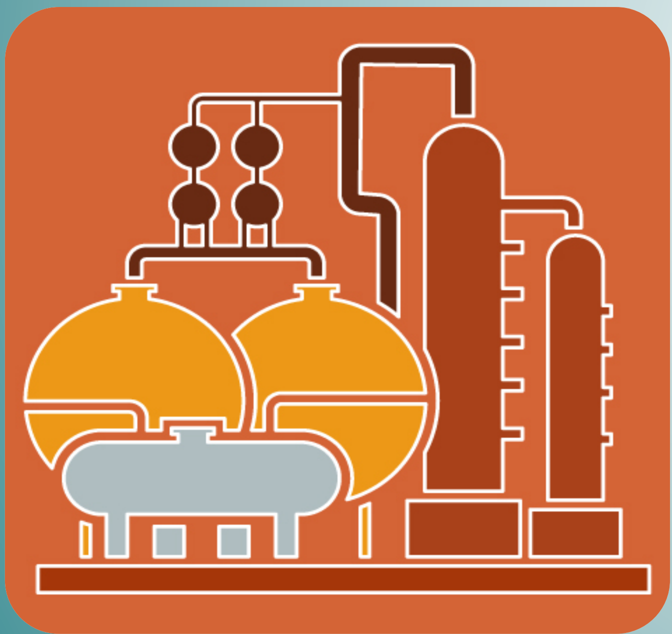
Chemical Process Design / Diseño de Procesos Químicos

Topic 9. Design and scheduling of batch processes



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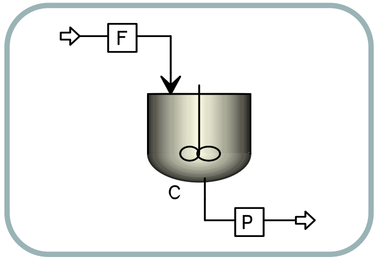
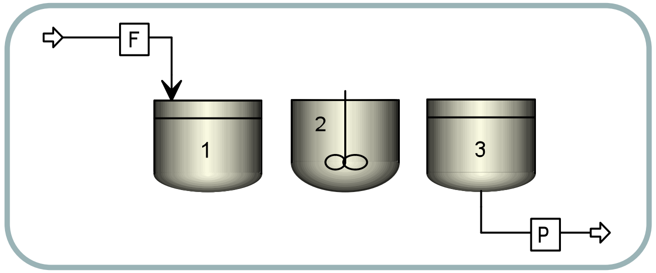
1.- Batch Processes: Introduction

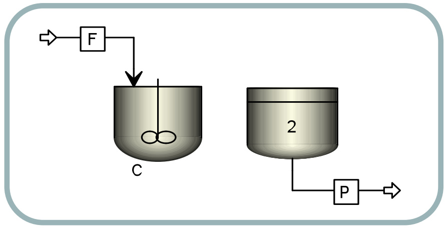


- **Continuous processes:** manufacture of commodities.

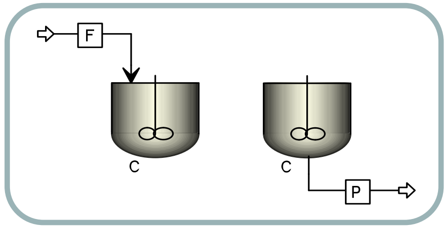


- **Batch processes:** specialty chemicals, pharmaceuticals.

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



* Fed-batch processes



* Batch-product removal

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.

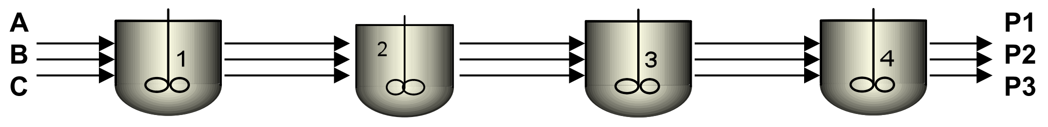
Recipe management system Batch in a pharmaceutical company to produce generics.
http://www.kolektorautomation.com/index.php?t=referenceNews&l=en&id=60.

Pesticides production in batch process.
http://argossouthafrica.weebly.com/about.html.

1.- Batch Processes: Introduction

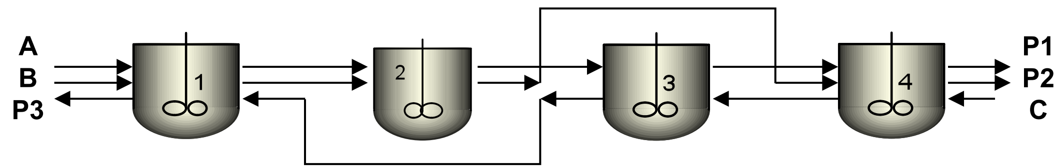
When a batch process is used to manufacture two or more products **(Multiple Product Batch Plants),** two major limiting types of plants can arise:

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



Flowshop plant

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

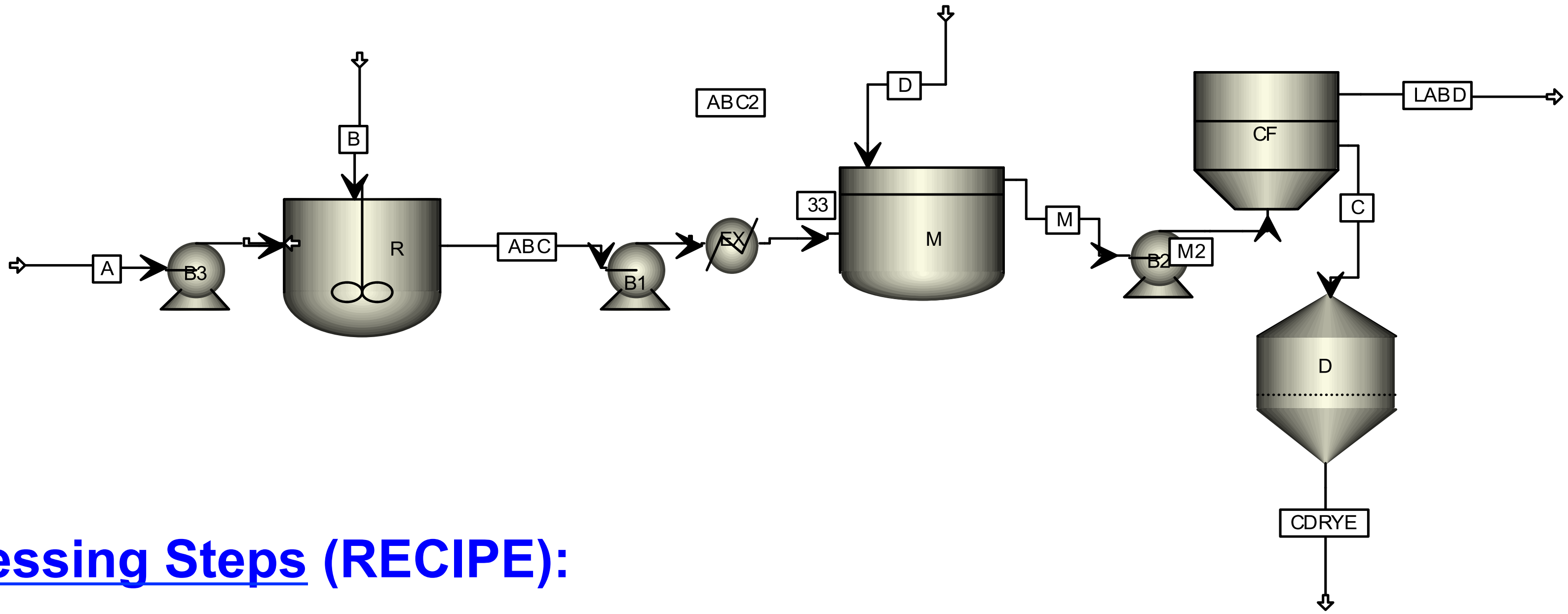


Jobshop plant

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



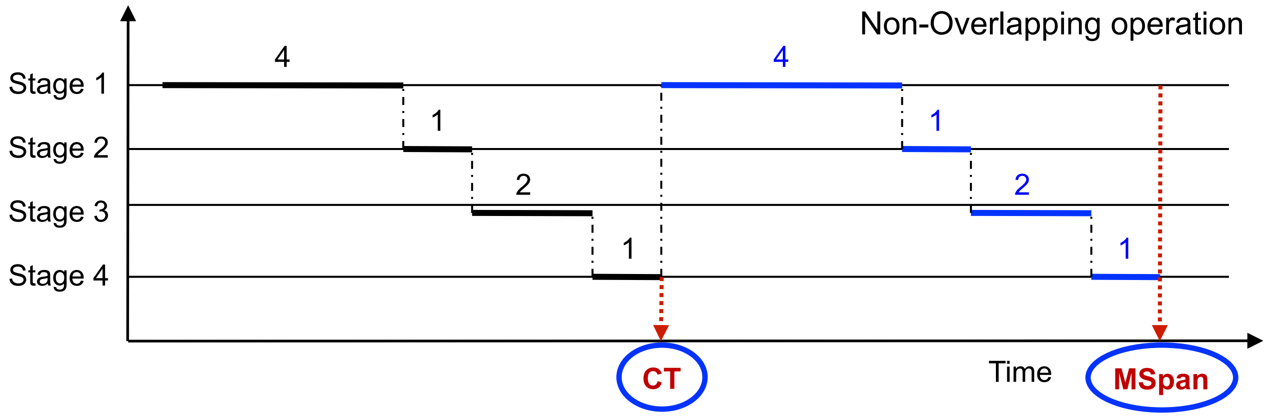
Processing Steps (RECIPE):

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.

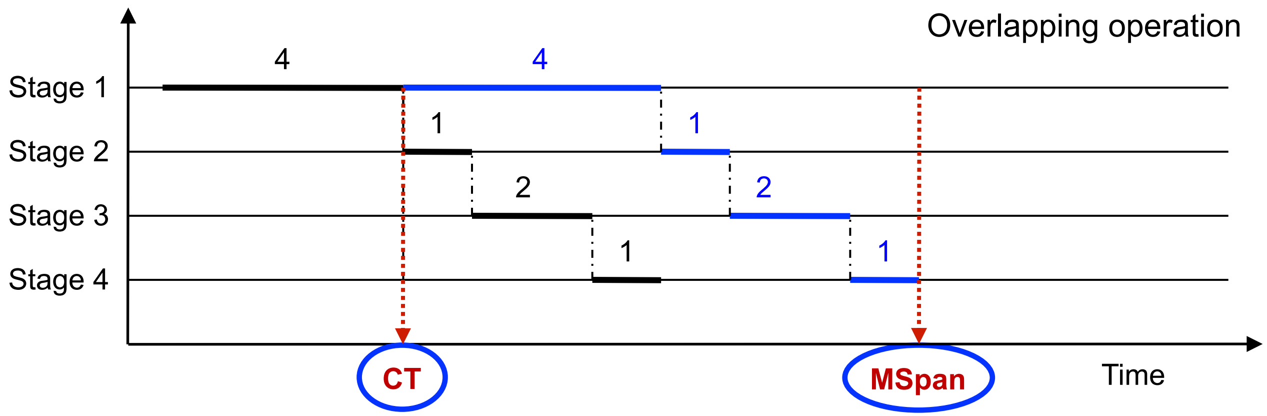
- Amounts are also specified.
- Assume processing times independent of batch sizes.
- Neglect transfer times.

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

Scheduling → Gantt chart (time activity chart)



- Cycle time (CT) = 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.

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:

$$CT = \max_{J=1,M} \left\{ \tau_j \right\}$$

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.

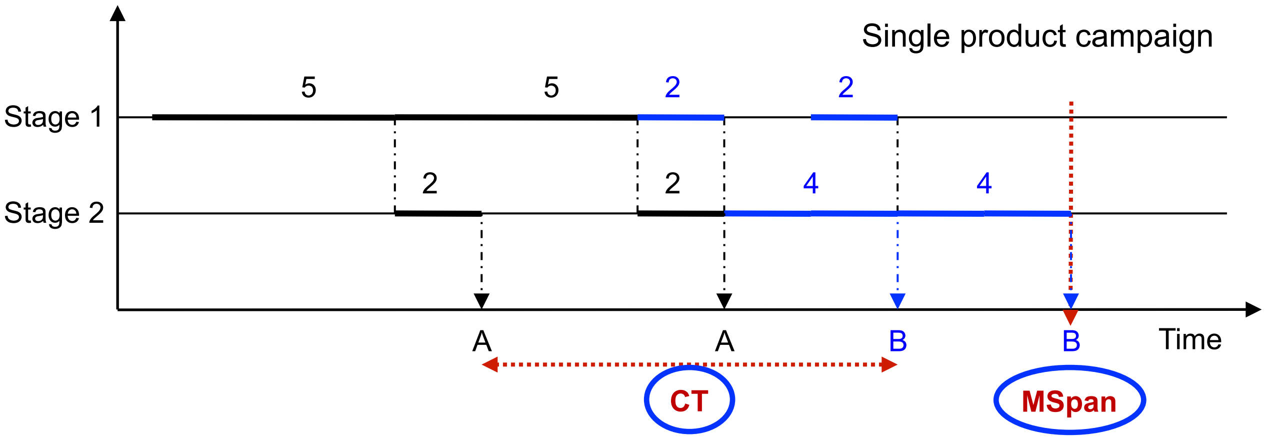
3.- Multiple Product Batch Plants

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

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

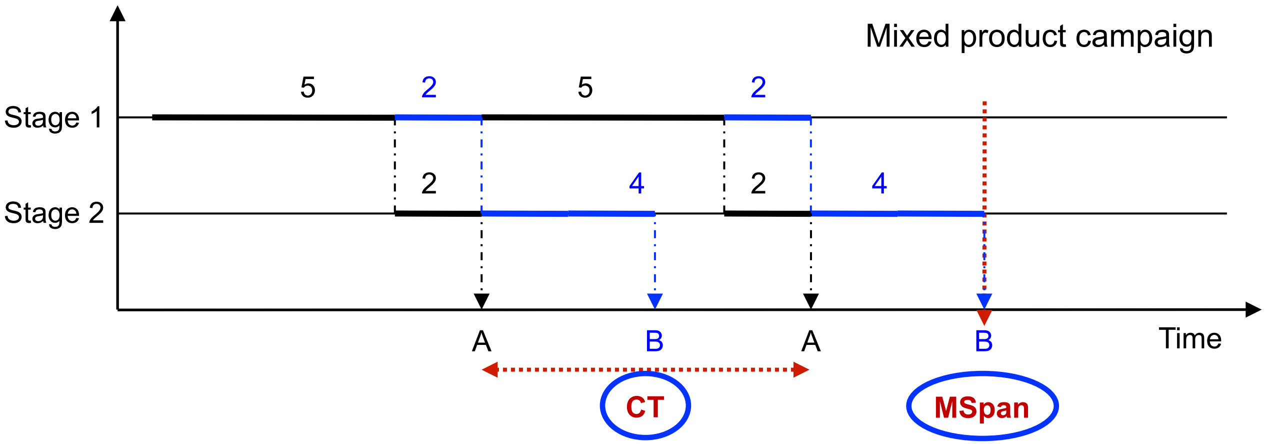
Product	Processing Time (hrs.)	
	Stage 1	Stage 2
A	5	2
B	2	4

a) Single Product Campaigns (SPC)



- Cycle time A = 5 hrs.
- Cycle time B = 4 hrs.
  → CT_{A+B} = 9 hrs.
  (To repeat AABB).
- Makespan (2 batches) = 20 hrs.

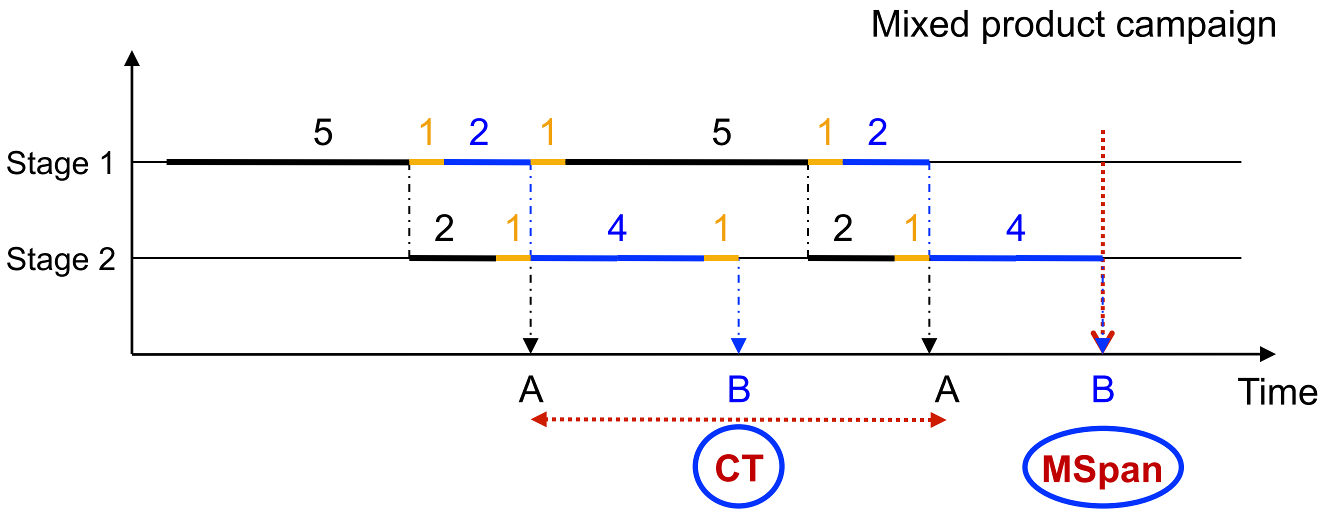
b) Mixed Product Campaigns (MPC)



- CT_{A+B} = 7 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 hrs. (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.

Product	Processing Time (hrs.)		
	Stage 1	Stage 2	Stage 3
A	6	4	3
B	3	2	2

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

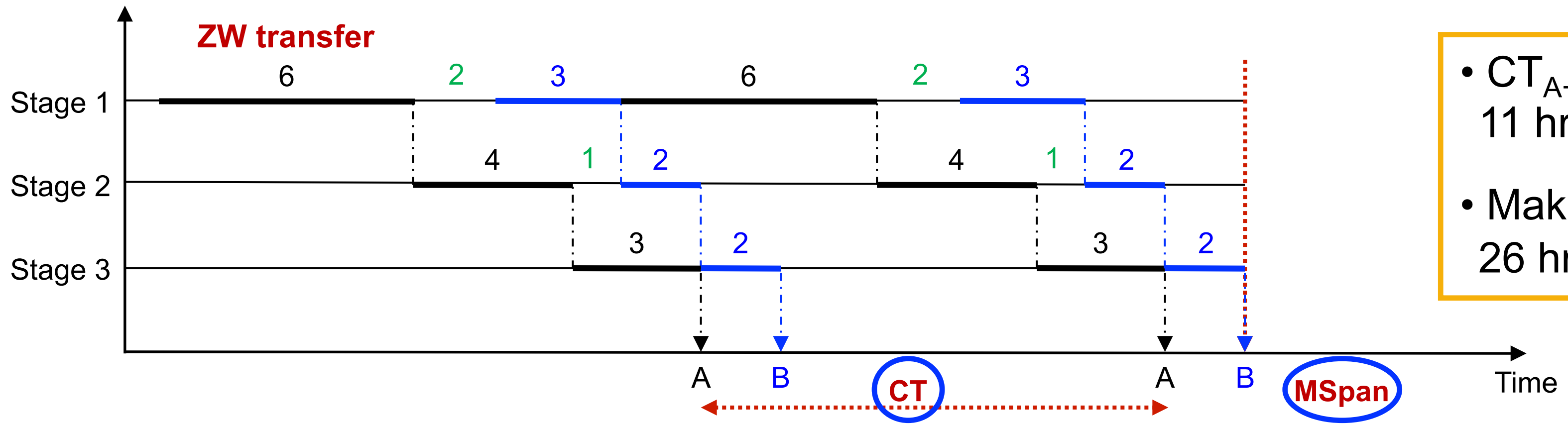
Product	Processing Time (hrs.)		
	j_1	j_2	j_3
i_1	t_{11}	t_{12}	t_{13}
i_2	t_{21}	t_{22}	t_{23}

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

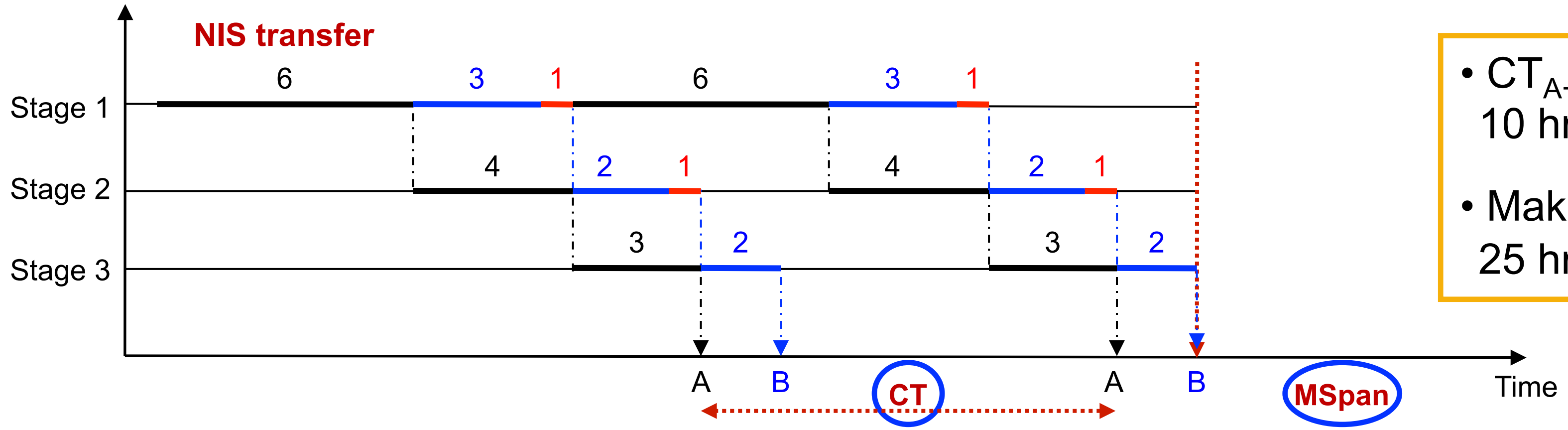
Is the absolute minimum (UIS) with:

τ_{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.

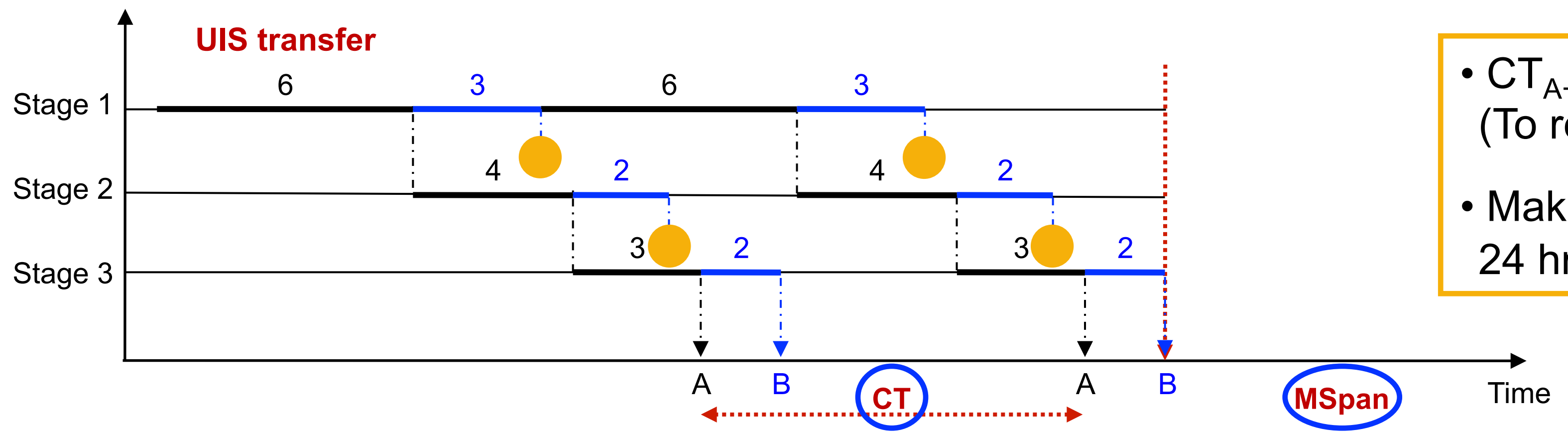
4.- Transfer policies



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



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



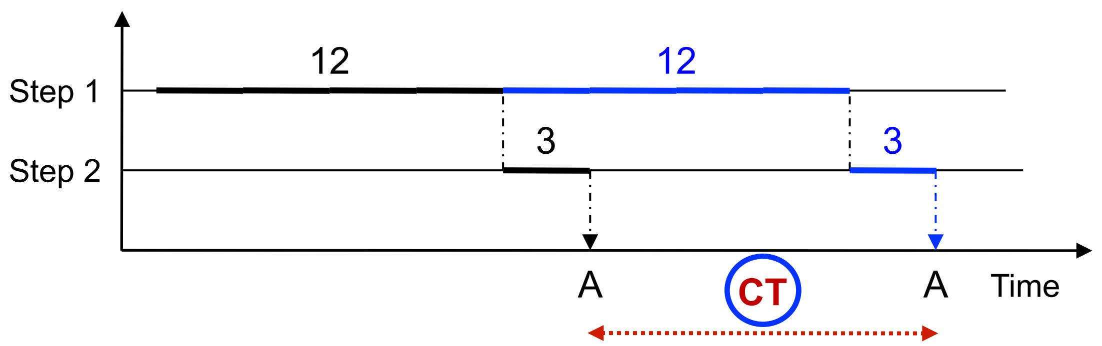
- CT_{A+B} = 6 + 3 = 9 hrs. (To repeat ABAB).
- Makespan (2 batches) = 24 hrs.

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 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).



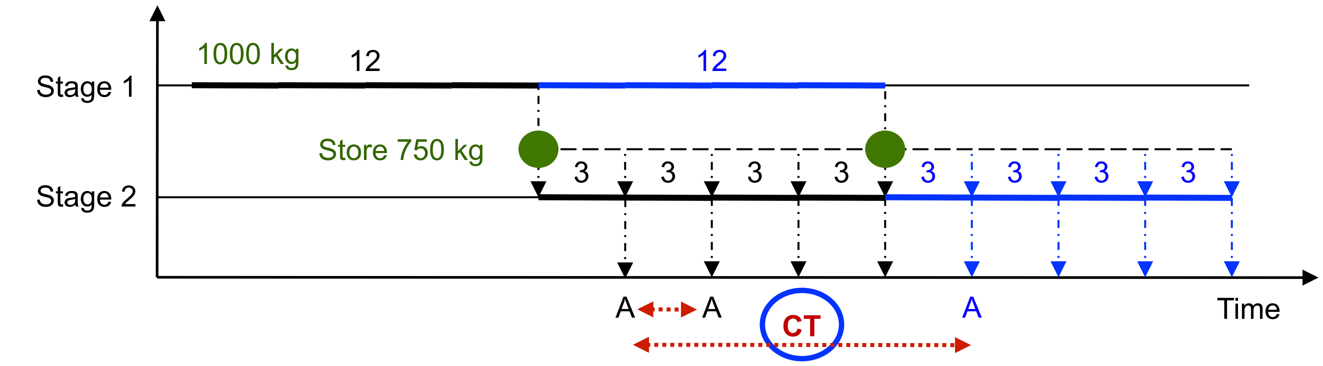
Alternatives to decrease CT:

a) Intermediate storage between stages.

b) Two parallel units in **Stage 1** (Bottleneck unit).

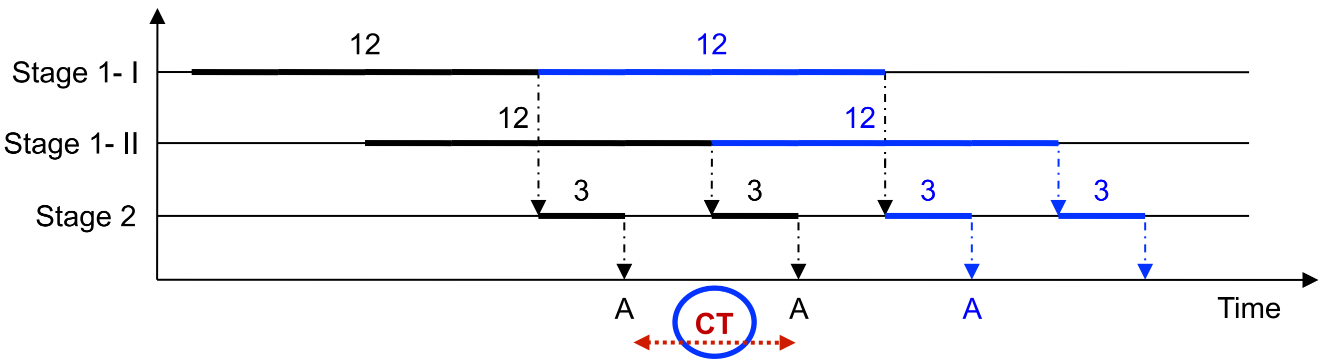
5.- Parallel units and Intermediate storage

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.



- $CT_{stage\ 1}$ = 12 hrs.; handles batches of 1000 kg.
- $CT_{stage\ 2}$ = 3 hrs.; handles batches of 250 kg.

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



$$CT = \max_{j=1\ldots M}\left\{\tau_{ij} / NP_j\right\}$$

τ_{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 hrs.

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

6.- Synthesis of Multiproduct Batch Plants (p. 196 Biegler *(et al.)* 1997)

- **STRUCTURAL DECISONS:**
  - **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.

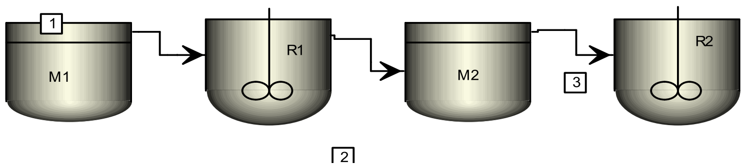
Assignment of tasks to equipment:

Recipe → Successive tasks.

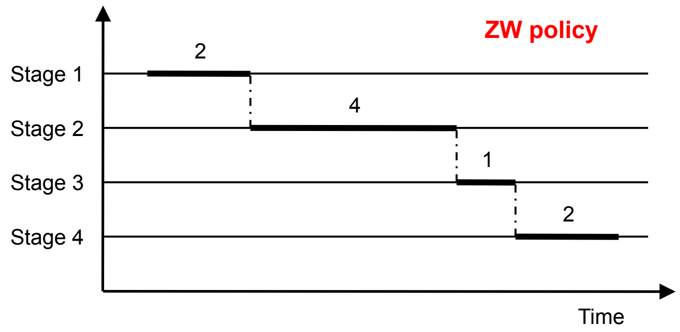
Ex. Single product batch process with four processing tasks.

Task N°	Task 1 →	Task 2 →	Task 3 →	Task 4
Operation (t)	Mix (2 hrs.)	React (4 hrs.)	Mix (1 hrs.)	React (2 hrs.)
Material	C/S	C/S	C/S	S/S

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

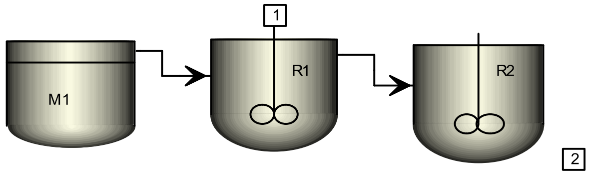


- Cycle time = 4 hrs.
- 4 pieces of equipment.

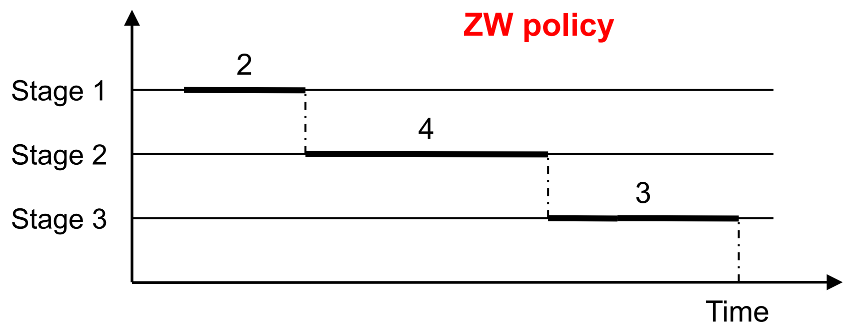


6.- Synthesis of Multiproduct Batch Plants

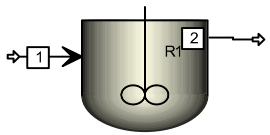
2. **The Second alternative is to assign Tasks 3 and 4 to one single piece of equipment, namely to the stainless steel (S/S) reactor. In this alternative, the cycle time remains unchanged in 4 hours despite the fact that we have eliminated one piece of equipment. This alternative is clearly superior to the 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".**



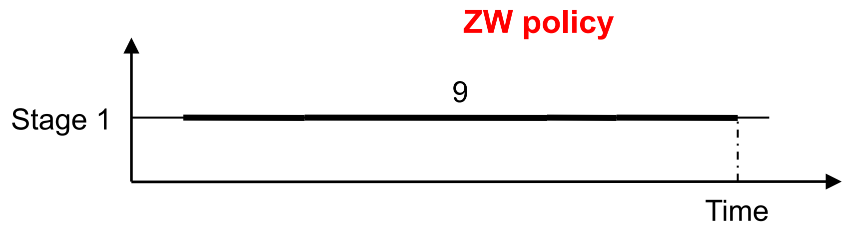
- Cycle time = 4 hrs.
- 3 pieces of equipment.



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



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



Economic evaluation → The best Alternative

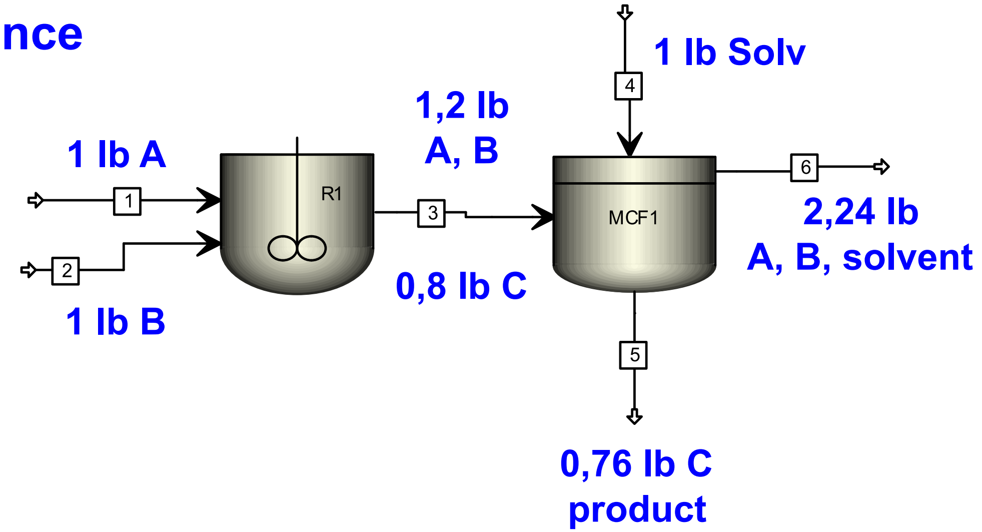
7.- Sizing Batch Processes: Single Product Plants

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, $\mathbf{r_m}$ 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 $\mathbf{r_m}$ 65 lb/ft^3.

Mass Balance



Define **Size Factors**, ***Sj*,** for each stage ***j***:

Sj *= volume vessel* ***j*** *required to produce 1 lb of final product.*

7.- Sizing Batch Processes: Single Product Plants

- **STAGE 1:** specific volume $v = 1 / r_m = 1/60 = 0.0166$ ft^3/lb mix.

  Size Factor: $S1 = 0.0166$ ft^3/lb mix · [2 lb mix / 0.76 lb prod.] = 0.0438 ft^3/lb prod.

- **STAGE 2:** specific volume $v = 1 / r_m = 1 / 62.5 = 0.0153$ ft^3/lb mix.

  Size factor: $S2 = 0.0153$ ft^3/lb mix · [3 lb mix / 0.76 lb prod.] = 0.0607 ft^3/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 = 500,000 lb prod. / 1500 = 333 lb prod.
  - **Size Vessel 1:** V1 = S1 · B = 0.0438 ft^3/lb prod. · 333 lb prod. = 14.6 ft^3.
  - **Size Vessel 2:** V2 = S2 · B = 0.0607 ft^3/lb prod. · 333 lb prod. = 20.2 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, V1 = 7.3 ft^3.
  - **Stage 2:** 1 vessel, V2 = 10 ft^3.

VT = 24.6 ft^3, 3 vessels < VT = 34.8 ft^3, 2 vessels.

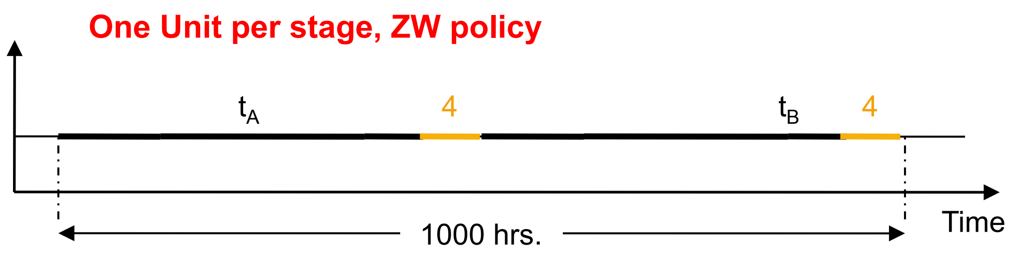
Reduction in the investment cost depending on the cost correlation.

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 campaigns] over one year.

Product	Processing Time (hrs.)		Side Factors (ft^3/lb prod.)	
	Stage 1	Stage 2	Stage 1	Stage 2
A	8	3	0.08	0.05
B	6	3	0.09	0.04
Cleanup times: 4 hrs. A to B, B to A.				



Cycle time A = CT_A = 8 hrs., **Cycle time B = CT_B** = 6 hrs.;

Effective time for production in each cycle = t_A, t_B ; $t_A + t_B$ = 992 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 Bi or product i is given by:

Bi = Production I (Pi) / n° batches i = Production I (Pi) / [production time ti / CTi]

Production per campaign (Pi) → P_A: 500,000 / 6 = 83,333 lb ; P_B: 300,0000 / 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:** 83,333 / [t_A / 8] = 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 ($V_{ij} = S_{ij} B_i$):

Product	Volumes Vij (ft^3)	
	Stage 1	Stage 2
A	77.9	**48.7**
B	**87.7**	39.0

The largest volumes to be selected in each stage are given by: $V_j = \max_{i=1,N} \{V_{ij}\}$

→ V1 = 87.7 ft^3 ; V2 = 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.

Product	Processing Time (hrs.)	
	Stage 1	Stage 2
A	5	3
B	3	4

a) Single Product Campaigns (SPC):

- Assume production cycle = 1000 hrs. → 8 campaigns.
- Same Batch Size. P_A = 62,500 kg., CT = 5 hrs. ; P_B = 125,000 kg, CT = 4 hrs.

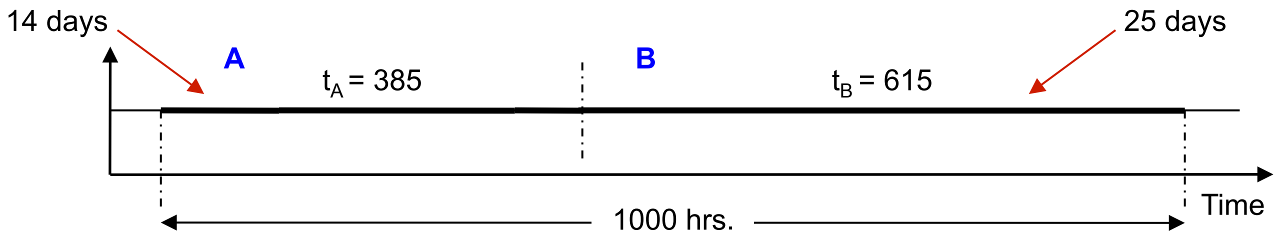
B = 62,500 / [t_A / 5] = 125,000 / [t_B / 4].

t_A = 385 ; t_B = 615 hrs. ; B = 812 kg.

$t_A + t_B$ = 1000 hrs.

N° batches A = 62,500 / 812 = 77 ; **N° Batches B** = 125,000 / 812 = 154.

8.- Inventories



- **Assume Constant demand rates, d_P:**

  d_A = 62,500 / 1000 = 62.5 kg/h. ; d_B = 125,000 / 1000 = 125 kg/h.

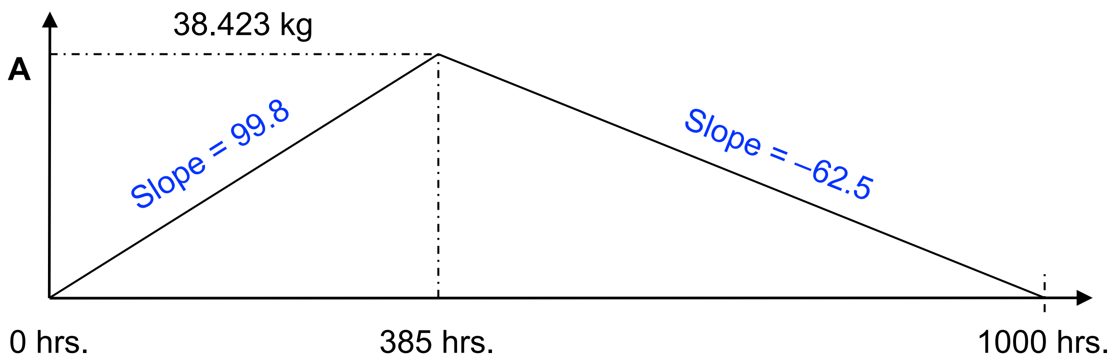
- **Production rates, p_P:**

  p_A = 62,500 / 385 = 162.3 kg/h ; p_B = 125,000 / 615 = 203.3 kg/h.

- **Inventory profile for A:**

  0 – 385: accumulation rate = $p_A - d_A$ = 162.3 – 62.5 = 99.8 kg/h.

  385 – 1000: depletion rate = $-d_A$ = –62.5 kg/h.



From 0 – 385 produced 62,500 kg, sold 24,257 kg. → Average Inventory = area under curve.

$$\bar{I} = \frac{1}{\tau} \bullet \int f(t)dt$$

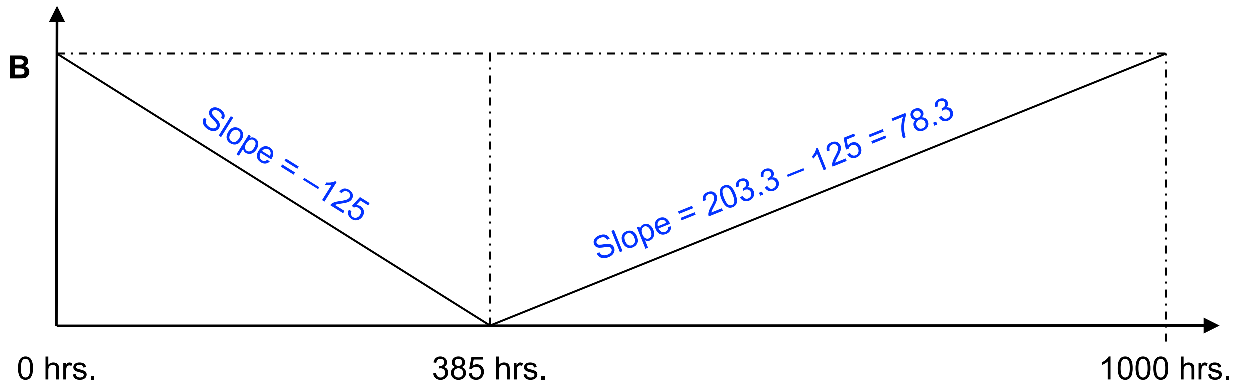
$$\bar{I} = \frac{1000 \times (38{,}423)}{2} / 1000 = 19{,}211\ kg$$

8.- Inventories

- **Inventory profile for B:**

  0 – 385: depletion rate = $-d_B$ = –125 kg/h.

  385 – 1000: accumulation rate = $p_B - d_B$ = 203.3 – 125 = 78.3 kg/h.

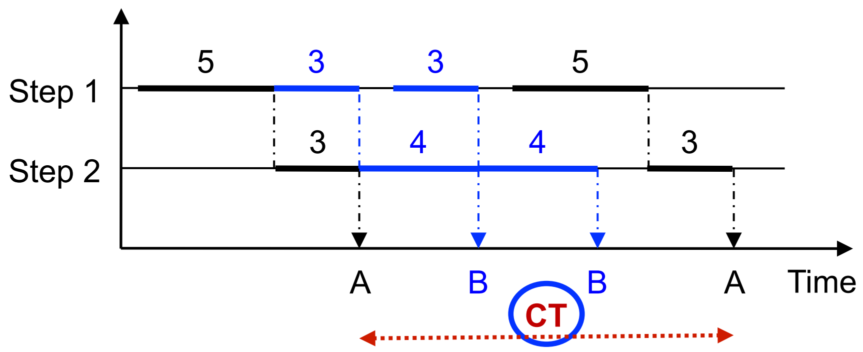


Average Inventory = area under curve.

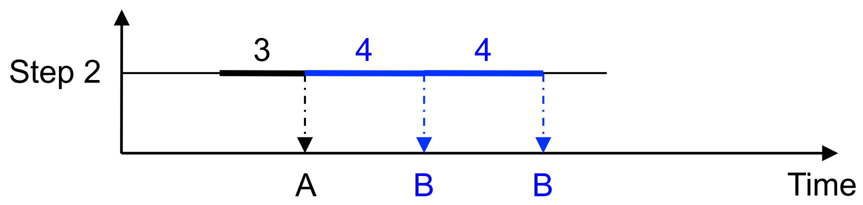
$$\bar{I} = 24{,}077\ kg$$

If **Inventory cost** 1.25 €/kg yr → Inventory Cost = 1.25 (19,211 + 24.077) = 54,110 €/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

- Biegler, L.; Grossmann, I. & Westerberg, A. (1997): *«Systematic methods of chemical process design»*. Prentice Hall.

- Seider, W.; Seader, J.; Lewin, D. & Widagdo, S. (2010): *«Product and process design principles. Synthesis, analysis and evaluation»*. 3rd Ed. John Wiley & Sons.

- Majozi, T. (2010): *«Batch chemical process integration. Analysis, synthesis and optimization»*. Springer.

PRACTICAL CHAPTER

- 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.***

Processing Time (hrs.) (Cleaning Time = 0)			
Product/ Step	Step 1	Step 2	Step 3
A	5	4	3
B	3	1	3
C	4	3	2