processing Time (hrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stage 1</td>
</tr>
<tr>
<td>A</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
</tr>
</tbody>
</table>

a) Single Product Campaigns (SPC):
- Assume production cycle = 1000 hrs. → 8 campaigns.
- Same Batch Size. \( P_A = 62,500 \text{ kg} \), CT = 5 hrs. ; \( P_B = 125,000 \text{ kg} \), CT = 4 hrs.

\[
B = \frac{62,500}{t_A/5} = \frac{125,000}{t_B/4}.
\]

\[
t_A = 385 \quad ; \quad t_B = 615 \text{ hrs.} \ ; \quad B = 812 \text{ kg}.
\]

\[
t_A + t_B = 1000 \text{ hrs.}
\]

\[
\text{N° batches A} = \frac{62,500}{812} = 77 \ ; \quad \text{N° Batches B} = \frac{125,000}{812} = 154.
\]
• Assume Constant demand rates, $d_p$:
  
  $d_A = \frac{62,500}{1000} = 62.5 \text{ kg/h}$;  
  
  $d_B = \frac{125,000}{1000} = 125 \text{ kg/h}$.

• Production rates, $p_p$:
  
  $p_A = \frac{62,500}{385} = 162.3 \text{ kg/h}$;  
  
  $p_B = \frac{125,000}{615} = 203.3 \text{ kg/h}$.

• Inventory profile for A:
  
  0 – 385: accumulation rate $= p_A - d_A = 162.3 - 62.5 = 99.8 \text{ kg/h}$.

  385 – 1000: depletion rate $= -d_A = -62.5 \text{ kg/h}$.

  From 0 – 385 produced 62,500 kg, sold 24,257 kg. $\rightarrow$ Average Inventory $= \frac{1}{\tau} \cdot \int f(t) dt$

  $\bar{I} = \frac{1000 \times (38,423)}{2} / 1000 = 19,211 \text{ kg}$.
8.- Inventories

- Inventory profile for B:
  0 – 385: depletion rate = \(-d_B = -125 \text{ kg/h.}\)
  385 – 1000: accumulation rate = \(p_B - d_B = 203.3 - 125 = 78.3 \text{ kg/h.}\)

Average Inventory = area under curve.

\[
\bar{I} = 24,077 \text{ kg}
\]

If inventory cost 1.25 €/kg yr \rightarrow\) Inventory Cost = 1.25 \((19,211 + 24.077) = 54,110 \text{ €/yr.}\)
8.- Inventories

- **CT (ABB)** = 12 hrs.
- **N° Cycles** = 8000 / 12 = 667 cycles.
  → 667 batches A; 1333 batches B.
- **Batch Size** = 500,000 / 667 = 750 kg (vs. 812 kg).

- **Stage 2** = 12 hrs.
- **If daily deliveries:** Accumulation =
  - A: 2 · 750 = 1,500 kg.
  - B: 4 · 750 = 3,000 kg.
- **Inventory costs** = 1.25 (1,500 + 3,000) = 5,625 €/yr.

If clean-up times ≠ 0 Mixed Product Campaigns (MPC) will require longer batch sizes but will still require lower Inventories.
9.- Further Reading and References


Examples of Batch process to obtain CT and makespan.
RELEVANT TO LEARNING (I)

• What are the reasons for designing a batch process instead of a continuous process?

• Flowshop and Jobshop processes.

• What is a recipe? What are CT and Makespan?

• Campaign (SPC, MPC) and Transfer policies (ZW, NIS, UIS).

• Alternatives for solving Bottleneck units.

• Characteristics of the synthesis of Multiproduct Batch Plants.

• In a Semi-Batch or Batch process, in what cases will it make sense to use process units in parallel?
RELEVANT TO LEARNING (II)

- Given the processing times of 3 products A, B and C in the table, determine the Gantt charts, the makespan and the cycle time to manufacture 2 batches of A, 1 batch of B and 1 batch of C in the following cases:
  - No Intermediate Storage (NIS) with the AABC sequence and the BAAC sequence.
  - Unlimited Intermediate Storage (UIS) with the AABC sequence and the BAAC sequence.

• Dados los tiempos de procesado de 3 productos A, B y C de la tabla, determinar las gráficas de Gantt, el makespan y el tiempo de ciclo para fabricar 2 lotes de A, 1 lote de B y 1 lote de C en los casos:
  - No Intermediate Storage (NIS) con la secuencia AABC y la secuencia BAAC.
  - Unlimited Intermediate Storage (UIS) con la secuencia AABC y la secuencia BAAC.

<table>
<thead>
<tr>
<th>Product/ Step</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>