Estimating the Capacity of a Batch Process

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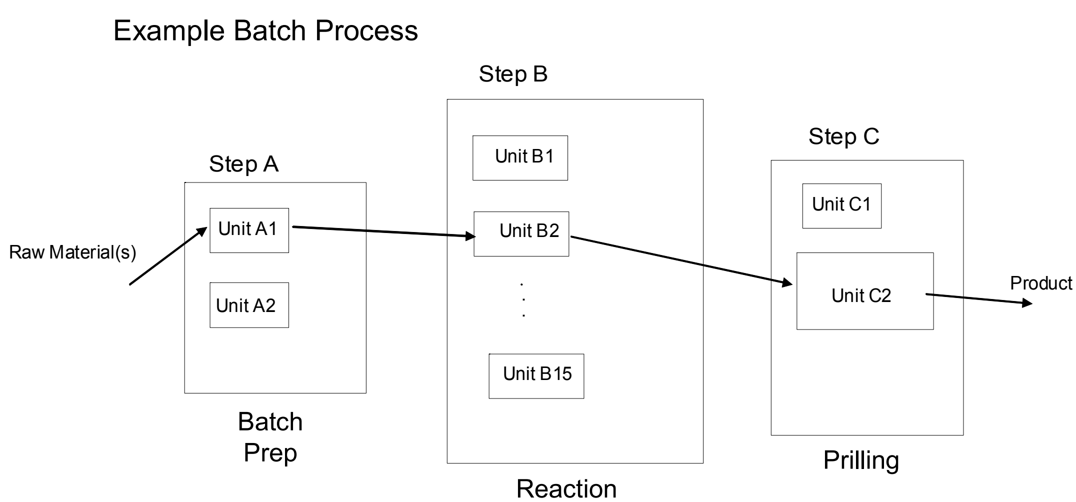
The batch process consists of a series of "steps" in sequence preformed on a discrete batch of material. If a particular step is not the bottleneck in the sequence of steps, then some of the equipment units within the step might be idle during operation. Good process design calls for matching in some way step cycle time so that no one step in the sequence is a bottleneck [1].

A batch process is comprised of :

- individual *steps*
- each step has one or more *units*
- units within a step may have *equal* or *unequal* cycle times
- we will distinguish between steps having units of *equal* and those having units of *unequal* cycle time.

An example of a simple batch process is shown in Figure 1.

Figure 1.



We are typically interested in determining:

- equivalent cycle time of a given step
- the bottleneck step
- the capacity of the *overall process*
- fraction of product produced by a given unit of bottleneck step

It will be found that analysis is complicated by steps which are composed of units of unequal cycle times. Possible reasons for having units of unequal cycle times within a step are:

- Production of different product characteristics by a different type of unit
- Production of different product characteristics by running same type of unit at different operating conditions
- Expansion of step capacity by adding new units having different cycle times

The assumptions that are made in the discussion which follows are:

- Batches all the same size
- Equipment availability is 100%
- Reagents for intermediate steps always available
- In determining the capacity of step, it is assumed that feed to the step is always available.

There are three categories of cycle times we refer to, namely:

- Unit (c, c*)
- Step (equivalent) (C, C*)
- Overall process (C^P)

where the asterisk denotes a step having units of equal cycle time. For a step with units of equal cycle time the equivalent cycle time of the step is

$$C^* = c^* / N \qquad (1.1)$$

where N = the number of units in the step.

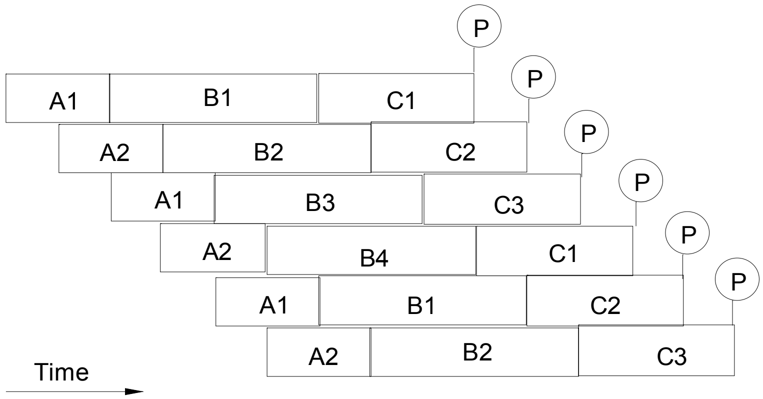
<u>Example A</u>
Consider a 3 step batch process in which each step has units of equal cycle times and the equivalent cycle time of each step is identical, for example:

Table 1 Steps of Equal Equivalent Cycle Times

Step	Number of Units in Step	Cycle Time of each unit in Step, hr	Equivalent Cycle Time of Step, hr
A	2	2	1
B	4	4	1
C	3	3	1

We can represent the functioning of this batch process as shown in Figure 2 In this process no unit is idle and the process cycle time is 1 hour per batch.

Figure 2 Three Step Batch Process with Steps having Units of Equal Cycle Time and Steps of Equal Equivalent Cycle Times



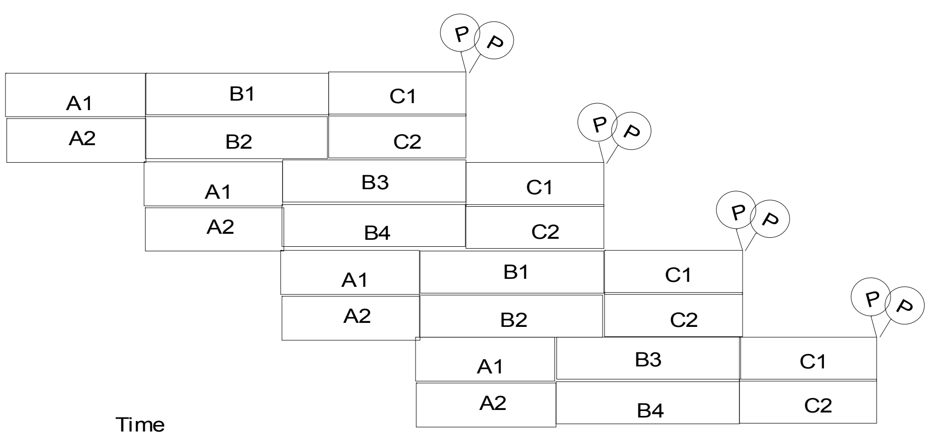
Example B

Consider now a 3 step batch process in which each step has units of equal cycle times but the equivalent cycle time of one of the steps is different. For example consider Example A where the cycle time of each of the A units is 3 hrs instead of 2 hrs, see Table 2. This process can be represented by Figure 3.

Table 2 Steps of Unequal Equivalent Cycle Times

Step	Number of Units in Step	Cycle Time of each unit in Step, hr	Equivalent Cycle Time of Step, hr
A	2	3	1.5
B	4	4	1
C	3	3	1

Figure 3 Three Step Batch Process with Steps having Units of Equal Cycle Time and Steps of *Unequal* Equivalent Cycle Times



It would appear from Table 2 that the bottleneck step is Step A and therefore the cycle process time is equal to the bottleneck process time, i.e., 1.5 hours. This is borne out by Figure 3. It will be noted that some of the units in Steps B are sometimes idle and in fact unit C3 is always idle. However, the units of Step A are never idle.

Equivalent Cycle Time of a Step Composed of Units of Unequal Cycle Time

For this case we recall the high school algebra problem of two boys, Billy and Joey, who can cut the lawn in 3 hrs and in 2 hrs, respectively. The question is how long will it take the two of them working together to cut the lawn. This line of reasoning leads to the expression for the cycle time of a step with units of unequal cycle times:

$$C = \frac{1}{\sum_{j=1}^{N} \frac{1}{c_i}} \qquad (1.2)$$

Example C

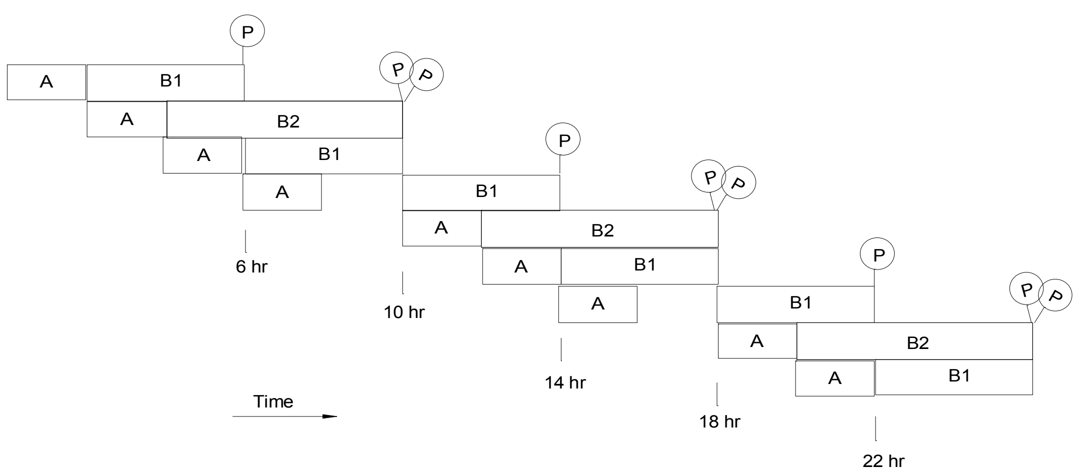
Here we consider a two step process in which one of the steps has units of unequal cycle time, see Table 3.

Table 3 Step with Units of Unequal Cycle Times

Step	Unit	Cycle time of unit, hr	Step Equivalent Cycle time, hrs
A	A	2	2
B	B1	4	2.4, by eq. (1.2)
	B2	6	

By examining Table 3 we would be inclined to say that the bottleneck step is B and the cycle time for the process is 2.4 hours per batch. The problem is that the assumption that step B, although it is the bottleneck step, always has feed is overly optimistic, for example see Figure 4 which is the schematic representation of the process.

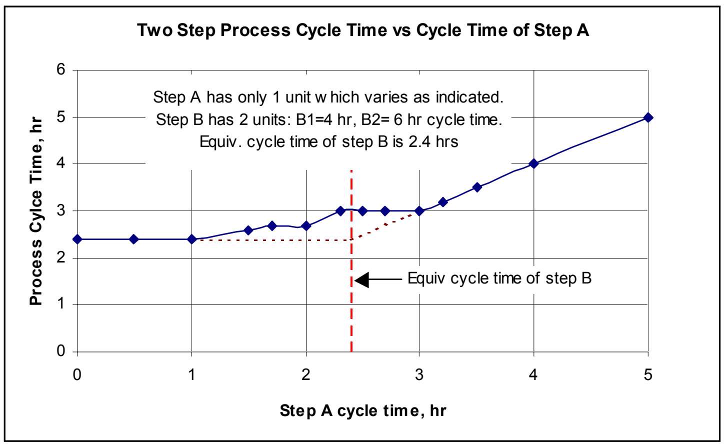
Figure 4 Two Step Batch Process in which the Second Step has Units of Unequal Cycle Time



It is seen in Figure 4 that at the end of 10 hrs B2, a unit of the so-called “bottleneck” step, is ready to receive feed but has to wait while A processes a batch first.

We now explore the effect of the cycle time of Step A on the overall process cycle time of Example C. A True Basic© computer program was developed to simulate this case. The results of holding the cycle times of B1 and B2 fixed at 4 and 6 hours, respectively, while the cycle time of unit A varied from 0 to 5 hours is shown in Figure 5. The ideal situation would be that the process cycle time is 2.4 hours for the cycle time of Step A $\leq$ 2.4 hr, and when cycle time of Step A $\geq$ 2.4 hr the process cycle is equal to the cycle time of A (see dashed curve of Figure 5). However, it is seen when the cycle time of Step A approaches 2.4 hr either from above or below, process cycle time is greater than theoretical due the idle time that the ‘bottleneck’ step experiences waiting for feed.

Figure 5



<u>Fraction of Product Produced by a Unit in the Limiting Step</u>
When the units in the limiting step are different and result in product of differing characteristics, then it is useful to know what the product mix will be at capacity production. If feed is always available to the limiting step, then the fraction of total product produced by a given unit, “j”, in the limiting step is

$$F_j = \frac{C}{c_j} \tag{1.3}$$

If feed is not always available to the limiting step then equation (1.3) is not strictly accurate but can be used as an approximation.

<u>Conclusions</u>
It is suggested that:

- For a step *comprised of units of equal cycle times*, c*, the step equiv cycle time is c*/N.
- For batch processes in which the units comprising a step are of *equal* cycle times, matching cycle times of the steps will result in a process with no units with idle time.

- For batch processes in which the units comprising a step are of *equal* cycle times the overall process cycle time is equal to the limiting step equivalent cycle time.
- For a step comprised of units of *unequal* cycle times, the equivalent step cycle time is given by $1/\Sigma(1/c_i)$
- For batch processes in which the units comprising a step are of *unequal* cycle times, overall process cycle time *may* be greater than or equal to the limiting step cycle time.
- A True Basic© computer code is available to calculate the simple 2 step type process of Example C.

Acknowledgement

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Reference

1. Manganaro, J., *Estimating the Capacity of Simple Batch Processes.* Chem. Eng. Progr., 2002. 98(August): p. 70.