Chemical Process Design
Subject 11. Design and scheduling of batch processes

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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

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.
2.- Single Product Batch Plants: Example, Scheduling by Gantt chart

Example of Batch Process

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)

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

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 φ scheduling (Campaigns)

**Example:** Production of 2 batches of A and 2 batches of B

<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>2</td>
</tr>
</tbody>
</table>

a) **Single Product Campaigns (SPC)**

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

b) **Mixed Product Campaigns (MPC)**

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

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

- $CT_{A+B} = 9$ hrs (To repeat ABAB).
- MSpan (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>j₁ j₂ j₃</td>
</tr>
<tr>
<td>i₁</td>
<td>τ₁₁ τ₁₂ τ₁₃</td>
</tr>
<tr>
<td>i₂</td>
<td>τ₂₁ τ₂₂ τ₂₃</td>
</tr>
</tbody>
</table>

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

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

- $CT_{A+B} = 6+3+2$ (slack) = 11 hrs (To repeat ABAB)
- Makespan (2 batches) = 26 hrs.

NIS transfer

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

UIS transfer

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

Intermediate storage tanks between stages

→ can increase the efficiency or equipment utilization

Parallel units operating out of cycle

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

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.

- Stage 1
  - Cycle time \( CT_{\text{stage 1}} = 12 \) h; handles batches of 1000 kg;
  - Handles 1000 kg
- Stage 2
  - Cycle time \( CT_{\text{stage 2}} = 3 \) h; handles batches of 250 kg.
  - Handles batches of 250 kg

\[ CT = \max \left\{ \frac{\tau_{ij}}{NP_j} \right\} \]

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

\[ CT = \max \{12/2, 3\} = 6 \text{ h} \]

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

- The cycle time has been halved \( \rightarrow \) can reduce the batch size to 500 kg
- 4 fermenters eliminate all idle times

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6.- Synthesis of Multiproduct Batch Plants

STRUCTURAL DECISIONS
a) Assignments of tasks to equipment
b) Number of parallel units or intermediate storage

SCHEDULING DECISIONS
a) Campaigns and transfer policies
b) Sequencing at products

Assignment tasks to equipment
Recipe → Successive Tasks
Ex. Single product batch process with four processing tasks

<table>
<thead>
<tr>
<th>Task Nº</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 h)</td>
<td>React (4 h)</td>
<td>Mix (1 h)</td>
<td>React (2 h)</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 equipment:

- Cycle time = 4 h
- 4 units equipment

ZW policy

Stage 1: 2
Stage 2: 4
Stage 3: 1
Stage 4: 2

Time
6.- Synthesis of Multiproduct Batch Plants

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 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](image1)

- Cycle time = 4 h
- 3 units 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](image2)

- Cycle time = 9 h
- 1 unit 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: 1: Mix 1 lb A, 1 lb B, and react for 4 hours to form C. The yield is 40% in weight and the density of the mixture, $\rho_m$ is 60 lb/ft$^3$

2: Add 1 lb solvent and separate by centrifuge during 1 h to recover 95% of product C. The density of the mixture is $\rho_m$ 65 lb/ft$^3$

Mass Balance

\[
1 \text{ lb A} \quad 1,2 \text{ lb A,B} \quad 0,8 \text{ lb C} \quad 1 \text{ lb Solv} \\
0,76 \text{ lb C} \quad \text{product} \\
2,24 \text{ lb A,B,solvent}
\]

Define **Size Factors, $S_j$,** for each stage $j$:

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

**STAGE 1:** Specific volume $v = 1/\rho_m = 0.0166 \text{ ft}^3/\text{lb mix}$.  
Size Factor: $S_1 = 0.0166 \text{ ft}^3/\text{lb mix} \times [2 \text{ lb mix} / 0.76 \text{ lb prod.}] = 0.0438 \text{ ft}^3/\text{lb prod.}$

**STAGE 2:** Specific volume $v = 1/\rho_m = 1 / 62.5 = 0.0153 \text{ ft}^3/\text{lb mix}$.  
Size factor: $S_2 = 0.0153 \text{ ft}^3/\text{lb mix} \times [3 \text{ lb mix} / 0.76 \text{ lb prod.}] = 0.0607 \text{ ft}^3/\text{lb prod.}$

*If One Unit per Stage, ZW policy transfer:*

Cycle time = Max $\{4,1\} = 4 \text{ h} \rightarrow$ Batches = 6000 h / [4 h/batch] = 1500 batches  
Batch Size Product. $B = 500,000 \text{ lb prod./} 1500 = 333 \text{ lb prod.}$  
Size Vessel 1: $V_1 = S_1 \times B = 0.0438 \text{ ft}^3/\text{lb prod.} \times 333 \text{ lb prod.} = 14.6 \text{ ft}^3$  
Size Vessel 2: $V_2 = S_2 \times B = 0.0607 \text{ ft}^3/\text{lb prod.} \times 333 \text{ lb prod.} = 20.2 \text{ ft}^3$

*Bottleneck Stage 1 → 2 Parallel Units in Stage 1:*

Cycle time = max $\{4/2, 1\} = 2 \text{ h} \rightarrow$ Batches = 6000/2 = 3000 batches  
Batch Size = 166 lb  
Stage 1: 2 vessels, $V_1 = 7.3 \text{ ft}^3$  
Stage 2: 1 vessel, $V_2 = 10 \text{ ft}^3$

$VT = 24.6 \text{ ft}^3$, 2 vessels $<$ $VT = 34.8 \text{ ft}^3$, 3 vessels

Reduction in the investment cost depending on the cost correlation
Sizing Batch Processes: Multiple 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 campaigns] over one year.

<table>
<thead>
<tr>
<th>Product</th>
<th>Processing time (h)</th>
<th>Size Factors (ft³/lb prod.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>St. 1</td>
<td>St. 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 h A to B, B to A

Cycle time $A = C_{T_A} = 8$ h, Cycle time $B = C_{T_B} = 6$ h;
Effective time for production in each cycle = $t_A, t_B = 992$ h

How to allocate the production of A and B (i.e., selecting $t_A, t_B$) during this time horizon? A simple solution is to use as a heuristic the same batch size for all products. The batch size $Bi$ or product $i$ is given by:

$$Bi = \frac{\text{Production } i}{\text{nº batches } i} = \frac{\text{Production } i}{\frac{\text{production time } ti}{CTi}}$$

Production per campaign $\rightarrow P_A: \frac{500,000}{6} = 83,333$ lb; $P_B: \frac{300,000}{6} = 50,000$ lb
7.- Sizing Batch Processes: Multiple Product Plants

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

\[
\text{Linear Equations: } \frac{83,333}{t_A/8} = \frac{50,000}{t_B/6}; \ t_A + t_B = 992
\]

\[
\text{Solutions: } t_A = 684 \text{ h}; \ t_B = 308 \text{ h}; \ B_A = B_B = 974 \text{ lb}
\]

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}) (ft(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>St. 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: 
\[V_j = \max_{i=1,N} \{V_{ij}\}\]
\[\rightarrow V1 = 87.7 \text{ ft}^3; \ V2 = 48.7 \text{ ft}^3\]
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 h horizon time.

<table>
<thead>
<tr>
<th>Product</th>
<th>Processing time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>St. 1</td>
</tr>
<tr>
<td>A</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
</tr>
<tr>
<td>Zero clean up times</td>
<td></td>
</tr>
</tbody>
</table>

a) Single Product Campaigns (SPC)

Assume production cycle = 1000 h → 8 campaigns
Same Batch Size. \( P_A = 62,500 \text{ kg}, \) CT = 5 h; \( P_B = 125,000 \text{ kg}, \) CT = 4 h

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

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

\[
t_A + t_B = 1000 \text{ h}
\]

\[
\text{Nº batches A} = \frac{62,500}{812} = 77; \quad \text{nº Batches B} = \frac{125,000}{812} = 154
\]
8.- Inventories

Assume Constant demand rates, \( d_p \)
\[
d_A = \frac{62,500}{1000} = 62.5 \text{ kg/h}; \quad d_B = \frac{125,000}{1000} = 125 \text{ kg/h}
\]

Production rates, \( p_p \)
\[
p_A = \frac{62,500}{385} = 162.3 \text{ kg/h}; \quad p_B = \frac{125,000}{615} = 203.3 \text{ kg/h}
\]

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 = area under curve.

\[
\bar{I} = \frac{1}{\tau} \cdot \int f(t)dt
\]

\[
\bar{I} = \frac{1000 \times (38,423)}{2} / 1000 = 19,211 \text{ kg}
\]
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 → Inventory Cost = 1.25 \((19,211 + 24.077) = 54,110 \text{ €/yr}. \)
8.- Inventories

b) Cyclic Schedule, Mixed Product Campaign (MPC): ABBABB....

CT (ABB) = 12 h;
Nº Cycles = 8000 / 12 = 667 cycles
→ 667 batches A, 1333 batches B.

Batch Size = 500,000 / 667 = 750 kg (vs.812 kg)

Stage 2 = 12 h;
If daily deliveries: Accumulation
A: 2 x 750 = 1,500 kg
B: 4 x 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

